INSEAD

The Business School for the World®

Social Innovation Centre

Faculty & Research Working Paper

Increase Supplies, Increase Efficiency: Evidence of Causality Between the Quantity and quality of Energy Consumption and Economic Growth.

Benjamin S. WARR
Robert U. AYRES
Eric WILLIAMS
2009/22/EPS/ISIC
(Revised version of 2008/62/ISIC)

Increase supplies, increase efficiency: Evidence of causality between the quantity and quality of energy consumption and economic growth.

By

Benjamin S. Warr*****

Robert U. Ayres**

And

Eric Williams***

* INSEAD Social Innovation Centre Boulevard de Constance, Fontainebleau 77305 France.Ph: +33 (0) 1 60 72 92 31 Email : benjamin.warr@insead.edu

** Emeritus Professor of Economics and Political Science and Technology Management at INSEAD, Boulevard de Constance 77305 Fontainebleau Cedex; Visiting Professor at Chalmers University Gothenburg (Sweden); Institute Scholar at International Institute for Applied Systems Analysis (IIASA) Schlossplatz 1 A-2361 Laxenburg Austria

*** Assistant Professor, Department of Civil and Environmental Engineering and the School of Sustainability, Arizona State University Ph: (480) 727 6259 Email: ericwilliams@asu.edu

Abstract

The aim of this paper is to re-examine the energy-GDP relationship for the US for the period 1946-2000 by redefining energy in terms of exergy (the amount of energy available for useful work) and the amount of useful work provided from energy inputs. This enables us to examine whether output growth depends on either the quantity of energy supplied and / or the efficiency of energy use. Two multivariate models were estimated involving GDP, capital, labour and the two measures of energy. We find that unidirectional causality runs from either energy measure to GDP. We attribute the causation to both short- and long-run effects in the case of exergy, but only long-run effects in the case of useful work. We find no evidence of causality running from GDP to either energy measure. We infer that output growth does not drive increased energy consumption and to sustain long-term growth it is necessary to either increase energy supplies or increase the efficiency of energy usage. Faced with energy security concerns and the negative externalities of fossil fuel use the latter option is preferred.

Keywords: energy, exergy, energy efficiency, economic growth, causality, cointegration.

1. Introduction

The primary motivation of this paper is to understand the long term relationship between energy consumption and economic growth. Energy is essential for any form of economic activity and advances in energy consuming technologies, coupled with increasing energy consumption, have characterised industrialisation and economic development processes over the past century. However, it can also be argued that the relative importance of energy consumption for economic growth has changed over time as 'developed' economies have evolved, shifting their production structure away from energy intensive industries to less energy intensive service activities.

From a theoretical standpoint, assuming a single sector economy, conventional economic theory attributes only marginal importance to energy as a factor of production by following the argument that energy's share in total factor cost is small compared to the cost shares of capital and labour. Following this logic, the share for oil is about 4% of US GDP, therefore a typical cut of 10% in oil consumption would result in a GDP reduction of 0.4%, from the average 3.5% annual growth. It is then possible to argue that this is only a small fraction of the growth that will be generated by exogenous technological progress. It follows that reducing energy consumption will not significantly impact output growth, in other words that energy is neutral to growth. This line of argumentation has given rise to the "neutrality hypothesis". However, experience of the effects of resource scarcity and energy conservation measures adopted following the dramatic oil price hikes in 1973/74 and 1979/80 suggest that constraints on energy consumption can adversely affect economic output. Indeed, empirical evidence shows that oil-shock related declines, relative to trend, were on average nearer 4 %, or ten times that predicted by the conventional factor share argument (1).

The relevant question then is whether energy consumption causes economic growth or whether it is simply a consequence of the level of economic activity? The first studies to address this question through empirical research were stimulated by the oil crises of the early 70s and focussed on the US (2-7). More recently, interest in the causality question has gained new momentum with concerns about climatic change, proposals to limit CO_2 emissions by restricting fossil fuel consumption (8,9), with concerns about Peak Oil, finally with the development of new analytical techniques (10).

