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A MULTIVARIATE COINTEGRATION ANALYSIS OF THE ROLE OF ENERGY IN THE U.S. MACROECONOMY

by

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Abstract

This paper extends my previous analysis of the causal relationship of GDP and energy use in the USA in the post-war period to a cointegration analysis of that relationship. It is found that the majority of the relevant variables are integrated justifying a cointegration analysis. The results show that cointegration does occur and that energy input cannot be excluded from the cointegration space. The results are plausible in terms of macroeconomic dynamics. The results are similar to my previous Granger Causality results and contradict claims in the literature (based on bivariate models) that there is no cointegration between energy and output.

1.0 Introduction

Stern (1993) addressed the debate among economists and energy analysts regarding the role of energy in the US macroeconomy. Several analysts (Kraft and Kraft, 1978; Akarca and Long, 1980; Yu and Hwang, 1984; Abosedra and Baghestani, 1991) had used Granger (1969) or Sims (1972) tests to test whether energy use caused economic growth or whether the level of energy use was determined by the level of output. Generally the results were inconclusive. Where significant results were obtained they indicated causality running from output to energy use. Erol and Yu (1987) found some indications of a causal relationship between energy and output in a number of industrialized countries. This relationship was particularly significant in the case of Japan for the period 1950-1982. However, when the period was restricted to 1950-1973 the relationship was no longer significant. Yu and Choi (1985) also found a causal relationship running from energy to GDP in the Philippines economy, and causality from GDP to energy in the economy of South Korea. In the latter economy causality from energy to GDP was significant only at the 10% level. Ammah-Tagoe (1990) found causality running from GDP to energy use in the Ghanaian economy.

My study advanced beyond the previous work by testing for Granger causality in a multivariate setting using a vector autoregression (VAR) model of GDP, energy use, capital, and labor inputs. I also used a quality-adjusted index of energy input in place of gross energy use. The multivariate methodology is important because changes in energy use are frequently countered by opposite movements in the employment of other factors, due to substitution, resulting in an insignificant overall impact on output. Weighting energy use for changes in the composition of the energy input is important because a large part of the growth effects of energy are due to substitution of higher quality energy sources such as electricity for lower quality energy sources such as coal (Jorgensen, 1984; Hall *et al.*, 1986). When both these innovations were employed, energy was found to Granger cause GDP. These results are supported by the findings of Hamilton (1983) and Burbridge and Harrison (1984), who found that changes in oil prices Granger-caused changes in GNP and unemployment in VAR models whereas oil prices were exogenous to the system. More recent support for the role of energy in economic growth has come from Moroney (1992) who presents a theoretical and empirical analysis that counters some of the earlier arguments, by Berndt (1980), Denison (1979,1985), Perry (1977) and Solow (1978) etc., that because energy costs are only a small proportion of GDP, energy use is unlikely to be a very important factor in changing rates of economic growth. Moroney (1992) uses a labor-intensive form of a production function with capital embodied technological change to investigate the effects of changes in capital and energy used per unit of labor on labor productivity. He estimates similar output elasticities for both the latter variables and a breakdown of the sources of growth finds that in the period 1950-1973 changes in energy used per unit of labor contributed an annual average 1.17 percentage points to economic growth, while from 1974-1984 declines in energy use reduced growth by an annual average of 0.5 percentage points.

Yu and Jin (1992) were the first to test whether energy and output cointegrate. They found that no such relationship exists between energy use and either employment or an index of industrial production. However, it seems that the lack of a long-run equilibrium relationship between gross energy use and output alone does not necessarily imply that no relation between the variables exists. Only a few analysts think that capital, labor, and technical change play no significant role in determining output. If these variables are integrated then there will be no cointegration between energy and output whether there is a relationship between the latter two variables or not. Also decreasing energy intensity, due to increased energy efficiency, shifts in the composition of the energy input, and structural change in the economy, mean that energy and output will drift apart. Similar comments apply to the bivariate energy-employment relationship. Further, the insensitivity of the test may be compounded by their use of total energy use in the economy as a whole but measurement of output as industrial output alone.

Masih and Masih (1996) find cointegration between energy and GDP in India, Pakistan, and Indonesia, but no cointegration in Malaysia, Singapore, or the Philippines. Granger causality runs from energy to GDP in India but in the opposite direction in the other two countries.

Ohanian (1988) and Toda and Phillips (1993) showed that the distribution of the test for block exogeneity in a VAR with non-stationary variables is not the standard chi-square distribution. This means that the significance levels reported in previous studies of the Granger-causality relationship between energy and GDP are incorrect as both variables are generally integrated series. If there is no cointegration between the variables then the causality test should be carried out on a VAR in differenced data, while if there is cointegration standard chi-square distributions apply when the cointegrating restrictions are imposed. Thus testing for cointegration is a necessary prerequisite to causality testing.

