Energy-Output Linkages in Australia: Implications for Emissions Reduction Policies

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The study investigates the long-run and dynamic relationships between energy consumption and output in Australia using a multivariate cointegration and causality framework. Using both Engle-Granger and Johansen cointegration approaches, the study finds that energy consumption and real Gross Domestic Product are cointegrated. The Granger causality tests suggest bidirectional Granger causality between energy consumption and real GDP, and Granger endogeineity in the system. Since the energy sector largely contributes to carbon emissions in Australia, we suggest that direct measures to reduce carbon by putting constraints on the energy consumption would pose significant economic costs for the Australian economy.

INTRODUCTION

In recent years, the issues on the relationships between energy consumption and output have garnered interest due to the consensus on reducing greenhouse gases (GHGs) emissions to combat global warming. Among the various GHGs implicated, carbon dioxide emissions account for more than three quarters of total anthropogenic GHGs emissions. These have grown at a rapid rate since pre-industrial times, leading to an increase in global average air and ocean temperatures and a rise in sea levels (IPCC, 2007a, 2007b; McKibbin & Wilcoxen, 2002). These exacerbations in climatic conditions are linked to population and plants by a variety of negative consequences (Garnaut, 2008; Pickering & Owen, 1997; Stern, 2008; Wills, 2006). In fact, GHGs emissions are largely attributed to the use of energy necessary to produce goods and services, as well as to act as a final good for end-users. Any measures to reduce GHGs, therefore, pose implications for economic growth, via the linkages with energy consumption.

In Australia, the energy sector, comprising of stationary energy, transport and fugitive emissions, contributed to about 70% of total emissions in 2006, rising from about 52% in 1990 (Department of Climate Change, 2008). Energy related emissions in the country increased by about 40% from 1990 to 2006, whereas a substantial decline (about 71%) in non-energy emissions like land use, land use change and forestry occurred during this period (Department of Climate Change, 2008). Australia is a top per capita GHGs emitter in the world as attributed to its high-energy consumption, as well as its reliance upon the fossil fuel as energy source. Its per capita energy use increased from, on average, 3726.8 kilotonnes (kt) of oil equivalent during 1965–70 to 5694.6 kt of oil equivalent during 2001–05 (Table 1). The proportion of fossil fuel energy consumption increased gradually from 89.8% in 1965–70 to 94.1% in 2001–05, and there was a reduction of the ratio of clean energy production to total energy use during 1996–05 from the previous periods (Table 1).

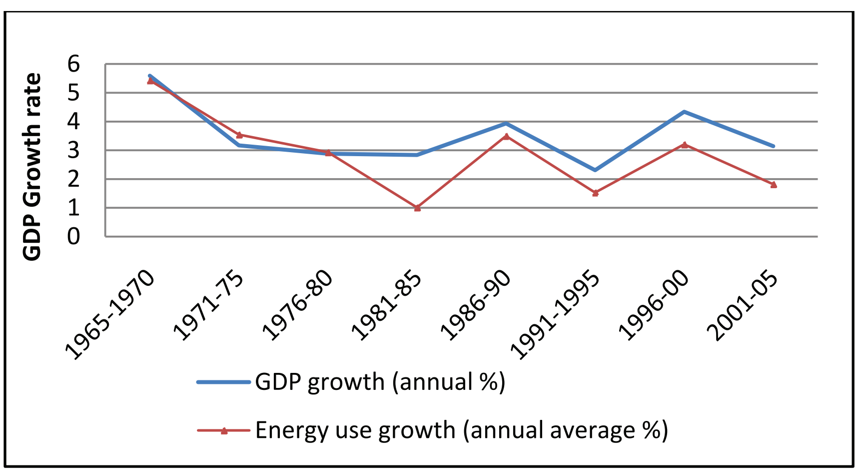
TABLE 1
ENERGY CONSUMPTION IN AUSTRALIA

	Energy use per capita *kg of oil equivalent*	**Fossil fuel energy consumption** *(% of total)*	**Clean energy production** *(% of total energy use)*	**Electricity production from coal sources** *(% of total)*
1965–70	3726.8	89.8	1.5	75.2
1971–75	4229.2	91.7	1.9	70.9
1976–80	4675.7	92.7	1.8	70.9
1981–85	4725.8	93.0	1.6	72.6
1986–90	4912.1	93.8	1.6	76.3
1991–95	5152.1	94.0	1.6	77.7
1996–-00	5660.8	93.9	1.4	78.8
2001–05	5694.6	94.1	1.3	77.7