Empirical research has not provided conclusive evidence to unambiguously determine the existence or the directionality of causal relationships between energy consumption and economic growth. A review of the literature describing empirical studies for the US provides an example of the general lack of consensus. Kraft and Kraft (2) and Abosedra and Baghestani (11) found evidence of unidirectional causality running from GNP growth to energy consumption. Stern (12) found evidence of unidirectional causality running in the opposite direction, from energy consumption to GDP. However, the majority of published studies have found little or no evidence of causality (4,5,13). There are several similar energy – economy studies for other countries. Erol and Yu (7) found a significant causality relationship running from energy to GDP. For Korea, Oh and Lee (14) found evidence for causality running in the opposite direction from GDP to energy consumption for the period 1960-2001. Notwithstanding country-to-country differences, the results for any given country differ with the period studied, the choice of methodology, and the method of aggregation of energy flows.

Issues of temporal coverage and choice of method have been comprehensively discussed by several authors (12,15,16). We summarise them briefly here. The original results of Kraft and Kraft (2), for the US over the period 1947-1974, were put in doubt by Akarca and Long (3) who showed, using the same Sims (17) methodology, that the results were sensitive to the time period under investigation. They found no evidence of causality for the period 1947-1972. Similarly the unidirectional causality relationship running from energy to GDP identified by Erol and Yu (6) for Japan for the period 1950-1982, again using tests based on Sim's method, was no longer found to be significant if the period was restricted to 1950-1973. As well as affecting the statistical properties of the sample data, it can be argued that the relationship between economic growth and energy consumption changes over time as economies evolve, react to and restructure after exogenous shocks.

The use of time series analyses, based on the Granger (18) and Sims tests, overcame initial concerns about the inappropriate use of OLS with non-stationary data[1]. But a two-step Engle and Granger (19) method is not able to test hypotheses concerning the long-run relationship between variables. Moreover, bivariate methodologies may fail to detect additional channels of causality. A multivariate methodology is important because changes in energy use are likely to be countered by the substitution of other factors of production, resulting in little overall impact on output (8). However, a multivariate vector autoregressive (VAR) model is not suitable in the presence of cointegration. To be robust, causality tests for cointegrated variables must be applied to vector error correction models (VECMs) that describe a stable long run relationship between the variables *and* the adjustment of each variable back towards 'equilibrium'

[1] In studies applying ordinary least squares (OLS) to log transforms of variables, the failure to account for the time series properties of the data has been a potential source of spurious and contradictory results. The OLS method is not appropriate for non-stationary time series (36).

following disturbances caused by (temporary) changes in the relationships with the others and shocks that have pushed the system away from its 'steady-state'. Multivariate cointegration analysis based on Johansen's multiple cointegration tests has been widely accepted as the most suitable method to analyse the causality structure of non-stationary macroeconomic time series.

Arguably questions concerning the data to include in the multivariate analysis have received less attention. As we mention, the omission of relevant information may be the reason why the time series do not cointegrate (or *decouple*) and causality between output and energy consumption is not detected (20). Decoupling between energy and output may also occur as the relationship between the two varies, through technological change, shifts in the composition of energy inputs and / or the energy intensity of industry. For macroeconomic studies the variables that are generally considered important are of course the other factors of production, capital stock and labour force, but energy prices, consumer price index, money supply and government spending have been incorporated in certain analysis (21).

The method of aggregation of energy flows can also exert a significant effect on the results of the analysis (22). Energy flows are most commonly aggregated in units of thermal equivalents, but this method fails to reflect the qualitative differences among energy inputs. Two alternatives exist: the economic approach using price-based aggregation (the Divisia Index[2]); the exergy approach based on application of the second law of thermodynamics. In two studies, Stern (8,12) tests for cointegration and causality between energy use and economic activity and compared the results when energy is measured in thermal equivalents, with those provided using a quality-adjusted

[2] The Divisia price-based aggregation assumes that energy quality can be measured by using the price of fuels, expressed as expenditure shares, to weight their heat equivalents.

energy (Divisia) index. For the US (1947-1990) using a multivariate model with energy measured in thermal equivalents he finds statistically significant evidence for unidirectional causality running from GDP to energy. With the same multivariate model using a quality-adjusted energy index he finds that the direction of causality is reversed; quality-adjusted energy 'Granger causes' GDP. In the more recent study of the US energy – economy relation (1900-1994) he finds statistically significant evidence for mutual (bi-directional) causality between quality-adjusted energy and GDP.