It seems that if a multivariate approach helps in uncovering the Granger causality relations between energy and GDP a multivariate approach should be useful in investigating the cointegration relations between the variables. In this paper, I investigate the time series properties of GDP, quality weighted energy, labor, and capital series, estimate some simple static single equation production functions, and estimate three versions of a dynamic cointegration model using the Johansen methodology. The methods are outlined in the next section of the paper which is followed by the results and finally some conclusions.

2. Methodology

a. General

The basic model is a four equation VAR on annual data for U.S. GDP, energy input, capital input, and labor input, for the period 1948 to 1994. The general form of the VAR is :

$$f(x_{1t}) = f(x_{rt})' \Gamma + u_t \qquad (1)$$

$$f(x_{rt})' = [1, t, \ln(GDP_{t-1}),..., \ln(GDP_{t-r}), \ln(K_{t-1}),..., \ln(K_{t-r}), \ln(L_{t-1}),..., \ln(L_{t-r}), \ln(E_{t-1}),..., \ln(E_{t-r})] \qquad (2)$$

where GDP is gross domestic product, K is capital input, L is labor input, and E is energy input. r is the number of lags. Γ is a $((4 \cdot r)+2) \infty 4$ matrix of regression coefficients and u_t a $4 \infty 1$ random error vector. The time trend is intended to capture the effects of exogenous technical change. The optimum lag length r was chosen using the the Schwartz Information Criterion and Hannan-Quinn Information Criterion. The maximum lag length considered is four. Energy input is measured by quality adjusted index of final energy use. This quality adjusted index is created using Divisia aggregation.

b. Tests for Integration

The variables in (2) may be integrated. I test this hypothesis using four "unit root tests". The Dickey-Fuller (Dickey and Fuller, 1979, 1981) and Phillips-Perron (Phillips and Perron, 1988) tests are the same but use different approaches to deal with serial correlation in the data. For both tests the null hypothesis is that the series contains a stochastic trend. The model for the Dickey Fuller test is:

$$\Delta y_t = \alpha + \beta t + \gamma y_{t-1} + \sum_{i=1}^{p} \delta_i \Delta y_{t-i} + \varepsilon_t \qquad (3)$$

where y is the variable under investigation and ε_t is a random error term. The number of lags p is chosen using the Akaike Information Criterion (Akaike, 1973). The maximum lag length considered is four. The lagged variables provide a correction for possible serial correlation. The null hypothesis is given by $\gamma = 0$. The alternative hypothesis is that the process is stationary around the deterministic trend. A further battery of tests looks at other alternatives including levels stationarity.

The Phillips-Perron test uses the same models as the Dickey-Fuller tests, but rather than using lagged variables, it employs a non-parametric correction (Newey and West, 1987) for serial correlation. We chose the lag truncation for this nonparametric correction using an automated bandwidth estimator employing the Bartlett kernel (Andrews, 1991). The test statistics for both the

Dickey Fuller and Phillips Perron tests have the same distributions. Critical levels are reproduced in Hamilton (1994) and Enders (1995).

The model used in the Schmidt-Phillips test (Schmidt and Phillips, 1992) is given by:

$$\Delta y_t = \alpha + \gamma S_{t-1} + \varepsilon_t \tag{4}$$

$$S_t = y_t - y_1 - \frac{t-1}{T} \sum_{t=1}^{T} \Delta y_t \tag{5}$$

where T is the number of observations, and ε_t is a random error term. First the "residual" S_t is computed using equation (5) and then the regression in equation (4) is estimated. The test statistic is again a t-test on γ. The null is again the presence of a stochastic trend, while the alternative is trend stationarity. Critical values for the test statistic are presented in Schmidt and Phillips (1992). I use the same correction for serial correlation as for the Phillips Perron test.

The Kwiatowski, Phillips, Schmidt, and Shin (1992) test (KPSS) differs from the other three tests in that the null hypothesis postulates that the series is stationary, the alternative is the presence of a stochastic trend. A second version has a null of trend stationarity. The test statistic is a Lagrange Multiplier statistic which is calculated as the square of the sum of residuals divided by the estimated error variance from a regression of the variable in question on either a constant or a constant and a trend. We again use the Andrews / Newey-West procedure to correct for serial correlation.

c. Cointegration Analysis

On condition that at least some of the variables are integrated the VAR model (1), (2) can be estimated subject to cointegrating restrictions. Maximum likelihood estimation is carried out using the Johansen procedure (Johansen, 1988; Johansen and Juselius, 1990). Practical and theoretical background is given by Hansen and Juselius (1995) and background is provided by Hamilton (1994) and Enders (1995).