Source: World Bank (2009)

On the other hand, the historical alignment of energy and output/income is very high in Australia. Figure 1 shows the five-year averages of the growth rate of its Gross Domestic Product (GDP) and energy use over the period 1965 to 2005. As seen in Figure 1, both GDP and energy use growth remained perfectly aligned from 1965 to 1980, along with the veracity that growth rate energy use outpaced the growth of the GDP in the 1980s. Since 1980, while growth in energy consumption has reduced, it moved with the changes in economic activities quite closely.

FIGURE 1
GROWTH RATE OF GDP AND ENERGY CONSUMPTION



Source: World Bank, 2009

The carbon exposure of the energy sources and the energy intensity of the economy is a great concern for Australia in the context of formulating domestic policies on emissions reduction. This is because any policy to reduce emissions would hurt the ongoing pace of economic growth through its impact on energy consumption because of the carbon intensity of the energy sector. Nonetheless, the potential impact of emissions reduction policies can be different depending on the direction of causality and dynamics between energy and output in short- and long-run. As for example, in the case where energy consumption is found to stimulate economic growth, it can be argued that measures to reduce emissions that directly affect energy consumption (conservation) would hurt economic growth. Conversely, if the direction of causality runs from GDP to energy consumption, then direct measures of emissions reduction through energy conservation may be implemented with little or no adverse impacts on economic growth. In essence, it is important to go beyond the simple knowledge that energy and output are interrelated but to understand the direction of causality between them in the both short- and long-run. The policy implication of such analysis is that its helps to understand the predicted impacts of the various energy conservation and emission reductions policies on economic activities.

The purpose of this study is to investigate long-run and dynamic causal relationship in Australia, using the multivariate cointegration approach. Given the growing concerns over the negative impacts of GHGs emissions and global consensus on the issue, it has now become a priority agenda for leading economies to implement domestic targets on emissions reduction. The findings of the study will be relevant to a number of countries, which are developing emissions reduction policies, but are concerned about the tradeoffs between energy and output. Yet, a number of past studies have investigated the causal relationship between energy consumption and GDP/GNP (Gross National Product), and provided a rich set of perspectives and insights; but they failed to provide unanimous results (Belloumi, 2009; Jobert & Karanfil, 2007). We provide a more detailed review of the literature for different countries in the next section.

In the case of Australia, only three studies broadly covered the issues, however, they failed to provide unanimous results. Fatai, Oxley and Scrimgeour (2004) suggest the existence of unidirectional causality running from real GDP to energy consumptions. Narayan and Smyth (2005) find the evidence of a long-run (cointegrated) relationship between electricity consumption, employment, and real income in Australia, where a long-run causality runs from employment and real income to electricity consumption. On the other hand, Narayan and Prasad (2008) find the evidence of unidirectional causality from electricity consumption to real GDP in Australia. While the studies in the context of Australia mainly rely on a bivariate framework to study the long-run relationship and Granger causality, this study applies a multivariate procedure to reduce the problems of omitted variables (Akinlo, 2008; Ghali & El-Sakka, 2004; Stern & Cleveland, 2004).

