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The Energy-GDP Nexus; Addressing an old question with new methods

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Abstract

This paper reassesses the causal relationship between per capita energy use and gross domestic product, while controlling for capital and labour (productivity) inputs in a panel of 30 OECD countries over the past 40 years. The paper uses panel unit root and cointegration testing and specifies an appropriate vector error correction model to analyse the nexus between income and energy use. In doing so we contribute to an old debate using modern tools that shed a new light. There is some evidence that over the short-run bidirectional causality exists. Our results also show a strong unidirectional causality running from capital formation and GDP to energy usage. In the long run the reverse causality, found in recent work, is lost. We then show that we can reproduce these earlier results in our data if we reproduce a slightly misspecified model for the Engle-Granger two-step procedure used in these earlier papers. Our findings thus imply that results are very sensitive to model misspecification and careful testing of specifications is required. Our results have some strong policy implications. They suggest that policies aimed at reducing energy usage or promoting energy efficiency are not likely to have a detrimental effect on economic growth, except over the very short run.

Keywords: Energy; GDP; capital; labour; causality; cointegration.

JEL classification: C23; O10; Q40; Q43

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1. Introduction

Energy use and per capita GDP are highly correlated over time and space. This correlation has lent support to the claim of "resource economics" that energy is an essential input in the economy, but can also be explained by mainstream arguments that posit energy use is the result of higher income and high income elasticities on energy intensive products and services. Empirically the direction of causation is notoriously hard to establish and an ongoing debate has unfolded in the literature since the seminal article by Kraft and Kraft (1978). Due to rapid developments in econometrics much of the early work in this field was outdated before a consensus could be reached on the direction of the relationship. The answer to this question, however, is of growing importance, because the direction of causality has big implications for public policy in the fields of climate change and energy security. If energy can be shown to "cause" economic activity, then all efforts should be put in getting and maintaining access to a cheap but greener and safer energy supply. If energy use is found to be a consequence of economic activity and driven by growing incomes and demand, however, than the response should be to reduce energy demand using market based and regulatory instruments. Bidirectional causation and/or neutrality (no causation) would call for an appropriate mix of both approaches.

The question has and continues to attract the attention of many scholars in the field (see e.g. Mehrara (2007) and Stern (2000) for overviews of this debate). The contributions of this paper are that it will reassesses the causal relation between energy and income by means of a literature study and state of the art econometric analysis. The literature review serves to position the paper. Then we analyse a panel of 30 OECD countries over the time period between 1960 and 2000. Therein lies our first contribution as to our knowledge the issue has not been studied in a panel of such breath (30 countries) or length (40 years) to date.[3] Between them these countries account for about 65 (1960) to 55 % (2000) of world GDP and comparable percentages of global energy use and greenhouse gas emissions.[4] Our second contribution comes from the fact that we employ appropriate state-of-the-art multivariate panel data cointegration techniques to assess the specific mechanism by which the causality between income and energy use runs. A final contribution follows when we show that a slightly misspecified error correction term causes our results to

3 Only in an unpublished working paper by Sinha (2009) did we find a panel of comparable dimensions (88 countries and 28 years), but that paper adds more diversity among countries, notably adding 58 developing countries, at the cost of losing the ability to control for capital as such data are lacking. We agree with Narayan and Smyth (2008) and Lee, Chang and Chen (2008) that not controlling for capital is a serious omission that can bias the results and we argue that the time dimension is much more relevant when we study the causal relationship between energy use and GDP. We therefore chose depth over breath and our sample contains longer time series on much more similar (OECD) countries.

4 See for example Energy Information Administration (2006)

be overturned, explaining why our results differ from those in the few studies that have employed multivariate panel cointegration techniques (e.g. Mahadevan and Asafu-Adjaye (2007), Narayan and Smyth (2008), Lee, Chen and Chang (2008)) and stressing the importance of appropriate specification. Finally, we contrast our results to those in Sinha (2009) who analyses a much broader set of countries (including 58 developing countries) over a shorter time span without controlling for capital. We conclude that, with a correct model specification and controlling for capital intensity, GDP growth drives energy use in the long run (>2 years) and not the other way around in the OECD. OECD countries should therefore not hesitate and implement energy demand reducing policies to achieve climate objectives and reduce energy dependency.

The remainder of the paper is structured as follows; section 2 starts with an overview of previous studies conducted in this field. Section 3 describes our data, introduces the methodology and presents the results of the empirical analysis, after which section 4 concludes.

2. Literature review

The topic of causality between energy use and economic growth has been under study for 30 years and scores of papers have been published on the topic.[5] Despite these efforts, however, a consensus has not emerged. In this section we do not intend to be complete in our review of the literature, but rather discuss some selected publications that are representative for many others. Previous work by different authors can broadly be divided into four categories of results (no causation, causation from energy to GDP, causation from GDP to energy and bidirectional causation) and five categories of methodologies (Simple causality tests, Bivariate and Multivariate VECM, Bivariate and Multivariate Panel VECM). Table 1 gives an overview of some representative papers in this literature. First there are several publications finding unidirectional causality between energy and income, either from energy to income or vice versa. Second, the hypothesis of the 'neutrality' of energy to income has been confirmed using different methodologies. And finally, different authors have claimed bidirectional causality exists.