Based on my previous Granger causality results (Stern, 1993) it should not be possible to exclude energy from the cointegration space. Neither should it be possible to exclude the relevant cointegration residual from the GDP equation.

Some initial specification testing is also carried out with single equation Cobb-Douglas production functions estimated using ordinary least squares.

3. Results

a. Tests for Integration

The Dickey-Fuller test suite (Table 1) indicates that all variables but the quantity of labor are integrated. Labor input is trend stationary. Though the logs of capital and labor appear stationary in the τ_μ test this cannot be taken seriously as it would imply that these strongly trending series are levels stationary. The Phillips-Perron test (Table 2) finds that all of the series are integrated. The τ_μ statistic is significant for the energy input variable, but given that the variable has a strong trend up till 1973 this result is anomalous.

The Schmidt Phillips test results (Table 3) are similar to those for the Dickey-Fuller results at the 5% significance level, but at the 1% significance level all variables are found to be integrated. The KPSS test (Table 4) shows that all the variables with the exception of labor input and energy prices are integrated with drift when compared to a trend stationary specification. Labor input is trend stationary.

b. Single Equation Specification and Cointegration Tests

Table 5 presents the estimates of four different Cobb-Douglas aggregate production functions. On the top left of the table are estimates of a production function with an exogenous technical change trend. While the Durbin-Watson statistic indicates that there is cointegration (Engle and Granger, 1987), the coefficient on capital input is insignificant and has the wrong sign. The lower left panel presents the results where a restriction has been imposed so that GDP exhibits constant returns to scale in capital and labor. This restriction can be accepted at the 5% level. Now all the coefficients are significant and the model still cointegrates. The estimated rate of technical change is lower than before. As the coefficient of energy is significant and positive, we find that there are increasing returns in terms of GDP when energy is also increased in addition to the two primary inputs. Some of this effect is absorbed by the time trend in the unrestricted model.

In the upper right panel, estimates of a Cobb-Douglas function without a time trend are presented. All the input coefficients have the expected sign and are significant. There are increasing returns to scale to both capital and labor alone and to all three inputs. There is cointegration. In the lower right panel, constant returns to primary inputs are imposed on this model. This restriction is, however, easily rejected and the equation no longer cointegrates.

These results show that the system can be represented as either one with constant returns in capital and labor and exogenous technical change or as an unrestricted increasing returns specification with no exogenous technical change. The latter model can be estimated using the CATS package (Hansen and Juselius, 1995) while the constant returns to scale restriction cannot be implemented in that package. Also the increasing returns approach is more compatible with the idea of endogenous technical change. However, models with time trends were also estimated in the multivariate analysis.

c. Multivariate Cointegration Analysis

The optimal lag length was selected using the information criteria in Table 6. These statistics refer to a model with a constant restricted to the cointegration space and no time trends. Clearly the optimal lag length is two lags. The residual properties of the two lag models are also very adequate compared to the other models. Table 7 reports the Johansen trace cointegration test statistics and 90% critical values for cointegration ranks of 1, 2, and 3 - as there are four equations a rank of 4 would imply that the model was stationary - and different deterministic specifications. These results are for 2 lags. Any model of rank 2 is acceptable. As a consequence I estimate all three of these models. As the residual properties of all of these models are perfectly adequate they are not reported.

Table 8 presents the results for the model with the constant restricted to the cointegration space. This model is that favored by the single equation analysis above. The second cointegrating vector is clearly the production function. Because of this I have not tested identifying restrictions of the vectors as this would imply setting at least one of the coefficients in this equation to zero. The exclusion test statistics suggest that the relation could, however, be identified by excluding capital. The most important result from the point of view of this paper is that energy cannot be excluded from this cointegrating relation. Energy is, however, the only variable that can be considered weakly exogenous. As shown by the t statistics for alpha the second CV loads strongly into the GDP equation. There is, therefore, Granger causality from energy to GDP. The first cointegrating vector loads strongly into the GDP and labor equations. I have therefore normalized it on labor. It could possibly be interpreted as a labor supply function. I investigate this hypothesis by plotting in Figure 1 the percentage changes in the long-run equilibrium values of labor predicted by the two cointegrating relations. Actual labor use closely follows the predicted value from the first cointegrating vector, albeit with a smaller variance. The predicted value from the production function - the second cointegrating vector - moves in the opposite direction to actual labor use or rather labor use responds with a lag to changes in labor demand. From Table 8 we can see that in the long-run disequilibrium between labor demand and supply closes at 14% per year. This fits the stylized fact that declines in unemployment tends to lag GDP growth. However, labor use tends to accelerate further in response to disequilibrium in the first cointegrating relation. This is a labor discouragement/encouragement accelerator. In recessions labor use is below long-run equilibrium but more workers are discouraged from searching. In booms more labor enters the work-force when labor supply is above equilibrium. GDP obviously responds positively to this labor oversupply.