It is suggested that bivariate tests of causality can produce misleading results because of the substitution effects that may take place between energy and other inputs of production, such as capital (Ghali & El-Sakka, 2004; Stern, 2000; Stern & Cleveland, 2004). Moreover, capital investment seems to play an important role during the process of economic upliftment (Jobert & Karanfil, 2007). Energy conservative policies may also stimulate fixed investment through the installation of energy efficient machinery (Thompson & Taylor, 1995). Accordingly, this study investigates the causal relationship between energy consumption and real GDP, controlling for possible affects of gross fixed capital formation as a proxy of capital accumulation (as used by Soytas & Sari, 2009; Soytas, Sari, & Ewing, 2007), and to capture the effects of omitted variables.

Therefore, given the contradictory results on the causal relationship between energy consumption and income in Australia, this study can be considered as complementary, where the new part of the study introduces capital accumulation in the model. In addition, this study added data for the recent periods, which would be beneficial in respect of new energy/environment policies. Furthermore, both Engle-Granger (Engle & Granger, 1987) and Johansen's (Johansen, 1991, 1995) methods are applied to explore the long-run relationship(s) in a multivariate framework. Finally, in order to perform a more comprehensive analysis on the direction of causality, Granger causality was examined through three different channels (short-run, long-run, and overall system) using vector error correction (VEC) models. As a result of these advantages, this study provides a unique set of perspectives and insights and contributes to the growing body of literature on this subject.

The organization of the paper is as follows: the next section presents the review of literature; section 3 incorporates descriptions on the methodology and data; section 4 provides analyses and findings of the study; and section 5 explains the conclusions and policy implications.

REVIEW OF LITERATURE

In the literature, we can find cointegration and Granger causality analyses on the relationship between energy consumption and income/output, but with considerable variations in results. A cointegration test can analyse the existence of a long-run relationship but fails to discover the direction of causality. Therefore, testing for both cointegration and Granger causality is important from policy perspective. Four forms of hypotheses have been identified: (a) unidirectional causality from energy to income/output; (b) unidirectional causality from income/output to energy; (c) bidirectional causality; and (d) no causality. The existence of a unidirectional causality from energy to income/output suggests that energy conservative polices may adversely impact income/output. On the other hand, existence of unidirectional causality from income/output to energy infers that energy conservation policies would be undertaken without any adverse impacts on income/output. Existence of bidirectional causality suggests that an economic system exhibits feedback, therefore, shocks to energy consumption would have direct negative impacts on income/output and feedback impact on its own. Finally, existence of no causality suggests that energy (income/output) shocks are neutral to income/output (energy).

Kraft and Kraft (1978) accomplished the pioneering work on the causal relationship between energy and income. The Granger causality tests on a bivariate model for the United States (US) for the period 1947 to 1974 suggest evidence of unidirectional causality running from GNP to energy consumption. Unidirectional causality from GDP to energy is also found in Fatai, Oxley and Scrimgeour (2004) for New Zealand and Australia; the same was found by Lise and Van Montfort (2007) and Erdal, Erdal, and Esengün (2008) for Turkey; Chiou-Wei, Chen, and Zhu (2008) for the Philippines and Singapore; Akinlo (2008) for Sudan and Zimbabwe; and Yuan, Kang, Zhao, & Hu, (2008) for China.

On the other hand, unidirectional causality from energy consumption to GDP was found in Stern (2000) for the US; Soytas and Sari (2003) for Turkey, France, Germany, and Japan; Fatai, Oxley and Scrimgeour (2004) for India and Indonesia; and Belloumi (2009) for Tunisia. Bidirectional causality has also been reported by Fatai, Oxley and Scrimgeour (2004) for Thailand and the Philippines; Ghali and El-Sakka (2004) for Canada; Lee and Chang (2005) for Taiwan; Chiou-Wei, Chen, and Zhu (2008) for Malaysia and Indonesia; and Akinlo (2008) for Gambia, Ghana, and Senegal.

Some studies also found existence of no causality between the variables, supporting the view of neutrality hypothesis (see, for instance, Jobert and Karanfil (2007) for Turkey, and Chiou-Wei, Chen, and Zhu (2008) for the US, South Korea, and Thailand). Table 2 summarizes some of the recent time series studies on energy consumption and income for different countries. As can be observed from Table 1, several differences exist with respect to the direction of causality as described above.