Following Mehrara (2007), these publications can also be divided into four 'generations'. The first generation (e.g. Kraft and Kraft (1978) and Yu and Hwang (1984)) of the literature used a 'traditional' VAR regression approach to infer causality

5 See Mehrara (2007) for an excellent overview.

between the two series under study, assuming stationarity of the data under study. Analysis by means of this methodology was conducted from 1978 to the end of the 1980's. With the rise of stationarity testing and correction in econometrics the analysis evolved and measures were taken to account for the presence of unit roots in time series. Second-generation publications (e.g. Masih and Masih (1996) and Glasure and Lee (1997)) made use of error correction models (ECM) and cointegration to assess Granger (1988) causality in a bivariate framework. Making use of the new methodology, first generation studies where put aside as the regression results could be considered 'spurious'. Building upon this, the third generation (e.g. Asafu-Adjaye (2000) and Stern (2000)) used a multivariate ECM approach following Johansen's (1991) causality testing method to account for omitted variable bias, a critique by which second-generation studies are repeatedly refuted. This third generation framework allowed for a correction of other inputs into the production function, such as capital, labour, prices, etc. However, with such specifications, country and time specific effects were not taken into account. Therefore, a fourth generation literature (e.g. Lee (2005, 2006), Soytas and Sari (2003, 2006), Ghali and El-Sakka (2004) and Sinha (2009)) is published from approximately 2003 onwards and makes use of (bivariate) panel cointegration and panel error correction models to allow for these specific time and country dimension effects. Unfortunately none of the published studies in this generation to date have made use of the full benefits of large variation in data made possible by panel analysis. This is mainly caused by lack of data, which confines most panels to less than 10 members (most studies above have less than 20 countries and span at most 40 years). Notable exception is an unpublished working paper Sinha (2009) that has analysed 88 countries over 28 years.

In what we consider a fifth generation, papers start using the multivariate panel VECM tools to also control for capital-energy complementarities (e.g. Lee and Chang (2008), Lee, Chang and Chen (2008), Naryan and Smyth (2008)). These papers generally conclude that energy consumption Granger causes economic growth and income, where only Lee, Chang and Chen also find the reverse causation. This contrasts sharply with our finding that income (growth) and capital Granger cause energy use but not the other way around. We can trace this back to the specification of our error correction term and discuss these differences at some length in our results section.

Authors	Year	Method	Main Results	countries included in study	timespan
Kraft & Kraft	1978	Sims causality test	Income causes energy	USA	1947 - 1974
Yu & Hwang	1984	Sims causality test	Neutral	USA	1947 - 1979
Yu & Jin	1992	Bivariate cointegration model	Neutral	USA	1974 - 1990
Masih & Masih	1996	Multivariate VECM	Different per country	Malaysia, Singapore, Philippines, India, Indonesia, Pakistan	1955 - 1990
Glasure & Lee	1997	Bivariate VECM	Bidirectional causality	South Korea, Singapore	1961 - 1990
Asafu-Adjaye	2000	Multivariate VECM	Different per country	India, Indonesia, Thailand, Philippines	1972 - 1995
Stern	2000	Multivariate VECM	Energy causes income	USA	1948 - 1994
Glasure	2002	Vector autoregression	Neutral	Korea	1961 - 1990
Soytas & Sari	2003	Bivariate VECM	Different per country	G7 & top 10 emerging markets	1950 - 1992
Ghali & El-Sakka	2004	Bivariate VECM	Bidirectional causality	Canada	1961 - 1997
Lee	2005	Bivariate panel VECM	Energy causes income	18 developing countries	1975 - 2001
Soytas & Sari	2006	Multivariate panel VECM	Different per country	G7	1960 - 2004
Al-Iriani	2006	Bivariate panel VECM	Income causes energy	Gulf Cooperation Council	1971 - 2002
Mehrara	2007	Bivariate panel VECM	Income causes energy	11 oil exporting countries	1971 - 2002
Mahadevan & Asafu	2007	Multivariate panel VECM	Bidirectional causality	20 developing/developed countries	1971 - 2002
Lee & Chang	2007	Multivariate panel VECM	Energy causes income	16 Asian countries	1971 - 2002
Narayan & Smyth	2008	Multivariate panel VECM	Energy and capital cause income	G7	1972 - 2002
Lee, Chang & Chen	2008	Multivariate panel VECM	Bidirectional causality between capital, energy and growth	22 OECD countries	1960 - 2001

3. Data, Methodology and Empirical Results

We first collected a dataset on 30 OECD countries[6] for the period 1960-2000, containing GDP and Gross Fixed Capital Formation (GFCF) (OECD-STAN database), energy use[7] (United Nations International Energy Agency's (IEA) Energy Statistics of OECD countries and Energy Balances of OECD and other IEA/OECD statistical databases), employment (OECD annual labour force statistics) and educational attainment of the workforce (World Bank, Barro and Lee (2001)). We follow Lee (2005) and Soytas & Sari (2006) among others in taking GFCF as a proxy for the capital stock and use the multiple of labour and educational attainment as a proxy for human capital in the production function. Tables A1 and A2 in the appendix provide the descriptive statistics for our dataset over the country and time dimension.