The alpha coefficient that loads the production function relation into the GDP equation is also positive. When GDP is above its long-run equilibrium it tends to accelerate further and vice versa. As can be seen in Figure 2, GDP is normally below equilibrium (potential GDP) during booms and above equilibrium in recessions. Thus this mechanism tends to end booms and recessions by moving GDP down or up.

Table 9 shows the results that occur when the constant is unrestricted. These differ somewhat from the results for the model with constant restricted to the cointegration space and the model, described below, which includes a linear trend in the cointegration space. In the production function the returns to scale are similar to the restricted model in Table 8 but the role of capital is smaller. As in the other models capital can be excluded from the cointegration space. However, none of the variables can be treated as weakly exogenous. The sign of GDP in the second cointegrating vector is different to that in the other two models. Also the first cointegrating vector loads into the capital equation. So perhaps in this case the first cointegrating relation can be interpreted as a capital accelerator function rather than as a labor demand function. Accordingly I have normalized the vector on capital. The sign of the relevant alpha coefficient is negative - when there is over-accumulation of capital there is a regression to equilibrium. Plots of the two cointegrating relations (not shown) show that required capital from the production function relation is countercyclical, rising sharply in recessions and vice versa. Equilibrium capital from the first cointegrating relation moves with the economic cycle. Note that this model is theoretically less satisfactory than the other two alternatives. If there is a drift term in the short-run dynamics as implied by the unrestricted constant then there ought to be a time trend in the long-run relations.

Table 10 shows the results that occur when the a linear trend is included in the cointegration space. The coefficient signs are the same as in the model with the constant restricted to the cointegration space. The time trend in the production function is 0.9% which is very close to the 1.0% rate estimated in the static model in Table 5. However the output elasticity estimates are superior in this dynamic model in that they all have the correct sign but there are actually decreasing returns to capital and labor and roughly constant returns (1.08) to all three factors of production. The negative trend coefficient in the first cointegrating vector indicates that labor supply tends to decline when holding the other inputs constant. This expresses stylized facts such as increased use of capital per worker and the tendency to a shorter working week over time. Again capital can be excluded from the cointegration space but energy is not weakly exogenous. Both cointegrating vectors now have a significant effect on energy use. So in this model there is more a case of mutual causality between energy and GDP as in Stern (1993). The signs of all the alpha coefficients are similar but much larger than in the more restricted models. The patterns of the cointegrating relations are somewhat different than in the previous examples but still the effects on each of the variables of the two CVs move in opposite directions - cyclical and countercyclical.

4.0 Conclusions

Both the single equation static cointegration analysis and the multivariate dynamic cointegration analysis shows that energy is significant in explaining GDP. They also show that there is cointegration in a relationship including GDP, capital, labor, and energy. This result contradicts the analysis of Yu and Jin's (1992) bivariate analysis. Masih and Masih's (1996) showed cointegration and energy to GDP in only one country (India) of the six Asian countries investigated**.** The multivariate analysis shows that energy Granger causes GDP either unidirectionally as possibly indicated by the first of three models investigated or probably through a mutually causative relationship as indicated by the latter two models examined. These results support the results of Stern (1993) regarding Granger causality between energy and GDP.

In addition the results provide support for basic macroeconomic "stylized facts" concerning business cycle propagation, and for increasing returns as in some ways a more adequate model than exogenous technical change.

The results presented in this paper, strengthen my previous conclusions that energy is a limiting factor in economic growth. Shocks to energy supply will tend to reduce output.

Appendix : Data Sources and Construction

Detailed sources of data are described in Stern (1993). That database was updated to 1994 (from 1990) and all prices based on 1987 constant dollars. The following additional changes or improvements were made.

Labor is measured in terms of hours worked by full-time and part-time employees in domestic industries.

Capital is measured as the aggregate value of the non-residential private and government net capital stock in constant 1987 dollars. The capital series were updated from 1993 to 1994 using data on investment in 1994.

Energy is measured as a Divisia index of the energy content (BTU) of the final use of coal, natural gas, petroleum, electric power, and biofuels. These categories reflect changes that the Energy Information Administration has made in the way it reports energy data since 1990. The major change is expanded reporting of non-utility production of electricity and renewable energy sources. Final use of the fossil fuels is calculated as the primary inputs minus the amounts used in generation by electric utilities. Use of fossil fuels by non-utility electricity producers are considered as final use. This is so as to avoid a break in the data in 1989 when non-utility coverage is expanded. All use of biofuels by non-utilities is considered as final use - consumption by utilities is subtracted. All geothermal, solar, and wind power is included in terms of electricity produced regardless of whether it is produced by utilities or non-utilities.