Jobert and Karanfil (2007) wrote an excellent review of the existing literature and suggest that the conflicting results are due to differences in methodology and sample period. Karanfil (2009) illustrated the differences in empirical results on causality between energy and economic growth for India, Turkey, and the US, and supports the view that estimation results are highly sensitive to the methodology used and the time period considered. Erdal, Erdal, and Esengün (2008) identified the sample period as an important factor because of the transformation of an economy during the development process.

From the literature review, it is observed that the direction of causality between energy and income varies with respect to time, space, and methodology. There is merit in the application of alternative methodologies and the use of recent available data in the face of formulating new policies.

TABLE 2
OVERVIEW OF SOME TIME SERIES STUDIES ON ENERGY USE AND INCOME

Author(s)	Country	Period	Methods	Results	
				Cointegration	Granger causality
Stern (2000)	USA	1948–94	Multivariate VECM	Yes	EC to GDP
Fatai, Oxley and Scrimgeour (2004)	Australia, New Zealand and 4 Asian countries	1960–99	Cointegration & Granger causality	Yes, for EC for Australia No, for New Zealand	GDP to EC, for Australia and New Zealand
Ghali and El-Sakka (2004)	Canada	1961–97	Multivariate VECM	Yes	Bidirectional
Narayan and Smyth (2005)	Australia	1966–99	VECM	Yes	Income to ELC
Jobert and Karanfil (2007)	Turkey	1960–03	Cointegration & Granger causality	No	No causality
Lise and Van Montfort (2007)	Turkey	1970–03	VECM	Yes	GDP to energy
Akinlo (2008)	11 Sub-Saharan countries	1980–03	Cointegration & Granger causality	Yes (7)	Bidirectional(3); GDP to EC (3); No causality (5)
Chiou-Wei, Chen, and Zhu (2008)	USA and nine newly industrialized countries in Asia	1954–06	Linear & nonlinear Granger causality	Yes for US; Mixed results for other countries	No causality for USA; Mixed results for other countries
Erdal, Erdal, and Esengün (2008)	Turkey	1970–06	Cointegration & Granger causality	Yes	Bidirectional
Narayan and Prasad (2008)	30 OECD countries including Australia	1960–02	Bootstrap approach	-	ELC to GDP (8) GDP to ELC (6)
Yuan, Kang, Zhao, & Hu, (2008)	China	1963–05	Cointegration, VECM & Granger causality	Yes	GDP to EC in the short run
Belloumi (2009)	Tunisia	1971–04	VECM	Yes	Bidirectional in long-run; EC to GDP in short-run

Notes: EC and ELC represent final energy consumption electricity consumption, respectively. Number in a parenthesis is the number of countries in the category. VECM stands for Vector Error Correction Model.

METHODOLOGY

Variables and Data

One problem regarding the pair wise Granger causality test is that it can produce misleading results when both series are caused by a common third variable. To solve this problem, we applied a multivariate approach so that the true relationship between energy consumption and real GDP could be investigated. Specifically, our model consists of three variables; total energy consumption (eg), real GDP (yr), and capital accumulation (ks). As mentioned in the introduction, gross fixed capital formation is a reliable proxy for capital accumulation.

All variables are in the form of natural logarithm; therefore, their first differences approximate the growth rates. The annual model is estimated with time series data spanning from 1965 to 2006. The annual time series data were collected from the Australian Bureau of Statistics (ABS) and World Development Indicators CD ROM 2009 (World Bank, 2009). Data for the GDP chain price index and the gross fixed capital formation were collected from the ABS, while data for total energy consumption was collected from the World Bank (2009).