An alternative to the Divisia index method of aggregating energy flows is based on thermodynamic principles; the concept of available energy (exergy) and the ability of exergy to provide 'useful work' at the point of use. No single method of aggregation is able to fully capture usefulness; as such exergy does not capture certain aspects of economic utility such as cleanliness, ease of storage or of transport. Exergy does however aggregate energy inputs according to their principle defining quality criteria - and provides a science-based and time-invariant measure of - the potential of energy inputs to generate useful work that can be delivered to the point of use. In turn, the aggregate measure of useful work provides an index describing changes in the structure of energy supply (quantity and quality of energy inputs), technological progress (precisely the efficiency of energy conversion technologies) and the structure of energy service demand (the type of useful work or energy services – heat, light, mechanical drive.)

To date the exergy and useful work – output relations have not been examined using multivariate cointegration methods. Yet, finding that useful work is causal on economic growth would suggest that economic growth can be stimulated by improving (a) the exergy content of energy inputs (b) energy efficiency or (c) altering the pattern of energy service demand rather than simply increasing total energy (exergy) consumption. In other words it may be possible to decouple energy consumption and economic growth whilst increasing energy service provision through improved efficiency of energy conversion technologies. The implications of this are highly relevant for economies today facing energy security and more rational use of GHG emitting fossil fuels.

The principle objective of this paper is to compare the exergy–GDP and the useful work–GDP relationships of the US for an unprecedented time period (1946-2000). To facilitate direct comparison of our results with those of others we perform the tests using a framework that takes commonly used inputs (capital, labour) to a single sector energy augmented production function of Cobb-Douglas type[3]. We calibrate two vector error correction models (VECM), the first taking exergy as a measure of energy inputs, the second 'useful work', using Johansen's methodology (10).

The paper is organised as follows. First we introduce the concepts of exergy and useful work and summarise how they were estimated (section 2) before describing the methodology and empirical results (section 3). Finally (section 4) we summarise our findings and provide suggestions for further analysis.

2. Variables definition and data sources

Energy fails to reflect the differences in the ability of a unit of energy to do useful work (and produce goods and services) in the economy. Exergy is an unfamiliar term, but it is really what non-technical people usually mean when they speak of energy. Exergy is

[3] The inputs to the analysis are the same, but by inclusion of lagged error correction terms, the lack of any constraints of constant returns to scale and non-negative coefficients (elasticities), the resulting univariate VECM for GDP is not a production function. The error-correction term in the VECM, describing the long run relationship, can sometimes be interpreted as a production function if the coefficients have the correct sign and magnitude but in practice their value is more often than not unrealistic.

available work: specifically it is the maximum amount of work that can be recovered from a system as it approaches reversible equilibrium with its surroundings. There are several kinds of exergy, including physical exergy (kinetic energy), thermal exergy (heat) and chemical exergy embodied in fuels (which can be equated approximately to the heat of combustion of that fuel.)

The term 'useful work' was introduced several times above without definition. In physics texts, work is usually defined as a force operating over a distance. However this definition is not helpful if force is undefined. The best explanation may be historical. Useful work was originally conceptualized in the 18th century in terms of a horse pulling a plow or a pump raising water against the force of gravity. During the past two centuries several other types of work have been identified, including thermal work, chemical work and electrical work. It is possible to state that whatever increases the kinetic or potential energy of a subsystem can be called 'work' (it being understood that the subsystem is contained within a larger system in which energy is always conserved, by definition). Electricity can be regarded as 'pure' useful work, because it can perform either mechanical or chemical work with very high efficiency, i.e. with very small frictional losses.

We emphasize that the exergy content of fuels and other raw materials can be equated to the theoretical maximum amount of (physical) work that can be extracted from those materials as they approach equilibrium reversibly. It follows from the definition of exergy that the actual amount of *useful work* done by the economic system is less than the theoretical maximum (available work or exergy.) Indeed, the ratio of actual to theoretical maximum can be regarded as an approximation of the *technical efficiency* of energy use in the economy.

The exergy and useful work database were developed from available statistical sources. Details of the methodology can be found in (23) and are summarised here. The accounting methodology to estimate exergy and useful work consumption comprises three distinct stages. The first involves compilation of apparent consumption of natural resource exergy flows (coal, oil, gas, wind, water, nuclear and biomass), the second allocation of exergy to each category of useful work (thermal, mechanical-prime movers, light, muscle), and the third estimation of the useful work provided by each.

The method of exergy accounting depends on the resource input. For fossil fuels historical consumption data is converted from heat content to exergy content using well-defined coefficients[4]. Estimates of hydroelectricity, aeolian, solar and nuclear exergy inputs are not equal to the electricity they generate and are not available in statistical records. Our approach is to develop time series of estimates of the efficiency of conversion from exergy to electricity (pure useful work) for each technology to estimate the original exergy inputs[5]. As an example if the average efficiency of hydroelectric stations is 85% then we simply use the reciprocal to estimate the exergy content of the water flowing through the system.