Fossil fuel prices for the aggregation were improved by using the expenditure data reported in the *Annual Energy Review* (U.S. Department of Energy, Energy Information Administration, 1992, 1995) to produce better estimates of actual final use fuel prices for oil, natural gas, and coal.

References

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

Akaike H. (1973) Information theory and an extension of the maximum likelihood principle, in B. N. Petrov and F. Csaki (eds.) *2nd International Symposium on Information Theory,* Budapest, Akademini Kiado, 267-281.

Akarca A. and T. Long (1980) On the relationship between energy and GNP: A reexamination, *Journal of Energy and Development* 5, 326-331.

Ammah-Tagoe F. A. (1990) *On Woodfuel, Total Energy Consumption and GDP in Ghana : A Study of Trends and Causal Relations*, Center for Energy and Environmental Studies, Boston University, Boston MA (mimeo).

Andrews, D. W. K.: 1991, 'Heteroskedasticity and autocorrelation consistent covariance matrix estimation', *Econometrica* **59**, 817-858.

Berndt E. R. (1980) Energy price increases and the productivity slowdown in United States manufacturing, in *The Decline in Productivity Growth*, Federal Reserve Bank of Boston Conference Series, Federal Reserve Bank, Boston MA.

Burbridge J. and A. Harrison (1984) Testing for the effects of oil prices rises using vector autoregressions, *International Economic Review* 25, 459-484.

Denison E. (1979) Explanations of declining productivity growth, *Survey of Current Business* August 1979, 1-24.

Denison E. (1985) *Trends in American Economic Growth, 1929-1982,* The Brookings Institution, Washington DC.

Dickey D. A. and Fuller W. A. (1979) Distribution of the estimators for autoregressive time series with a unit root, *Journal of the American Statistical Association* 74, 427-431.

Dickey, D. A. and Fuller, W. A.: 1981, 'Likelihood ratio statistics for autoregressive processes', *Econometrica* **49**, 1057-72.

Enders, W.: 1995, *Applied Econometric Time Series,* John Wiley, New York.

Engle, R. E. and Granger, C. W. J.: 1987, 'Cointegration and error-correction: representation, estimation, and testing', *Econometrica* **55**, 251-276.

Erol U. and E. S. H. Yu (1987) On the causal relationship between energy and income for industrialized countries, *Journal of Energy and Development* 13, 113-122.

Granger C. W. J. (1969) Investigating causal relations by econometric models and cross-spectral methods, *Econometrica* 37, 424-438.

Hall C. A. S., C. J. Cleveland, and R. K. Kaufmann (1986) *Energy and Resource Quality : The Ecology of the Economic Process*, Wiley Interscience, New York.

Hamilton J. D. (1983) Oil and the macroeconomy since World War II, *Journal of Political Economy* 91, 228-248.

Hamilton, J. D.: 1994, *Time Series Analysis*, Princeton University Press, Princeton NJ.

Hansen, H. and K. Juselius, 1995: *CATS in RATS: Cointegration Analysis of Time Series*, Estima, Evanston IL.

Johansen, S., 1988: Statistical analysis of cointegration vectors. *Journal of Economic Dynamics and Control*, **12**, 231-254.

Johansen, S. and K. Juselius, 1990: Maximum likelihood estimation and inference on cointegration with application to the demand for money. *Oxford Bulletin of Economics and Statistics*, **52**, 169-209.

Johansen, S. and K. Juselius, 1994: Identification of the long-run and the short run structure: an application to the ISLM model. *Journal of Econometrics*, **63**, 7-36.

Jorgenson D.W. (1984) The role of energy in productivity growth, *Energy Journal* 5(3), 11-26.

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

Kwiatowski, D., Phillips, P. C. B., Schmidt, P., Shin, Y.: 1992, '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', *Journal of Econometrics* **54**, 159-178.

Masih A. M. M. and R. Masih (1996) Energy consumption, real income and temporal causality: results from a multi-country study based on cointegration and error-correction modelling techniques, *Energy Economics* 18, 165-183.

Moroney J. R. (1992) Energy, capital and technological change in the United States, *Resources and Energy* 14, 363-380.

Newey, W. K. and West, K. D.: 1987: 'A simple positive semi-definite heteroskedasticity and autocorrelation consistent covariance matrix', *Econometrica* **55**, 1029-1054.

Ohanian L. E. (1988) The spurious effects of unit roots on vector autoregressions: A Monte Carlo study, *Journal of Econometrics* 39: 251-266.

Perry G. L. (1977) Potential output and productivity, *Brookings Papers on Economic Activity* 1.