Properties of Data and Granger Causality

A major shortcoming of the early literature on causality test between income and energy relationship is the failure to capture the stationary property of data (Ghali & El-Sakka, 2004; D. Stern & Cleveland, 2004). This is important because Granger causality implies that the test cannot be performed in case of non-stationary series. A series is called non-stationary if its distribution shifts over time. Accordingly, if a non-stationary series needs to be differenced *d* times in order to find a stationary form; the series is called integrated of order *d*, that is, I (d). While non-stationary series have to be differenced to find a stationary series, a major problem of differencing is the loss of information regarding series levels. Engle and Granger (1987) devised a way to run a model with non-stationary variables in level form, popularly known as the error correction model.

Engle and Granger (1987) postulated that a linear combination of two or more non-stationary series might be stationary if they have the same order of integration. Furthermore, if such a linear combination exits, the series are cointegrated implying long-run relationships. Following Granger (1988) and Engle and Granger (1987), VEC specifications for the set variables in this study can be written as follows:

$$\Delta yr_t = \lambda_1 + \sum_{i=1}^{r} \alpha_{1,i} \Delta yr_{t-i} + \sum_{i=1}^{r} \delta_{1,i} \Delta eg_{t-i} + \sum_{i=1}^{r} \beta_{1,i} \Delta ks_{t-i} + v_1 \varepsilon_{t-1} + \eta_{1,t} \quad (1)$$

$$\Delta eg_t = \lambda_2 + \sum_{i=1}^{r} \alpha_{2,i} \Delta yr_{t-i} + \sum_{i=1}^{r} \delta_{2,i} \Delta eg_{t-i} + \sum_{i=1}^{r} \beta_{2,i} \Delta ks_{t-i} + v_2 \varepsilon_{t-1} + \eta_{3,t} \quad (2)$$

$$\Delta ks = \lambda_3 + \sum_{i=1}^{r} \alpha_3 \Delta yr_{t-i} + \sum_{i=1}^{r} \delta_{3,i} \Delta eg_{t-i} + \chi_{3,i} \sum_{i=1}^{r} \beta_3 \Delta ks_{t-i} + v_3 \varepsilon_{t-1} + \eta_{3,t} \quad (3)$$

In equations (1) to (3), the parameters v_1 , v_2, and v_3 represent the adjustment coefficients, and ε_{t-1} are the cointegration vectors derived from the long-run relationships (in level). Using the VEC models, Granger causality tests between the variables can be investigated by three different channels:

(i) A Wald coefficient test or joint F-test applied to the coefficients of each explanatory variable. For example, to investigate whether causality (short-run) runs from energy consumption to GDP, we test the null hypotheses whether $\delta_{11} = \delta_{11} = \ldots = \delta_{1p} = 0$.

(ii) Statistical significance of lagged error correction terms to investigate the long-run causality.

(iii) A joint F-test or Wald coefficient test applied jointly to the sum of the lagged dynamic terms and lagged error correction terms to investigate the Granger endogeneity or system causality.

ANALYSIS AND FINDINGS

Unit Root Test

Given the importance of the stationary property of data for identifying the causal relationship, three different tests are applied to find robust results. These tests are Augmented Dicky-Fuller (ADF), Dicky-Fuller GLS (DF-GLS), and Phillips-Perron (PP). The DF-GLS test is implemented along with the conventional DF, as the former performs better in the case of small sample sizes and power (Elliott, Thomas, & Stock, 1996). The null hypothesis for all tests indicates that the series has a unit root (non-stationary) in the level forms. We applied the Akaike Information Criterion (AIC) (Akaike, 1969) to select the lag structure for the ADF and DF-GLS, while the bandwidth for the PP test was selected with the Newey-West Bartlett Kernel. Six was chosen as the maximum lag length.

Table 3 reports the unit root test results for the variables, together with the optimal lag lengths reported in the parentheses. The battery of unit root tests presented in the table almost unanimously indicates that all the variables are non-stationary in level (with and without trend) and stationary in the first difference form. This indicates that the integration of the variables in the study is of order one, e.g. *I* (1).