The next step is to allocate all exergy flows to one of four use categories. The first use category is fuel used to generate heat, either as process heat for industry (high and mid temperature heat) or for space heat and hot water (low temperature heat). The second use category is fuel used to drive prime movers, including all kinds of internal and external combustion engines, from stationary steam turbines to jet engines. We subdivide this category into two groups: the first includes fuels used to generate

[4] The coefficients adjust heat of combustion measures to account for work done by diffusion products on the atmosphere.
[5] For nuclear exergy we assume that the conversion process equals the efficiency of steam conversion to electricity approximately 33%. Food and feed exergy is estimated by back-calculation from energy consumed and an estimate of the efficiency of the food and feed conversion process.

electricity (or pure work) that must then be further allocated across the other end-uses (24); the second includes all other forms of mechanical work (mostly transport). The third use category is exergy used to generate light. The fourth use category includes muscle work provided by draught animals and human workers.

The final stage requires development of time series of the efficiency of conversion from exergy to each of the use categories to estimate the useful work supplied (if both exergy input and useful work output are unavailable, as is the case for electricity generation from fossil fuels). Efficiency estimates are derived from engineering studies or from simple thermodynamic process calculations, the details of which can be found elsewhere (23).

The aggregate useful work, U^* in year t is then simply the exergy input E to each exergy use category, $i=1,\ldots,N$, multiplied by the estimated time dependent conversion efficiency λ_t,

$$U_t^* = \sum_{i=1}^{N} \lambda_{it} E_{it} \ . \qquad (1)$$

Yearly estimates of GDP, capital and labour for the period 1946 to 2000 were provided by Maddison (25) augmented by own estimates where lacking. Prior to analysis all variables (GDP = Q, capital = K, labour = L, exergy = E and useful work = U) were indexed by dividing the value in each year by its initial value in 1946 and log transformed for example ($q = \ln(Q/Q_{t=1946})$, and are hereafter represented by small letters (q,k,l,e,u).

3. Empirical study

We use a three stage procedure to test for the presence and direction of causality. In the first stage we test for the presence of unit roots[6] in the presence of structural breaks to ascertain the order of integration of the time series. In the second stage we test for the existence of a long-run equilibrium relationship. In the final stage we construct multivariate Granger-type causality tests within a vector-error correction modelling framework.

3.1. Unit root and structural break tests

Results of the Phillips-Perron unit-root test[7] applied to the data in levels and their first differences are shown in **Table 1** (26). The unit root hypothesis cannot be rejected for all variables in levels (5% critical level), but can be rejected for all variables in first differences, therefore all variables are I(1). However, standard statistical unit root tests are biased in favour of a unit root hypothesis in the presence of a structural break, where every shock may determine a new growth path.

The problem arises because there is no attempt to distinguish between a unit root process from a trend stationary series with breaks in the trend function. We therefore applied a modified unit root test that allows for a structural change in the time series, modelled as a change in slope or intercept of a modelled trend. Zivot and Andrews (27) extended the Dickey-Fuller unit root test to allow for the simultaneous estimation of

---

[6] Unit root tests applied to a time series determine whether the mean, variance or autocorrelation exhibit permanent shocks over time. If the fluctuations are not bounded the time series is non-stationary and the time series is said to possess a unit root. Non-stationary time series which possess a unit root and are stationary after differencing are said to be *integrated of order,* I(1), where the term ‘integrated’ refers to the summation of the error term over time.

[7] The Augmented Dickey-Fuller (ADF) unit-root test and the stationarity test of Kwiatkowski (31) were also applied. These tests confirm the results provided by the PP test.

possible breakpoints for the intercept and slope of the trend model[8]. Our tests confirmed, for all time series, that we could not reject the ZA null hypothesis (presence of a unit root and no structural break) in favour of trend stationarity about a deterministic trend with a single breakpoint.