We then use a multivariate panel approach based on panel cointegration and error correction techniques. To establish that this is econometrically appropriate, one needs to follow a clear 3-step procedure. First, all series have to be proven to be suitable for analysis by means of this framework. All data first have to be non-stationary and should not be integrated of order 1, I(1). Second, a long-term cointegrating relation needs to exist between the main variables in our model. After showing that our data

6 Australia, Austria, Belgium, Canada, Czech Republic*, Denmark, Finland, France, Germany, Greece, Hungary*, Iceland, Ireland, Italy, Japan, Korea*, Luxemburg, Mexico*, Netherlands, New Zealand, Norway, Poland, Portugal, Slovenia*, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States. Asterisk signifies missing values, implying these countries were dropped in tests and regressions that require a balanced panel.

7 Data on Energy use, as found in the 'Energy Statistics of OECD Countries' dataset, have been used to compare different amounts of energy inputs in different countries. Using conversion factors, derived from the 'Energy Balances of OECD Countries', measures of total energy consumption (EC) where constructed on a per country per capita basis, thus taking into account differences in the 'quality' of different energy inputs such as oil, coal, gas, water, wind, etc.

satisfy the requirements for using this method, we proceed to specify the model and present our results.

3.1. Unit Root Tests

To test the presence of unit roots in our data we present panel unit root tests for all series in table 2 below. Table 2 presents test statistics using methods developed by Levin, Lin and Chu (2002) (LCC), Im, Pesaran and Shin (2003) (IPS) and the Fisher test developed by Maddala and Wu (1999). The three tests mentioned above are constructed to test for non-stationarity in time series in a panel context as the (augmented) Dickey Fuller (1979) test can only be used for single time series.[8] In the right columns the results for these tests with first differenced data are presented.

Table 2 unit root statistics

Unit Root Statistics of variables in levels				Unit Root Statistics of variables in first differences			
	LLC test	IPS test	Fisher test		LLC test	IPS test	Fisher test
Variable	t-star	W[t-bar]	χ^2	Variable	t-star	W[t-bar]	χ^2
log(gdppppca)	-0.11 [2] [t]	2.26 [2] [t]	59.95 [2] [t]	Δ log(gdpppca)	-3.63 [2] [t] ***	-7.87 [2] [t] ***	156.78 [2] [t] ***
log(ecca)	-1.57 [2] [t] *	0.85 [2] [t]	77.67 [2] [t] *	Δ log(ecca)	-2.43 [2] [t] ***	-6.15 [2] [t] ***	171.98 [2] [t] ***
log(emp)	0.99 [2] [t]	2.33 [2] [t]	49.18 [2] [t]	Δ log(emp)	-4.19 [2] [t] ***	-7.47 [2] [t] ***	174.22 [2] [t] ***
log(gfcf)	-0.97 [2]	-1.00 [2]	38.22 [2]	Δ log(gfcf)	-7.59 [2] ***	-11.7 [2] ***	318.74 [2] ***
log(school)	-0.50 [2] [t]	0.38 [2] [t]	71.24 [2] [t]	Δ log(school)	-2.75 [2] [t] ***	-3.97 [2] ***	113.30 [2] ***

H0: nonstationarity / unit root
Number between [..] is the amount of lags used, [t] is trend
* signals significance on a 10% level, ** 5% and *** 1%

Table 2 displays the results of the LLC, IPS and Fisher test for all 5 variables in our dataset. The results clearly show that all data are integrated of order 1 but not of order 2, suggesting a specification in first differences is appropriate to avoid spurious regression bias.

3.2. Cointegration Test

The LLC, IPS and Fisher test results imply we consider a first difference specification of the final model. In a Granger causality framework, it is also required to establish the presence of stationarity between different variables included in the analysis. To do so we test for cointegrating behaviour. This can be tested by means of the Westerlund

8 As all tests have their specific strengths and weaknesses, we will show results for all three. The LLC-test tests for the presence of unit root by assuming that each individual unit root in the panel shares the same AR(1) coefficient. This test is best viewed as a pooled (augmented) Dickey Fuller test, with a null hypothesis of non-stationarity. The IPS-test tests for the presence of unit root in a heterogeneous panel setting. Comparable to the LLC test it allows for individual as well as time effects and trends. Bute here the results are based on the mean of the individual Dickey Fuller t-statistics of each individual series. Finally, the Fisher test 'combines the p-values from N independent unit root tests'. Based on the p-values of the individual unit root tests, the Fisher test assumes, comparable to the LLC and IPS test, that all series are I(1) under the null hypothesis of non-stationarity. It provides added insights because the data do not have to be balanced to come to consistent results, and it thus combines results for all members in the panel under analysis.