Phillips, P. C. B. and Perron, P.: 1988, 'Testing for a unit root in time series regression', *Biometrika*, **75**, 335-346.

Schmidt, P. and Phillips, P. C. B.: 1992, 'LM tests for a unit root in the presence of deterministic trends', *Oxford Bulletin of Economics and Statistics* **54**, 257-287.

Sims C.A. (1972) Money, income and causality, *American Economic Review* 62, 540-552.

Solow R. M. (1978) Resources and economic growth, *American Economist* 22, 5-11.

Stern D. I. (1993) Energy use and economic growth in the USA: A multivariate approach, *Energy Economics* 15, 137-150.

Toda H. Y. and P. C. B. Phillips (1993) The spurious effect of unit roots on vector autoregressions: an analytical study, *Journal of Econometrics* 59: 229-255.

U.S. Department of Energy, Energy Information Administration (1992) *Annual Energy Review 1991,* Government Printing Office, Washington, D.C.

U.S. Department of Energy, Energy Information Administration (1995) *Annual Energy Review 1994,* Government Printing Office, Washington, D.C.

Yu E. S. H and J-Y Choi (1985) The causal relationship between energy and GNP : An international comparison, *Journal of Energy and Development* 10, 249-272.

Yu E. S. H. and B. Hwang (1984) The relationship between energy and GNP : Further results, *Energy Economics* 6, 186-190.

Yu E. S. H. and J. C. Jin (1992) Cointegration tests of energy consumption, income, and employment, *Resources and Energy* 14, 259-266.

Table 1 Dickey Fuller Statistics

		Model 1					Model 2			Model 3	
Variables	Lags	τ_τ	$\tau_{\alpha\tau}$	$\tau_{\beta\tau}$	ϕ_3	ϕ_2	τ_μ	$\tau_{\alpha\mu}$	ϕ_1	τ	Unit Root
lqe	2	-0.97	1.01	-0.06	4.06	**6.02**	**-2.89**	**2.92**	**9.26**	2.90	yes
lqk	2	-0.08	0.11	-0.27	4.44	**7.09**	**-3.00**	**3.13**	**10.85**	3.13	yes
lql	1	**-4.50**	**4.51**	**4.40**	**10.28**	**13.21**	-0.90	0.93	**7.03**	3.64	no
lgdp	0	-2.10	2.12	1.90	3.58	**29.63**	-1.83	1.95	**40.24**	8.79	yes

$\tau_\tau, \tau_\mu, \tau$ $\gamma = 0$ ϕ_3 $\gamma = \beta = 0$

$\tau_{\alpha\tau}, \tau_{\alpha\mu}$ $\alpha = 0$ given $\gamma = 0$ ϕ_2 $\alpha = \gamma = \beta = 0$

$\tau_{\beta\tau}$ $\beta = 0$ given $\gamma = 0$ ϕ_1 $\alpha = \gamma = 0$

Figures in bold indicate that the statistic is significant at the 5% level.

Table 2 Phillips-Perron Tests

		Model 1					Model 2			Model 3	
Variables	Lags	τ_τ	$\tau_{\alpha\tau}$	$\tau_{\beta\tau}$	ϕ_3	ϕ_2	τ_μ	$\tau_{\alpha\mu}$	ϕ_1	τ	Unit Root
lqe	3	-0.82	0.83	-0.08	4.31	**14.88**	**-2.96**	**3.02**	**22.75**	4.50	Yes
lqk	4	0.19	-0.16	-0.40	2.16	**72.44**	-1.94	2.13	**96.54**	11.02	Yes
lqh	3	-3.27	**3.28**	**3.26**	5.36	**11.10**	-0.18	0.22	**13.62**	5.27	Yes
lgdp	2	-2.19	2.20	2.00	3.61	**26.49**	-1.79	1.91	**37.95**	7.71	Yes

$\tau_\tau, \tau_\mu, \tau$ $\gamma = 0$
$\tau_{\alpha\tau}, \tau_{\alpha\mu}$ $\alpha = 0$ given $\gamma = 0$
$\tau_{\beta\tau}$ $\beta = 0$ given $\gamma = 0$
ϕ_3 $\gamma = \beta = 0$
ϕ_2 $\alpha = \gamma = \beta = 0$
ϕ_1 $\alpha = \gamma = 0$

Figures in bold indicate that the statistic is significant at the 5% level.

Table 3   Schmidt-Phillips Tests

Variable	Lags	τ	$Z\tau$	Unit root
lqe	1	-0.94536	-0.99413	yes
lqk	4	-0.65845	-0.95208	yes
lqh	2	-3.25773	-3.53376	?
lgdp	1	-1.78818	-1.92883	yes

τ is the t statistic described in the text while $Z\tau$ is corrected for serial correlation.
Critical value at 5% significance level is -3.11 and at the 1% significance level is -3.73.

