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2008/62/ISIC

Either Increase Supplies or Increase Efficiency: Evidence of Causality Between the Quantity and Quality of Energy Consumption and Economic Growth in the U.S.

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Abstract

We describe the results of empirical analysis to investigate the causal relationship between the quantity and the way that energy is consumed and economic growth in the US over the second half of the 20th Century. We compared the results from two multivariate models of GDP, capital, labour with either exergy or useful work representing energy inputs. Our results provide evidence of unidirectional causality running from either energy measure to GDP. For exergy, causation stems from both the short-term and long-term error correction terms. For useful work, capital and labour, the causal effect on GDP stems from the long-term error-correction terms. We conclude that both exergy inputs and the useful work they provide, in combination with capital and labour inputs, are necessary for continued economic growth. To maintain long-term growth there is a choice, either increase energy supplies or increase the efficiency of energy use. Facing energy security, cost and environmental impact issues the latter option may be the more sensible.

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 half century years. 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. 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 then follows that reducing energy consumption will not significantly impact output growth, in other words that energy is neutral to growth, giving rise to what is referred to as 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 would 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), and 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’ 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

[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 (30).

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. 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 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. To date the 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 energy efficiency rather than increasing total energy consumption. In other words it may be possible to decouple energy consumption and economic growth. The implications of this are highly relevant today.

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[2]. 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 [Johansen 1988].

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

Exergy is an unfamiliar term, except to chemists or physicists. But it is really what non-technical people usually mean when they speak of energy. The formal definition in thermodynamics that is somewhat broader. Exergy is 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) and thermal exergy (heat). However for our macro-economic purposes only chemical exergy need be considered. The exergy embodied in a fuel 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

[2] 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.

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.

The methodology to estimate useful work consumption comprises three distinct stages. The first involves compilation of apparent consumption of natural resource exergy flows, the second allocation of exergy to each category of useful work, and the third estimation of the useful work provided by each. For purposes of empirical estimation, it is helpful to distinguish between four types of exergy use. The first category is fuel used to generate heat, either as process heat and chemical energy for industry (high temperature heat) or for space heat and hot water (low temperature heat). The second 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 distinguish two sub-groups for electricity[3] and 'other prime movers'. The third category comprises non-fuel uses, such as coking coal and petrochemicals. The fourth category includes muscle work provided by draught animals and human workers.

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

[3] Electricity can be used to provide all other forms of work.

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). Series of GDP, capital and labour are provided by Maddison (24), updated where necessary using WDI statistics. Prior to analysis all variables (GDP = Q, capital = K, labour = L, exergy = E and useful work = U) were indexed (q, k, l, b and u) and log transformed.

3. Empirical study

3.1. Unit root and cointegration tests

We apply the Phillips-Perron unit-root test[4] to the data in levels and their first differences to identify the order of integration of each variable (25)As shown in **Table 1** the unit root hypothesis is accepted for all variables in levels (5% critical level), but rejected for all variables in first differences, therefore all variables are I(1).

On the basis that the variables are integrated of the same order we use the multivariate cointegration analysis framework developed by Johansen (10,26,27)(Johansen, 1988, 1991 and 1995) and Johansen and Juselius (28) to test for the presence of cointegration[5]. 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

[4] 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.
[5] 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.

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

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 Aikaike 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[6] to identify both (15). The results of these cointegration tests for models without (*j=1*) and with

[6] 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[6]. 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.

($j=2$) 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 1**, we can express the VECM for GDP (q) as,

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

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 short-run or 'weak' Granger causality by testing the significance of the short-run coefficients. For example, 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 2**. 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 ((29).

The results of the 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, we find evidence of causality from exergy to GDP, but no evidence of causality running from GDP to exergy consumption. For model B we find no evidence of short-run causality between useful work and GDP in either direction, We conclude there is unidirectional short-run causality from exergy to GDP but no short-run causality in either direction between useful work and GDP, evidence supporting the neutrality hypothesis. However, the tests for long-run causality indicate, that in both models, there is evidence of unidirectional strong causality running from the energy measures, exergy and useful work, to GDP, refuting any hypothesis of energy neutrality.

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 energy. Having determined that the variables are cointegrated we used a vector error correction model to test for both short-term and long-term causality. In both cases we found evidence of unidirectional causality running from either energy measure to GDP, capital and labour. There was no evidence of causality in the other direction from GDP to exergy or useful work consumption. Neither was there evidence that labour or capital accumulation are causal on exergy consumption. In contrast both labour and capital Granger cause useful work consumption in the short-term (but not in the long-term).

We find no evidence of direct causality between GDP and exergy. These results stand in contrast to those 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.

Indeed, this is the first study to assess the causal relationship between useful work and economic growth.

These findings provide further evidence of the importance of energy consumption for GDP growth, measured either as fuel exergy or useful work. They imply that efforts to reduce energy consumption may have a negative effect on future GDP growth rates. However, they also indicate that GDP growth may be maintained by using the available work (exergy) more efficiently to supply ever increasing amounts of useful work per unit of exergy consumed. Increased energy efficiency is required to either reduce or stabilise energy consumption whilst increasing useful work supplies. Our findings imply that as long as increasing supplies of useful work can be sustained, energy consumption and economic growth may be decoupled. 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 some hope for future economic growth. These results indicate that government efforts can concentrate on identification and support of the most economically feasible and technologically desirable means to maintain energy efficiency improvements and growth into the future. For businesses the results are clear. They 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. Such decisions must be made in light of estimates of the future cost of energy supplies against capital costs required to increase energy efficiency and offset energy consumption. As the cost of energy reaches all time highs, it is increasingly investments in the latter option, energy efficiency that appear the more sensible.

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Table 1. Phillips-Perron unit root test

Variable	Levels	First Differences
	$Z(t_\alpha)$	$Z(t_\alpha)$
ln(*y*)	- 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

	Dependent variable								
Source of causation (independent variable)	*model A*					*model B*			
	ΔGDP	ΔExergy	ΔCapital	ΔLabour		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	

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