(2006, 2007) framework for panel cointegration testing.[9] Table 3 below presents the results of the Persyn and Westerlund (2008) panel cointegration tests performed in our data. All tests are between (log) energy consumption and the variables of interest, log GDP (LGDP), log Gross Fixed Capital Formation (LGFCF), log Employment (LEMP) and log Human Capital (LSCHOOL), where the latter is defined as the average years of education times the level of employment. First the co movement between log energy consumption (LEC) and log GDP is assessed, for which the Westerlund test provides clear evidence. All test statistics clearly reject the null hypothesis of no cointegration on a 1% significance value. This implies GDP and energy are cointegrated and GDP should be included in the error correction term.

Table 3 Panel cointegration statistics

Covariates	# Series	Statistic	Z-value	P-value
LGDP	31	Gt	-7,695	0 ***
LGDP	31	Ga	-1,647	0.05 **
LGDP	31	Pt	-7,741	0 ***
LGDP	31	Pa	-5,26	0 ***
LGDP & LGFCF	31	Gt	-3,766	0 ***
LGDP & LGFCF	31	Ga	-3,440	0 ***
LGDP & LGFCF	31	Pt	-3,097	0.001 ***
LGDP & LGFCF	31	Pa	-3,570	0 ***
LGDP, LGFCF & LEMP	25	Gt	-1,925	0.027 **
LGDP, LGFCF & LEMP	25	Ga	-3,381	0 ***
LGDP, LGFCF & LEMP	25	Pt	-0,272	0,393
LGDP, LGFCF & LEMP	25	Pa	-0,681	0,248
LGDP, LGFCF & LSCHOOL	30	Gt	0,304	0,620
LGDP, LGFCF & LSCHOOL	30	Ga	-0,249	0,402
LGDP, LGFCF & LSCHOOL	30	Pt	0,187	0,574
LGDP, LGFCF & LSCHOOL	30	Pa	-0,094	0,463

H0: no cointegration
* signals significance on a 10% level, ** 5% and *** 1%

Second, the co movement of (log) energy use, (log) gross fixed capital formation and (log) GDP is analysed. Again the evidence is strong with all four tests being significant at the 5%, and 3 out of 4 at the 1% level. This implies that GFCF should also be included in the error correction term. Finally, the results for co movement between

9 Because 'normal' unit root tests (see e.g. LLC, IPS and Fisher methodology described above) based on the residual of the cointegration relationship do not take into account the effects of structural breaks, if present, the null (a unit root) can often not be rejected while there is actually no unit root present (type II error). The Westerlund test tests for the absence of cointegration by determining if there exist error corrections for individual panel members or for the panel as a whole. This is done under the assumption that all variables are non stationary or I(1) as we have established for our data in first differences above. The test presents four test statistics: Ga, Gt, Pa and Pt. The Ga and Gt statistics test for the null that all parameters of the lagged dependent variable on the right hand side are not significantly different for zero for all members in the panel versus the alternative that at least one parameter of the lagged dependent variable is significantly different from zero. They differ because they start from a weighted average of the individually estimated coefficients (Ga), or their respective t-ratio's (Gt). The Pa and Pt test statistics pool all information over the cross-sectional dimension of the dataset to test the same hypothesis as above. The different statistics therefore, shed light on the rejection of the null that cointegration is present, under different assumptions.

four vectors, including employment and/or human capital suggest these variables are not cointegrated with energy consumption and shall be used as general control variables in the regression framework outlined below.[10] From these tests it can be concluded that the cointegration term in our model must be specified in terms of energy, capital and GDP, along the lines of Mehrara (2007).[11]

3.3. Model specification

Because cointegration is found, causality is best assessed using the Engle-Granger framework (Engle and Granger (1987), Granger (1988), Granger and Lin (1995)). We use a vector error correction model, or VECM, specification, which basically consists of a two-stage procedure. In the first stage of the regression analysis, we specify the cointegration relationship to assess the long-term co movement between energy, capital and output. This relation is regressed using the following specification:

$$LEC_{it} = \alpha_i + \delta_i t + \beta_1 LGDP_{it} + \beta_2 LGFCF_{it} + \varepsilon_{it} \tag{1}$$

The error correction term contains a country specific intercept, a_i, a time trend δ_t, a coefficient quantifying the influence of GDP β_1, a coefficient for gross fixed capital investment, β_2 and an error term ε_{it}.