3.2. Cointegration tests

On the basis that the variables are integrated of the same order we use the multivariate cointegration analysis framework developed by Johansen (10, 30, 31) and Johansen and Juselius (32) to test for the presence of cointegration[9]. We test two models: the first model (model A) includes GDP, capital, labour and exergy (*e*); the second (model B) replaces exergy with useful work (*u*). The vector error-correction model (VECM) is given by

$$\Delta \mathbf{y}_t = \alpha(\beta \mathbf{y}_{t-1} + \mu) + \sum_{i=1}^{p-1} \Gamma_i \Delta \mathbf{y}_{t-i} + \gamma + \boldsymbol{\varepsilon}_t \qquad (2)$$

where $\Delta\mathbf{y}_t$ contains the growth rates of the variables (in logarithms), μ is an *r x 1* vector of coefficients representing a constant in the cointegration space, γ a *K x 1* vector of parameters representing a linear trend in the levels of the data, α is a matrix of adjustment coefficients, β is the matrix of cointegrating vectors, Γ_i are matrices of short-run dynamics coefficients and ε_t is a vector of random disturbances.

The results of pre-estimation tests for the number of lags to include are presented in **Table 2**. The indicated number of lags to use varies from 1 to 5. The

[8] This development overcame problems with a similar extension of the Perron tests that rely on an exogenous estimate of the data of the structural change.
[9] If the log likelihood of the unconstrained model that includes the cointegrating equations is significantly different from the log likelihood of the constrained model that does not include the cointegrating equations we reject the null hypothesis of cointegration.

Akaike Information criterion (AIC) systematically selects more than the Schwarz Bayesian information criterion (SBIC). However, subsequent tests for normality based on the sample skew and kurtosis, also a Lagrange multiplier (LM) test for the absence of serial correlation, indicated that these models were correctly specified if 3 lags are included.

The next stage of the analysis involves identifying the rank and trend structure of the VECM. Parameter estimation and hypothesis testing are sensitive to the choice of cointegration rank and the decision to include or exclude a constant and/or linear trend in the variables and the cointegration space. We use a sequential application of Johansen's maximum likelihood estimator of the VECM parameters and the 'trace' statistic method[10] to identify both (15). The results of these cointegration tests for models without ($j=1$) and with ($j=2$) a linear trend are presented in **table 3**. We conclude that there are two cointegrating vectors for a model including a linear trend in the levels of the data.

3.3. Granger causality tests

The Granger representation theorem asserts that if the variables are I(1) and cointegrated, there must be either unidirectional or bidirectional Granger causality (19). On expanding out **equation 2**, we can express the VECM for GDP (q) as,

[10] Let $M_{i,j}$ denote the combination of rank and deterministic component, where i is the rank (i = 0, 1, 2) and j is the model, j = 0 is a model with no constants or time trends, j = 1 is the model with no linear trend in the data but with mean stationary cointegration equations and j = 2 is the model with a linear trend in the data and mean stationary cointegration equations[10]. The "trace" statistic method is applied for the most restricted model $M_{0,0}$ and the test statistic compared to the 95% critical value. If the model is rejected we keep the rank assumption and relax the trend assumption, testing model specification $M_{0,1}$. If this model is rejected we increase the rank then proceed to test j = 0 and j = 1, stopping once the trend specification and rank are both accepted.

$$\Delta q_t = \gamma_1 + \sum_{k=1}^{r} \alpha_{1,k} v_{k,t-p} + \sum_{s=1}^{p-1} \theta_{1,s} \Delta q_{t-s} + \sum_{s=1}^{p-1} \theta_{2,s} \Delta k_{t-s} + \sum_{s=1}^{p-1} \theta_{3,s} \Delta l_{t-s} + \sum_{s=1}^{p-1} \theta_{4,s} \Delta u_{t-s} + \varepsilon_t \quad (3)$$

where $\alpha_{i,k}$ are adjustment coefficients weighting the cointegration vectors $v_{k,t-p}$ and $\theta_{1,s}$ are short-run coefficients weighting the lagged growth rates of the dependent variables. Similar expressions can be written for the other variables.

We can investigate Granger causality by testing the significance of the coefficients using Wald test statistics[11]. To test for the short-run causality of useful work (*u*) on GDP we test the hypothesis H_0: $\theta_{4,s} = 0$ for all *p-1* in **equation 3**. We can also investigate how fast the dependent variable responds to deviations from the long-run equilibrium by testing the significance of the adjustment coefficients H_0: $\alpha_{1,k} = 0$ weighting the error-correction term (14). Finally we can check for 'strong' (or long-run) Granger causality by checking whether the two sources of causation are jointly significant. The joint test identifies which variable(s) are responsible for short-run adjustment of the variables to the long-run 'equilibrium' following a shock to the economic system (33). The results of both short-run and 'strong' Granger causality tests are presented in **table 4**.