TABLE 3
UNIT ROOT TEST RESULTS

Variables	ADF		DFGLS		PP	
	Level	First difference	Level	First difference	Level	First difference
yr	-2.59 (0)	-5.95* (0)	1.09(2)	-2.44^(1)	-2.57	-5.95*
eg	-2.98 (1)	-8.37* (0)	0.62(3)	-2.03^(2)	-3.12	-8.23*
ks	-1.72 (0)	-6.01* (0)	2.14(0)	-5.29*(0)	-1.89	-6.14*

Note: each test uses an intercept and trend when they are significant. *,^, and ˜ denote significance at the 1%, 5% and 10% critical levels, respectively.

Cointegration Tests

The stationary properties of the variables allow us to exploit the information content of the data in level form using cointegration theory. Cointegration theory suggests that a linear combination of two or more non-stationary series would be stationary (Engle & Granger, 1987). If this is the case, then a long run relationship among the variables can be established. This further leads to the conclusion that causality exits among the variables, even though the direction of causality is not precisely determined.

Testing a linear combination of two or more non-stationary series involves running a regression equation in level and then checking whether the residual is stationary. The estimation of the long run relationships (t-statistics in the parenthesis) are:

$$yr_t = 0.16 + 0.74eg_t + 0.39ks_t + \varepsilon_{1t} \quad (4)$$
(2.35) (18.87) (13.82)

$$eg_t = -0.05 + 1.22yr_t - 0.40ks_t + \varepsilon_{2t} \quad (5)$$
(-0.59) (18.87) (-6.88)

$$ks_t = -0.60 - 1.16eg_t + 2.14yr_t + \varepsilon_{3t} \quad (6)$$
(-4.27) (-6.89) (13.82)

Equations (4) to (6), ε_{it} represent the estimated residuals from the equilibrium regressions. Now, we test whether the estimated residuals from the estimated equations are stationary or not. For this purpose, we use the Dickey-Fuller (DF) unit root tests (Enders, 2004). The actual ε_{it} is not observable; therefore, it will be inappropriate to use the usual DF critical values to measure the significance levels of the estimated coefficients. We follow Mackinnon's (1991) Response Surface Estimation procedure to find the critical values for the cointegration test.

The DF test results indicate that the estimated residuals from all three equations are stationary at the 10% level. As the null for the DF test is no cointegration, it is not possible to reject the hypothesis that the variables are not cointegrated (Engle & Granger, 1987). It can now be concluded that that cointegrating relationship(s) of the order (1,1) exist among the set of variables in the study.

One problem with the above Engle and Granger (1987) method of the cointegration test is that it ignores the possibility of the existence of two or more cointegration vectors. This is particularly important as the model involves more than two variables. To explore this possibility, we employ Johansen's (1988, 1995) procedures to check whether the above results regarding cointegration from Engle and Granger (1987) are consistent with the Johansen method.

In the Johansen cointegration test, the presence and number of cointegration vector(s) is identified using two different likelihood ratio tests – one is based on trace statistics and the other on maximum eigenvalue. However, before going to the cointegration test, it is necessary to run an unrestricted VAR (vector autoregression) to determine the maximum lag length because the Johansen approach is sensitive to the lag length. A maximum lag length of four in the estimated VAR suggests that the residual in the model is out of any serial correlation. We then apply a number of lag length criterion, such as a LR test statistic (LR), a final prediction error (FPE), Akaike information criterion (AIC), Schwarz information criterion (SIC), and Hannan-Quinn information criterion (HQ) through the unrestricted VAR to determine the optimal leg length for the Johansen cointegration test. All criterions unanimously suggest no lag for the cointegration test. As there is no priory to include trend in the long-run equation, and given the visual plot of the data, we only allow a linear trend in data but intercept (no trend) in the long-run equation and the VAR.

As shown in Table 4, both trace and maximum eigenvalue statistics indicate the presence of one cointegrating equation at the 5% level.