Second, the residuals of (4) are used as a (lagged) regressor, $ECT= \varepsilon_{it}$, in the final VECMs. To test for causality we need to estimate both a model with growth in energy consumption and growth in GDP as the dependent variable. On the left hand side we include the (lagged) *ECT* specified above and lags of the dependent variables and explanatory variables. Moreover, we control for the growth in human and physical capital in both regressions. The estimated models are thus given by:

Model A:

$$\Delta LEC_{it} = \alpha_{ait} + \gamma_{ai} ECT_{it-1} + \sum_p \beta_{a1ip} \Delta LEC_{it-p}$$
$$+ \sum_p \beta_{a2ip} \Delta LGDP_{it-p} + \sum_p \beta_{a3ip} \Delta LGFCF_{it-p} + \sum_p \beta_{a4ip} \Delta LSCHOOL_{it-p} + \upsilon_{it}$$

Model B:

$$\Delta LGDP_{it} = \alpha_{bit} + \gamma_{bi} ECT_{it-1} + \sum_p \beta_{b1ip} \Delta LEC_{it-p}$$
$$+ \sum_p \beta_{b2ip} \Delta LGDP_{it-p} + \sum_p \beta_{b3ip} \Delta LGFCF_{it-p} + \sum_p \beta_{b4ip} \Delta LSCHOOL_{it-p} + \psi_{it}$$

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10 Note that for employment our panel is incomplete

11 But note Mehrara (2007) does not include capital or investment.

where subscripts *a* and *b* signal coefficients from the first or the latter model, subscripts *i* and *t* denote the country and time dimension of the regression and Δ signifies first differences. Subscript *p* denotes the lag length used for the different explanatory variables, from $t - 1$ to $t - p$, conditional on their significance. The coefficients labelled $\beta_{a,b1ip}$ to $\beta_{a,b4ip}$ quantify the relation between their respective (lagged) explanatory variables and the explained variable and the error terms are denoted by υ_{it} and ψ_{it} respectively. Finally, the relation between the *ECT* and the explained variable is quantified by the coefficient $\gamma_{a,bi}$ for models A and B, respectively. This coefficient will capture the long run causal relationship between the dependent variable and energy consumption. If it is significant in model A, the causality runs from GDP to energy use, whereas significance in model B suggests reverse long run causality.

We can estimate these equations by means of ordinary least squares (OLS). [12] From the significant coefficient on *ECT* in model A but not in model B in table 4 it can be concluded that output (GDP) and capital formation (GFCF) share a long run cointegration relationship with energy usage (model A), but not vice versa (model B). Over the short run, the relation is bidirectional, as both the lagged GDP variable in Model A and the lagged energy variable in Model B appear to be significant in predicting future values of the dependent variable. This dynamic interaction is only valid for the very short run, as longer-term effects (t-2 etc) are found to be insignificant.

Panel vector error correction model results

Model A: Δ log(EC) explained by variable of interest (and controls):

Variable	time lag	Coefficient	t-statistic	Significance
Δ log(GDP)	t-1	0.152	2.54	***
ECT	t-1	-0.008	-3.78	***

Model B: Δ log(GDP) explained by variable of interest (and controls):

Variable	time lag	Coefficient	t-statistic	Significance
Δ log(EC)	t-1	0.106	5.07	***
ECT	t-1	-0.001	-0.79	

* signals significance on a 10% level, ** 5% and *** 1%

12 For model A lagged LEC was significant up to 3 lags (not reported below). In Model B only one lag was significant for GDP. Model A was therefore estimated using a sample size, n=996 observations, whereas Model B was estimated with n = 1048. Our results, however, do not depend on the sample size or number of lags included.

In conclusion, our results strongly suggest that there is no evidence of a long run causal relationship from energy use to output in the OECD over the past 40 years. In the (very) short run the causality seems to run in both directions, but this makes perfect sense. In the period under investigation the OECD experienced several significant energy price hikes, causing a drop in energy use, followed by short run economic contractions. Over the longer run, however, such negative effects wear of rapidly and the long run causality runs from income to energy use. These results are in stark contrast to results reported in recent papers (published papers by Narayan and Smyth (2008), Lee and Chang (2008), Lee, Chang and Chen (2008) on the one hand and a working paper by Sinha (2009) on the other) using similar data and empirical methods in the literature. The following sections will first contrast our results to those reported by Lee, Chang and Chen (2008) and Narayan and Smyth (2008). Given the less than complete description of the analysis and results in Sinha's (2009) working paper, a final section is necessarily more speculative in contrasting our results to his.

3.4. The importance of the error term specification

Narayan and Smyth (2008) (NS) and Lee, Chang and Chen (2008) (LCC) are largely based on the same procedures and type of data, studying the G7 and 22 OECD countries for 3 and 4 decades, respectively. They concluded that energy, as well as capital, Granger cause output and that therefore energy should be seen as a vital input in the production function. Our analysis "nests" these earlier studies as our data has been broadened by including more countries (notably Czech Republic, Hungary, South Korea, Luxemburg, Mexico, Poland, Slovenia and Turkey) and controls for additional inputs (e.g. human capital). Excluding these variables, years and countries from the estimation and running our analysis in per worker terms as in Lee, Chang and Chen and Narayan and Smyth, however, does not affect our overall conclusion.[13] Therefore our opposite conclusions probably follow from a different model specification. The Lee, Chang and Chen (2008) and Narayan and Smyth (2008) results