We consider the evidence for short-run causality first and focus on the causality relations between the energy measures (exergy, useful work) and GDP. For model A (taking exergy as an input), we find evidence of causality from exergy to GDP, but no evidence of causality running from GDP to exergy consumption. In contrast, for model B (taking useful work as an input) we find no evidence of a short-run causality relationship between useful work and GDP in either direction. We conclude there is

[11] F-statistic tests applied to an integrated / cointegrated VAR or VECM system do not have a standard distribution because of the singularity of the asymptotic distribution of the least square estimators.

unidirectional short-run causality from exergy to GDP but no short-run causality in either direction between useful work and GDP.

Tests for 'strong' (long-run) Granger causality provide, for both models, evidence of unidirectional strong Granger causality running from either energy measure to GDP. The long-run relationship is not bidirectional and GDP is not responsible for adjustment of the other variables to the long-run equilibrium.

4. Summary and conclusions

We have examined the causal relationship between two alternative measures of energy inputs (exergy and useful work) and GDP for US over the period 1946-2000, using a multivariate production side model of GDP, capital, labour and exergy / useful work. Having determined that the variables are cointegrated we used a vector error correction model to test for both short-term and long-term Granger causality. We found evidence of unidirectional causality from exergy and useful work to GDP. An increase in exergy supplied has both a short-run and long-run effect to increase output. Variations in useful work have no short-run effect on GDP but do exert a long-run influence causing GDP to adjust to a new equilibrium level. These results suggest that an increase of exergy inputs alone is sufficient to stimulate output growth in the short-run, while over a period of several years GDP responds positively to increased exergy and useful work inputs by readjusting to the long-run equilibrium relationship.

In contrast we find no evidence of either short or long-run causality flowing from GDP to exergy, contradicting results from other similar studies which have found either evidence of unidirectional causality from GDP to energy (14) or bidirectional causality between energy consumption and GDP (12), albeit using different methods to aggregate the energy measure. These findings suggest that growth does not drive increased exergy / useful work consumption, rather output growth is ‘driven’ by increased availability of energy and increased delivery of useful work to the economy. They provide clear evidence of the importance of the quantity of energy consumption for GDP growth and that efforts to reduce exergy consumption may have a negative effect on future GDP growth rates. However, they also indicate, by virtue of the causality link between useful work and GDP, that GDP growth may be maintained by using the available work (exergy) more efficiently to increase the quantity of useful work per unit of exergy consumed. Output growth can be maintained in the face of constant exergy inputs if efficiency improvements are adequate to generate sufficient increases in useful work supplied. Output growth does not *ipso facto* cause an increase in exergy/useful work consumption.

The implication is that as long as increasing supplies of useful work can be sustained, exergy (energy) consumption and economic growth may be decoupled to an extent determined by our ability to convert exergy into useful work delivered at the point of use. In a world of ever increasing energy prices, concerns over energy security and the harmful effects of fossil fuel consumption, recourse to increased energy efficiency as a driver of growth provides hope for sustained future wealth creation. This indicates that government efforts should concentrate on identification and support of the most economically feasible and technologically desirable means to maintain year-on-year energy efficiency improvements to sustain output growth. Appropriate responses must focus on correcting some common systemic failures in: infrastructure provision and access to finance; transition failures in promoting the progress of a given technology from RD&D to full commercial maturity; removing lock-in of sub-optimal technologies and systems of production and consumption; correcting institutional failures to provide adequate incentives, networks and capacities for the commercial deployment of energy efficient technologies (34).

For businesses these results add to the weight of evidence suggesting, at the aggregated level of the economy, that improving the efficiency of energy use increases productivity and consequently output growth. Businesses have a choice either to increase output and energy consumption together using existing systems of production or to restructure their systems of production to increase energy efficiency and benefit from an increased supply of useful work per unit of exergy consumed (and paid for). Such decisions must be made in light of estimates of the future cost of energy supplies against capital costs / process modifications required to increase energy efficiency. To do so effectively will require new accounting measures and tools to quantify the firm-level productivity improvements that are generated by efficiency improvements.