TABLE 4
COINTEGRATION TEST RESULTS

Trace				
Ho	Eigenvalue	Statistic	5% Critical Value	Prob.**
r = 0 *	0.83	94.32	35.19	0.00
r ≤ 1	0.30	19.55	20.26	0.06
r ≤ 2	0.11	4.83	9.16	0.30
Maximum Eigenvalue				
H_o	Eigenvalue	Statistic	5% Critical Value	Prob.**
r = 0 *	0.83	74.77	22.30	0.00
r ≤ 1	0.30	14.72	15.89	0.08
r ≤ 2	0.11	4.83	9.16	0.30

Trace test indicates one cointegrating equation at the 5% level
Max-eigenvalue test indicates one cointegrating equation at the 0.05 level
* denotes rejection of the hypothesis at the 0.05 level
**MacKinnon (1999) p-values

Granger Causality Tests

While the cointegration results suggest a long-run relationship, they do not indicate the direction of causality. Therefore, Granger causality test between yr and eg is performed in equations (1) to (3), where $\varepsilon_{t-1} = yr_{t-1} - 0.16 - 0.74eg_{t-1} - 0.39ks_{t-1}$ is the normalized long-run relationship to yr. Note that in the cointegration system, one variable does not Granger cause another if the lagged value of the first difference form of the former does not enter in the error correction model of the latter. For example, eg does not Granger cause yr, if the lagged value of Δeg does not enter equation (1). Before testing the Granger causality, it is necessary to perform a number of diagnostic tests to validate standard assumptions. Serial correlation LM tests assert no serial correlation in the residual and CUSUM (Cumulative Sum of Recursive Residuals) and CUSUM square tests validate the parameter stability. The optimal lags are chosen based on minimum AIC. The CUSUM and CUSUM Squares test results reported in Figures 2, 3 and 4 suggest that the stability of the parameters is not rejected for all three equations. Finally, the existence of Granger causality can be tested using a Wald coefficient test. Table 5 reports the Granger causality test results.