Table 4 Kwiatowski-Phillips-Schmidt-Shin Tests

Variable	Lags	$\eta\mu$	Lags	$\eta\tau$	Unit Root
lqe	4	**0.76674**	4	**0.27111**	yes
lqk	4	**0.85094**	4	**0.25229**	yes
lqh	4	**0.86448**	4	0.05521	no
lgdp	4	**0.83443**	4	**0.25361**	yes

$\eta\mu$ is the test statistic against levels stationarity, $\eta\tau$ is the test statistic against trend stationarity.
Figures in bold indicate that the statistic is significant at the 5% level.

Table 5 Single Equation Models

Time Trend Model			No Time Trend Model		
Unrestricted Model			Unrestricted Model		
Variable	Coefficient	t Statistic	Variable	Coefficient	t Statistic
Constant	-2.0662297	-0.73066	Constant	-11.437203	-10.33692
LQE	0.31650549	7.37551	LQE	0.20188383	6.38223
LQK	-0.017248	-0.14952	LQK	0.34480711	5.77583
LQL	0.72826636	9.06428	LQL	0.86619211	10.95656
TREND	0.01022694	3.53407			
Durbin-Watson	0.571254		Durbin-Watson	0.574708	
Restricted Model			Restricted Model		
F(1,42)=	3.96243 (0.05305988)		F(1,43)=	33.12730 (0.00000083)	
Variable	Coefficient	t Statistic	Variable	Coefficient	t Statistic
Constant	-7.4114295	-8.08282	Constant	-8.5139545	-6.58477
LQE	0.24979798	9.01377	LQE	0.25689937	6.47713
LQK	0.17422267	2.64611	LQK	0.45017028	6.02302
LQL	0.82577733	12.54199	LQL	0.54982973	7.35641
TREND	0.00461337	6.87393			
Durbin-Watson	0.603921		Durbin-Watson	0.305158	

Table 6 Selection of Lag Length

Number of lags	Log Likelihood Function	Schwartz Criterion	Hannan-Quinn Criterion
4 lags	41.57	-35.01	-37.80
3 lags	40.72	-34.90	-37.08
2 lags	39.98	-36.28	-37.83
1 lag	38.40	-37.00	-37.41

Table 7 Joint Selection of Deterministic Components and Cointegration Rank

Cointegration Rank	Constant in Cointegration Space	Unrestricted Constant	Trend in Cointegration Space
1	44.862 (31.883)	30.965 (26.699)	46.683 (39.077)
2	15.912 (17.794)	12.648 (13.308)	20.273 (22.946)
3	5.617 (7.503)	2.644 (2.706)	9.354 (10.558)

The first figure is the Johansen trace cointegration statistic. Figures in parentheses are the 90% critical values of the trace cointegration statistic.

Table 8 Constant in Cointegration Space Model

	lgdp	lqe	lqk	lql	Constant
First cointegrating vector	-0.485	0.194	-0.251	1	-4.489
Second cointegrating vector	1	-.205	-.388	-.935	4.273
Chi-square test statistic for exclusion from cointegration space (5% critical level = 5.99)	2.88	8.23	1.25	8.86	8.93
Chi-square test statistic for weak exogeneity (5% critical level = 5.99)	21.31	5.41	10.35	15.50	-
First column of alpha (t stats in parentheses)	0.092 (4.612)	0.029 (1.094)	0.004 (0.818)	0.091 (4.623)	-
Second column of alpha (t stats in parentheses)	0.4 (4.505)	0.283 (2.387)	0.086 (4.157)	0.155 (1.775)	-

Table 9 Unrestricted Constant Model

	lgdp	lqe	lqk	lql
First cointegrating vector	-0.314	-0.123	1	-0.787
Second cointegrating vector	1	-0.232	-0.206	-1.137
Chi-square test statistic for exclusion from cointegration space (5% critical level = 5.99)	3.28	7.55	1.41	7.19
Chi-square test statistic for weak exogeneity (5% critical level = 5.99)	8.10	8.09	7.31	8.12
First column of alpha (t stats in parentheses)	-0.0016 (0.091)	-0.017 (-0.611)	-.012 (-2.321)	.0448 (2.167)
Second column of alpha (t stats in parentheses)	0.797 (4.666)	0.701 (3.160)	0.120 (3.030)	0.594 (3.589)