Acknowledgements

This work was supported by completed at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. We would like to thank the Director Leen Hordijk for supporting us in this work. The authors would also like to thank Jerry Silverberg also Chihiro Watanabe of the Tokyo Institute of Technology and the many delegates of IIASA-TiTech collaboration where this work was first presented. We would like to acknowledge the reviewers role in providing insights and comments significantly that improved the overall quality of this paper.

References

(1) Hamilton JD. What is an oil shock? J.Econ. 2003 2003;113(2):363-398.

(2) Kraft J, Kraft A. On the relationship between energy and GNP. Journal of Energy and Development 1978 Spring 1978;3(2):401-403.

(3) Akarca A, Long TVI. On the relationship between energy and GNP: A re-examination. Journal of Energy & Development 1980 Spring 1980Akarca and Long 1980;5(2):326-331.

(4) Yu ESH, Hwang B. The relationship between energy and GNP: Further results. Energy Econ 1984;6:186-190.

(5) Yu ESH, Choi J-. The causal relationship between energy and GNP: An international comparison. Journal of Energy and Development 1985;10(2):249-272.

(6) Erol U, Yu ESH. On the causal relationship between energy and income for industrialized countries. Journal of Energy and Development 1987;13(1):113-122.

(7) Erol U, Yu ESH. Time series analysis of the causal relationships between US energy consumption and employment. Resources Energy 1987:9:75-89.

(8) Stern DI. Energy use and economic growth in the USA: A multivariate approach. Energy Econ 1993;15:137-150.

(9) Masih AMM, Masih R. Energy consumption, real income and temporal causality: Results of a multi-country study based on cointegration and error correction modeling techniques. Energy Econ 1996;18(3):165-183.

(10) Johansen S. Statistical analysis of cointegration vectors. J.Econ.Dyn.Control 1988;12:231-254.

(11) Abosedra S, Baghestani H. New evidence on the causal relationship between United States energy consumption and gross national product. Journal of Energy and Development 1991;14:285-292.

(12) Stern DI. A multivariate cointegration analysis of the role of energy in the US macro-economy. Energy Econ 2000;22(2):267-283.

(13) Yu ESH, Yin J. Cointegration tests of energy consumption, income and employment. Resources and Energy 1992;14:259-266.

(14) Oh W, Lee K. Energy consumption and economic growth in Korea: testing the causality relation. Journal of Policy Modelling 2004;26(8-9):973-981.

(15) Ghali KH, El-Sakka MIT. Energy use and output growth in Canada: a multivariate cointegration analysis. Energy Econ. 2004;26(2):225-238.

(16) Guttormsen AG. Causality between energy consumption and economic growth. Energy Policy 2008:36(10):3838-3842

(17) Sims CA. Money, income and causality. Am.Econ.Rev. 1972;62(4):540-552.

(18) Granger CWJ. Investigating causal relations by econometric models and cross-spectral methods. Econometrica 1969;37:424-438.

(19) Engle RF, Granger CWJ. Cointegration and error correction: Representation, estimation and testing. Econometrica 1987;55:251-276.

(20) Glasure YU. Energy and national income in Korea: further evidence on the role of omitted variables. Energy Econ 2002;24(4):355-365.

(21) Climent F, Pardo A. Decoupling factors on the energy-output linkage: The Spanish case. Energy Policy 2007;35(1):522-528.

(22) Cleveland CJ, Kaufmann RK, Stern DI. Aggregation and the role of energy in the economy. Ecol.Econ. 2000;32(2):301-317.

(23) Ayres RU, Ayres LW, Warr B. Exergy, power and work in the US economy, 1900-1998. Energy 2003;28(3):219-273.

(24) Ayres, R. U., L. W. Ayres, L. Pokrovski. On the efficiency of US electricity usage since 1900. Energy 2005:30(7):1092-1145.

(25) Madisson, A. 2003, The World Economy: Historical Statistics, OECD, Paris

(26) Perron, P. "The great crash, the oil price shock, and the unit root hypothesis." Econometrica 1989;57:1361-1401.

(27) Zivot, E. and D. W. K. Andrews. Further evidence on the Great Crash, the Oil Shock and the unit root hypothesis. Journal of Business and Economic Statistics 1992;10(3):251-270.

(28) Newey WL, West KD. A simple, positive semi-definite, heteroscedasticity and autocorrelation consistent covariance matrix. Econometrica 1987;55:703-708.

(29) Phillips PCB, Perron P. Testing for a unit root in time series regression. Biometrika 1988;75(2):335-346.