13 We use (first differences in the log) of gross fixed capital formation as our proxy for the capital stock as do NS, whereas LCC use (first differences in log of) capital stocks as constructed by Kamps (2006). This, however, is not likely to affect the results qualitatively. In a VECM specification the final regression is done in log first differences, i.e. in growth rates. And we feel it is reasonable to assume that the variation in growth rates of GFCF and the capital stock itself are highly correlated for countries close to their steady states. The standard neoclassical growth model predicts that in steady state all variables, including the capital stock, depreciation and net investment and gross fixed capital formation grow at the common rate of labour augmenting technical change. If we assume all OECD countries are close to their steady state, we know that the level of GFCF is close to the level of deprecation and consequently proportional to the capital stock if depreciation rates are more or less stable. These assumptions are not very strong for OECD countries. This makes it very unlikely that LCC come to opposite conclusions based on their different proxy for the capital stock.

can be obtained in our data also by using their specification for the cointegration term, namely:[14]

$$LGDP_{it} = \alpha_i + \delta_i t + \beta_1 LEC_{it} + \beta_2 LGFCF_{it} + \varepsilon_{it} \quad (2)$$

If we use (2) instead of (1) in an Engle-Granger two-step procedural estimation, energy and capital inputs are found to Granger cause output over the long and short term in our data as well. The question is then, however, if these authors are justified in using (2) instead of (1). For this to be the case it must thus be shown that specification (2) is truly the long run equilibrium, or cointegration, relationship. NS and LCC offer theoretical arguments and references to earlier papers, but in the end *assume* this specification without testing for its appropriateness explicitly.

Table 5 Panel cointegration statistics

	on the logarithm of GDP						on the logarithm of GDP			
Covariates	# Series	Statistic	Z-value	P-value		Covariates	# Series	Statistic	Z-value	P-value
Log(GFCF)	31	Gt	-6.378	0	***	Log(GFCF) & Log(EC)	31	Gt	0.780	0.78
Log(GFCF)	31	Ga	1,000	0.84		Log(GFCF) & Log(EC)	31	Ga	1.120	0.87
Log(GFCF)	31	Pt	-4.563	0	***	Log(GFCF) & Log(EC)	31	Pt	1.347	0.93
Log(GFCF)	31	Pa	-1.959	0.03	**	Log(GFCF) & Log(EC)	31	Pa	1.125	0.87

H0: no cointegration
* signals significance on a 10% level, ** 5% and *** 1%

Again the Westerlund panel cointegration test can be used. Table 5 presents panel cointegration tests on the logarithm of output for the covariates capital and for capital and energy together. Clearly, as one would expect from theory, LGFCF shares a long run relationship with LGDP and is highly significant in three out of the four tests, rejecting significance for only one member of the panel in the second test. However, as energy usage is added as a second covariate, the test results cannot reject the null that there is no covariation on the basis of the statistical outcome. These results justify energy use as a possible control variable, but *not* in the error correction term in a Granger causality cointegration framework. Our results show that (wrongly) adding energy consumption in the cointegration relationship leads to very different conclusions on the causal relationship of between energy and GDP. Assuming, on theoretical grounds, that energy is a factor of production thus leads to the conclusion that it indeed Granger-causes output. But if we allow the data to speak freely, the results are overturned.

3.5. Adding Developing Countries and Omitting Capital

14 NS are a bit implicit about the specification of their error correction term, but their equations (1) and (2) suggest they use a specification similar to that in LCC.

The analysis in Sinha (2009) is presented in such a way that it is hard to reproduce in our data. In his paper Sinha does state that for the 30 OECD countries in his sample results are "*quite similar*" to those for the entire sample, that is, he finds a significant long run relationship in both directions. When we redo our analysis, restricting our sample from 1975 to 2000, we do not find this reverse causality, suggesting our model specifications (or data) must differ. An obvious difference in the two papers is the fact that we follow Narayan and Smyth (2008) in controlling for capital (proxied by gross fixed capital formation). Given that capital is typically complementary to energy use and OECD countries are highly capital intensive, the omission of this variable will bias Sinha's results. Sinha (2009) probably did not include this variable because such data are notoriously hard to come by for developing countries. Dropping capital from our analysis, however, does not change our results qualitatively. Again, it seems, the specification of the error correction term is the main culprit, although we cannot be certain, as Sinha (2009) is not explicit about his specification.

Another explanation suggests itself, however. Taking 58 developing countries increases the weight of developing countries in the panel along two dimensions. It shortens the time dimension and broadens the cross-section. The available evidence on developing countries only (e.g. Lee (2005)) suggests that for developing countries the causation may well run the other way in the long run. Given their largely resource and agriculture driven economies, developing countries may experience growth only if energy use can first increase to build up the manufacturing sector and industrial infrastructures. Adding 58 such countries (without adjusting for their much smaller share in global GDP and energy use) can then "bias" the results towards finding bidirectional causality as well. This suggests a multi-regime modelling approach would be more appropriate in such broad panels.

3.5. Summary

The results of our vector error correction model clearly show strong unidirectional causality from GDP and capital formation to energy use, as the cointegration term is significant at the 1% level in model A and not at all in model B. However, model B confirms that there are some short run influences of energy use running in the opposite direction. Contrasting our results to those found by other authors we conclude that the differences are probably caused by our specification of the error correction term. We can only be sure, however, if we exactly reproduce their results using their data, which we do not have. Tests in our data, however, show that our specification is the one the properties of the data would suggest, also if we limit our panel to the dimensions and variables used in the other studies. Furthermore we argue that excluding capital and including developing countries without properly weighing them may well have biased results in earlier studies towards finding evidence for a causal link from energy use to GDP.