Table 10 Trend in Cointegration Space Model

	lgdp	lqe	lqk	lql	Trend
First cointegrating vector	-1.174	0.354	-0.191	1	0.014
Second cointegrating vector	1	-0.237	-0.157	-0.689	-0.009
Chi-square test statistic for exclusion from cointegration space (5% critical level = 5.99)	13.24	18.08	1.62	17.92	11.48
Chi-square test statistic for weak exogeneity (5% critical level = 5.99)	11.80	16.13	8.18	16.27	-
First column of alpha (t stats in parentheses)	0.046 (2.005)	0.053 (2.150)	-0.005 (-0.974)	0.087 (4.239)	-
Second column of alpha (t stats in parentheses)	1.155 (4.213)	1.624 (5.472)	0.229 (3.551)	0.801 (3.271)	-

Figure 1 Predicted Precentage Changes in Equilibrium Values for Labor Input

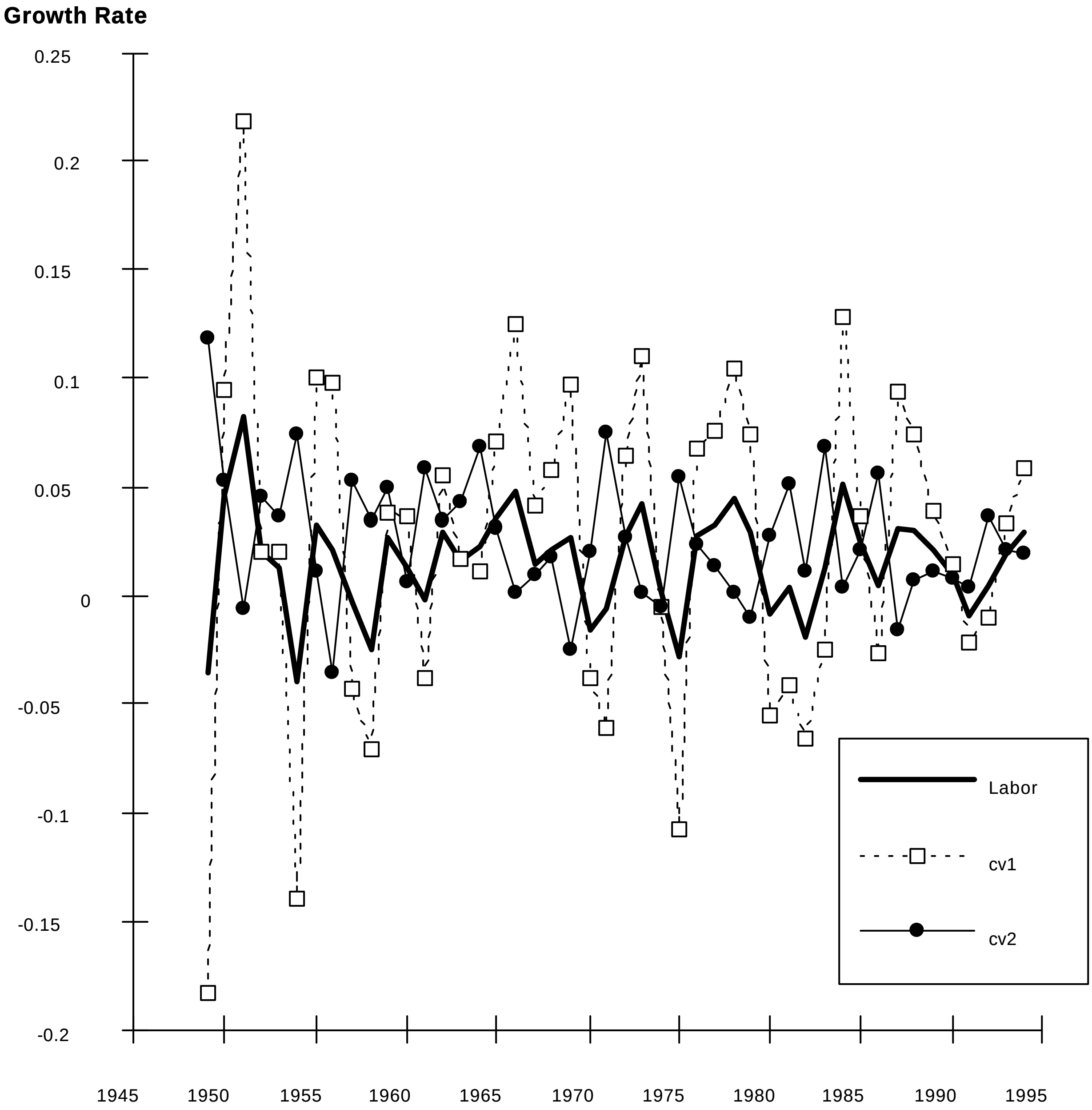

Figure 2 Predicted Precentage Changes in Equilibrium Values for GDP