(30) Johansen S. Estimation and hypothesis testing of cointegration vectors in Gaussian vector autoregressive models. Econometrica 1991;59(6):1551-1580.

(31) Johansen S. Testing weak exogeneity and the order of cointegration in UK money demand data. Journal of Policy Modeling 1992;14(3):313-334.

(32) Johansen S, Juselius K. Maximum likelihood estimation and inference on cointegration with applications to the demand for money. Oxford Bull.Econ.Stat. 1990;52:169-209.

(33) Asafu-Adjaye J. The relationship between energy consumption, energy prices and economic growth: Time series evidence from Asian developing countries. Energy Econ 2000;22(6):615-625.

(34) Foxon, T.J. Gross, R., Chase, A., Howes, J., Arnall, A., and D. Anderson. UK innovation systems for new and renewable energy technologies: drivers, barriers and systems failures. Energy Policy 2005;35:2123-2137.

(35) Granger CWJ, Newbold P. Spurious regression in econometrics. J.Econ. 1974;35:143-159.

(36) Kwiatkowski D, Phillips PCB, Schmidt P, Shin Y. Testing the null hypothesis of stationarity against the alternative of a unit root: How sure are we that economic time series have a unit root? J.Econ. 1992;54:159-178.

Table 1. Phillips-Perron unit root test

Variable	Levels	First Differences
	$Z(t_\alpha)$	$Z(t_\alpha)$
$\ln(q)$	- 0.31	- 7.07***
$\ln(k)$	0.97	- 5.02***
$\ln(l)$	- 0.40	- 7.91***
$\ln(e)$	- 1.41	- 3.89***
$\ln(u)$	- 2.25	- 10.37***

The number of truncation lags to calculate the Newey-West standard errors for the PP test is chosen as $\text{int}\{4(T/100)^{2/9}\}$ (24).

For ease of presentation we present only the Phillips-Perron $Z(t_\alpha)$ statistic and not the $Z(\alpha)$ statistic which in all cases carried the same information.

Asterisks indicate rejection of the null hypothesis of the presence of a unit root at *10%, **5% and ***1% critical value.

Table 2. Selected lag truncation for use in VECM

	Models taking total natural resource exergy (model A) or useful work (model B)			
	1900-1941		1946-1998	
	Model A	Model B	Model A	Model B
SBIC	1	1	2	5
AIC	5	1	5	5

Table 3. VECM model trend and rank selection

	Without a trend			With a trend		
Cointegrating Rank	Model A	Model B	Critical values	Model A	Model B	Critical values
$j = 0$	97.72	99.82	53.12	75.06	83.61	47.21
$j \leq 1$	59.07	48.98	34.91	39.33	34.86	29.68
$j \leq 2$	28.84	27.29	19.96	12.68*	14.51*	15.41
$j \leq 3$	10.28	10.93	9.42	2.29	1.98	3.76

Table 4. Causality tests

Source of causation (independent variable)	Dependent variable: *model A* ΔGDP	ΔExergy	ΔCapital	ΔLabour		*model B* ΔGDP	ΔWork	ΔCapital	ΔLabour
Short run									
ΔGDP		0.66	2.10	0.54	*ΔGDP*		0.51	2.07	0.82
ΔExergy	20.46***		6.17**	12.55	*ΔWork*	0.34		8.35**	1.51
ΔCapital	4.58	2.34		0.03	*ΔCapital*	1.06	4.65*		0.98
ΔLabour	0.68	0.53	4.63*		*ΔLabour*	1.67	5.06*	0.75	
Long run									
ECT/ΔGDP		5.63	3.89	18.25***	*ECT/ΔGDP*		1.99	2.19	6.18
ECT/ΔExergy	56.78***		11.03***	25.96***	*ECT/ΔWork*	17.71***		12.89**	12.80***
ECT/Capital	57.91***	5.87		17.40***	*ECT/Capital*	15.09***	5.62		5.57
ECT/ΔLabour	45.46***	6.07	6.12		*ECT/ΔLabour*	13.45***	7.77	1.03	

Europe Campus
Boulevard de Constance
77305 Fontainebleau Cedex, France
Tel: +33 (0)1 60 72 40 00
Fax: +33 (0)1 60 74 55 00/01

Asia Campus
1 Ayer Rajah Avenue, Singapore 138676
Tel: +65 67 99 53 88
Fax: +65 67 99 53 99

www.insead.edu

Printed by INSEAD

INSEAD

The Business School
for the World®