4. Conclusion

We show that in the OECD Granger causality runs from output growth and capital formation, or broadly stated 'economic activity' to energy use, and not the other way around. Energy can therefore not be seen as a vital input into the production function complementing capital and labour. This results stands in direct opposition to results found earlier in the literature. As we have shown, however, those results were obtained *under the assumption* that energy is an input in the production function. Testing for the appropriate specification of the long run relationship between energy use and GDP, suggests the error correction term should *not* be specified as suggested by the KLEMs-production function. More empirical research is urgently needed to establish this result more robustly. Quick wins would be to provide specification tests for the Lee, Chang and Chen (2008) and Narayan and Smyth (2008) datasets. It would furthermore be interesting to collect capital stock data on developing countries to extend the panel, including the important capital stock proxy, to developing countries.

The issue at hand is of key importance. Policies aiming at reducing either industrial or residential demand for energy can therefore only be expected to have a small short-run detrimental effect on overall economic activity. Additionally, the fear that prolonging the Kyoto protocol might negatively influence global economic recovery is unfounded if our results are found to be robust. When energy use is not a vital input in the production function, recovery policies should focus on capital, labour and productivity inputs (education and R&D etc.) and there is no reason why a reduction of greenhouse gas emissions by increasing energy prices, pricing carbon emissions or implementing energy efficiency measures, should cause a fall in output over the longer term. However, as stated, there may be a short lived and short run negative effect, validating the argument that the implementation of these policies in the worst part of the downturn of the business cycle may not be the optimal solution. Starting negotiations now to have policies in place in a few years, however, seems like a good prospect for both the environment and the economy.

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Appendix A – Descriptive Statistics over the country dimension

Country	Gross Domsetic Product in PPP per capita			Employment			Gross Fixed Capital Formation in billions of 2000 USD			Energy consumption in kWH per capita		
	mean	st.dev.	median	mean	st.dev.	median	mean	st.dev.	median	mean	st.dev.	median
Australia	16810	3995	16497	6454	1410	6356	49,45	20,41	44,74	5845	2612	5914
Austria	15785	4876	16402	3262	270	3191	27,55	9,64	26,31	4468	1627	4697
Belgium	16366	4769	17080	3734	108	3724	29,24	8,90	27,46	4786	2021	4908
Canada	18500	4431	19231	10466	2653	11019	75,43	30,00	74,88	12231	3905	12804
Czech Republic	10662	1907	11384	5032	153	5037	10,26	3,25	10,27	4878	687	5057
Denmark	18268	3941	18177	2451	190	2420	17,15	6,13	15,72	4300	1833	4590
Finland	14853	4594	15350	2265	132	2233	16,75	4,51	17,05	8342	4292	8295
France	15566	4180	16145	21677	1188	21823	164,40	44,20	164,30	4337	1899	4417
Germany	16196	4325	16587	29101	4251	26829	266,60	70,55	255,00	4966	1795	5796
Greece	10498	2928	11684	3480	278	3424	16,73	4,91	17,33	2192	1302	2247
Hungary	7642	2309	8486	3778	139	3752	6,71	2,22	7,44	2623	755	2900
Iceland	17664	5455	19430	108	27	106	1,02	0,37	1,03	11697	6410	12689
Ireland	11780	5490	10707	1155	144	1111	8,57	4,51	8,19	2834	1390	2836
Italy	14731	4495	15332	20579	644	20590	147,60	39,69	148,70	3031	1227	3096
Japan	15631	6308	15659	55771	6699	55360	767,00	368,30	772,90	4745	2162	4717
Korea	5551	3854	4283	14365	4394	14201	55,08	56,97	32,36	2131	1747	1409
Luxembourg	21822	8544	18592	168	36	158	1,97	0,89	1,59	11392	2697	11648
Mexico	6242	1253	6742	30175	7215	32159	58,29	28,22	57,14	1114	355	1117
Netherlands	16442	4175	16477	5476	1043	5055	47,33	14,20	43,03	4053	1506	4293
New Zealand	14976	1873	15017	1323	287	1274	6,00	2,10	6,02	6282	2122	6292
Norway	16143	5648	16366	1841	267	1908	20,71	6,21	22,26	18257	5480	18860
Poland	6229	1270	6346	15529	1466	15450	12,37	10,35	9,24	2539	833	2961
Portugal	9342	3648	9242	4000	504	4013	14,08	6,42	12,70	1702	1087	1558
Slovak Republic	8769	805	8608	2181	50	2166	4,93	1,87	4,81	4286	795	4490
Spain	11244	3508	11142	12666	839	12580	75,11	29,60	67,69	2520	1299	2643
Sweden	16395	3508	16550	4018	250	3986	29,05	6,54	28,02	11011	4226	10703
Switserland	22533	3408	22919	3387	410	3256	38,24	9,69	36,82	5686	1612	5931
Turkey	4297	1147	4253	16541	3232	16280	26,18	14,00	23,51	598	434	490
United Kingdom	14357	3465	13750	25180	839	25014	142,40	46,60	126,10	4564	944	4669
United States	21516	5398	20955	99982	21602	100907	872,50	397,90	795,10	9331	2908	9698

Appendix B – Descriptive Statistics over the time dimension

Year	Gross Domsetic Product in PPP per capita			Employment in thousands of jobs			Gross Fixed Capital Formation in billions of 2000 USD			Energy consumption in kWH per capita		
	mean	st.dev.	median	mean	st.dev.	median	mean	st.dev.	median	mean	st.dev.	median
1960	7581	3370	7800	11263	15893	3599	49,73	99,25	11,63	2128	1794	1587
1961	7865	3419	8192	11352	15964	3633	52,45	102,80	12,12	2259	1891	1659
1962	8134	3488	8429	11463	16178	3657	56,24	109,80	12,88	2421	2057	1774
1963	8439	3543	8708	11399	16044	4028	60,38	117,70	13,76	2617	2223	1903
1964	8872	3712	9132	11540	16324	4127	64,73	126,20	14,61	2864	2504	2069
1965	9187	3818	9475	11692	16635	4166	67,67	133,20	15,19	2972	2642	2161
1966	9500	3868	9772	11858	17001	4191	72,10	141,00	16,16	3122	2719	2263
1967	9731	3848	10151	11963	17280	4177	75,77	146,10	16,96	3262	2796	2367
1968	10086	3895	10452	12094	17580	4205	81,15	156,30	17,73	3471	2953	2604
1969	10614	4086	10955	12253	17918	4260	86,73	166,50	18,63	3734	3026	2843
1970	11012	4163	11550	12388	17714	4790	90,97	174,50	19,50	4081	3123	3041
1971	11236	4219	11814	12471	18162	4336	95,35	183,30	22,18	3998	3244	3221
1972	11724	4310	12379	12634	18561	4320	102,10	198,00	24,45	4244	3329	3414
1973	12313	4461	13049	12935	19135	4329	109,50	213,00	24,96	4566	3571	3631
1974	12524	4488	13245	13091	19361	4372	105,50	202,00	25,96	4711	3747	3778
1975	12458	4251	13361	12725	18866	4743	101,30	192,40	24,67	4640	3552	3775
1976	12861	4367	13673	12897	19338	4755	104,80	199,90	25,61	4935	3720	4078
1977	13146	4427	14067	13114	19902	4801	109,20	210,60	27,80	5043	3680	4148
1978	13486	4544	14356	13364	20590	4859	115,60	225,70	26,05	5262	3814	4346
1979	13860	4698	14847	13589	21085	4927	121,20	236,90	27,64	5508	4040	4542
1980	14074	4811	15350	13968	20860	5094	121,70	234,90	28,64	5615	4078	4599
1981	14138	4863	15613	13748	21394	5118	120,90	233,80	27,17	5714	4229	4590
1982	14165	4799	16012	13698	21287	5119	117,10	225,50	26,31	5766	4265	4676
1983	14366	4878	16353	13770	21558	5055	117,50	228,20	26,20	5991	4504	4740
1984	14823	5111	16822	13970	22250	5084	123,20	243,20	26,21	6307	4816	4959
1985	15206	5274	17108	14149	22624	5178	129,00	256,00	27,83	6532	4941	5258
1986	15596	5445	17437	14380	23055	5225	133,70	264,90	28,67	6652	4936	5328
1987	16000	5524	17790	14654	23557	5243	139,90	275,40	30,32	6872	5057	5548
1988	16511	5697	18342	14922	24043	5251	151,10	297,20	33,13	7100	5209	5725
1989	17003	5915	19142	15213	24537	5245	161,00	315,80	37,02	7225	5170	5856
1990	17241	6017	19506	15722	24461	5676	168,20	330,20	40,20	7320	5197	5947
1991	17158	6188	19333	16198	24676	5670	168,10	330,80	37,96	7401	5256	6222
1992	17217	6246	19173	15810	24500	4883	168,80	332,70	38,06	7359	5179	6162
1993	17311	6349	18710	15757	24767	4874	166,20	329,60	37,97	7424	5251	6098
1994	17788	6513	19343	15520	24904	4685	171,60	339,10	39,39	7601	5314	6149
1995	18221	6547	19952	15672	25167	4688	177,30	350,90	39,72	7779	5375	6312
1996	18670	6614	20136	15868	25480	4708	186,00	369,60	41,58	7888	5261	6406
1997	19307	6880	20697	16129	25998	4733	194,20	385,40	42,85	8064	5406	6427
1998	19841	7166	21328	16310	26277	4871	201,20	400,40	44,38	8273	5700	6481
1999	20430	7421	22206	16474	26556	4852	211,30	423,40	46,23	8467	5891	6480
2000	21174	7731	22974	22747	42769	5041	221,50	443,60	48,32	8715	6057	6560