FIGURE 2
CUSUM AND CUSUM SQUARE TESTS FOR EQUATION 1

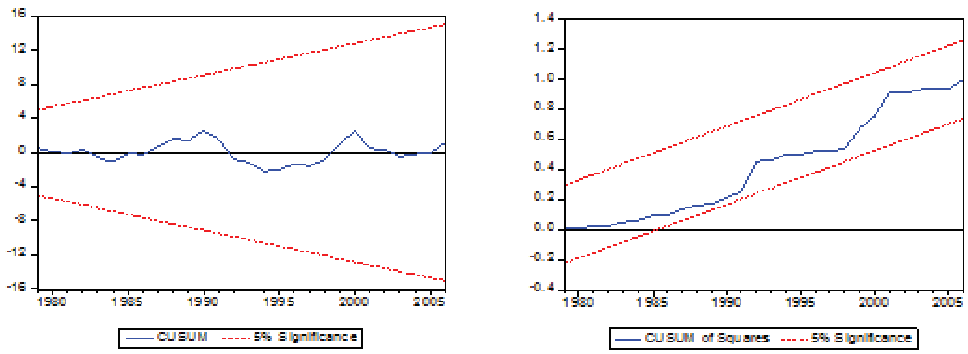


FIGURE 3
CUSUM AND CUSUM SQUARE TESTS FOR EQUATION 2

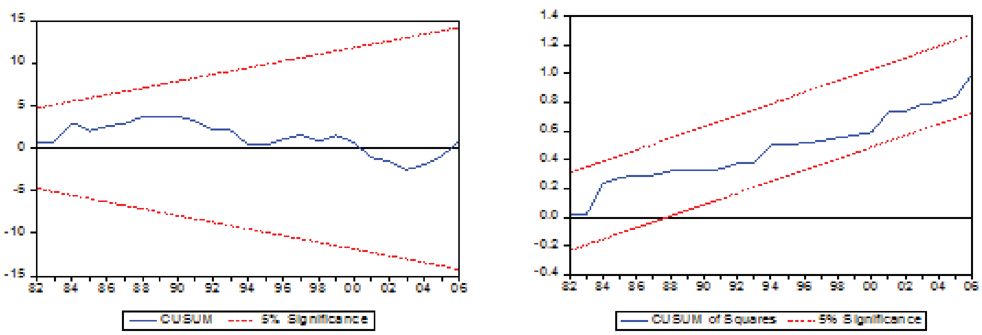


FIGURE 4
CUSUM AND CUSUM SQUARE TESTS FOR EQUATION 3

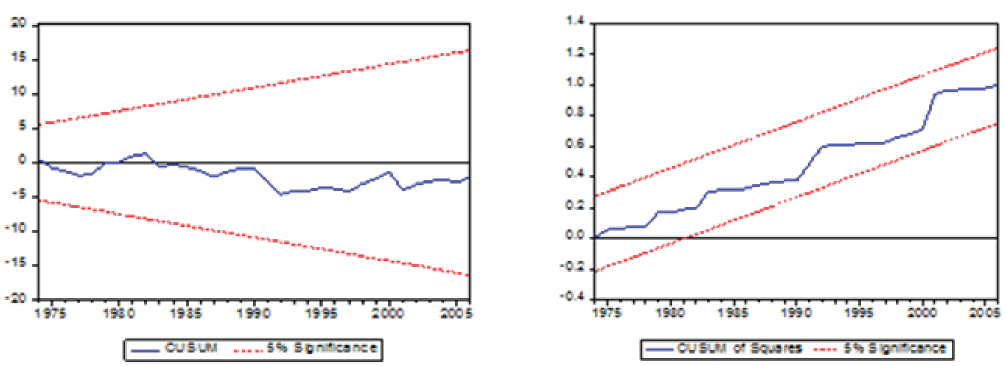


TABLE 5
TEST OF GRANGER CAUSALITY

Equation	Short-run			Long-run			
	Δyr	Δeg	Δks	Error correction	EC DGP	EC EG	EC GCF
	F-statistics			T-statistics	Joint F-statistics		
1	-	3.53^{b}	3.17^{b}	-0.44^{a}	-	4.02^{b}	4.75^{b}
2	4.57^{a}	-	5.14^{b}	0.28^{c}	4.20^{b}	-	8.27^{a}
3	2.97^{b}	0.68	-	1.30^{a}	4.45^{b}	4.76^{b}	-

Note: superscripts a, b and c denote significance at 1%, 5% and 10% critical level respectively.

Some important observations can be made from the estimation results. First, error correction terms are significant in all three equations, suggesting convergence to long-run equilibrium whenever there is a deviation from the cointegrating relationship. Second, there is significant short-run bidirectional causality between energy consumption and output in Australia. Regarding the short-run Granger causality between energy consumption and capital formation energy consumption does not Granger cause capital formation, but capital formation Granger causes energy consumption.

The error correction terms in equations 1 and 3 equations are significant at the 1% level, while the error correction term in equation 2 is significant at the 10% level. Finally, the joint significance of the sum of the lags of the explanatory variable and the error-correction term are used to test the overall causality in the system. Testing the joint significance of the lagged dynamic terms of an explanatory variable and error-correction term is considered a strong endogeneity test as it is more restrictive than a single variable. Test results suggest the existence of Granger endogeneity. As such, bidirectional Granger causality runs between energy consumption and real GDP in Australia in both short- and long-run.

CONCLUSION AND POLICY IMPLICATION

This study investigated the linkages between energy consumption and output/income in Australia using multivariate cointegration and causality analyses during the period of 1965–2006. Empirically, while many of the earlier studies have investigated the relationship, the results are at best mixed. Moreover, there are few studies in the Australian context and the majority use a bivariate framework to explore cointegration and Granger causality. None of them considered capital accumulation as a control variable.

Based on the prediction that both energy consumption and capital formation play important roles in the economic upliftment process, and given the possibility that energy policy may also affect procurement of energy efficient machinery, the study controls for gross fixed capital formation. The study also used the latest available data and employs two alternative methods to explore the long-run relationships between energy consumption and real GDP. VEC models investigated the direction of causality through three different channels: short-run, long-run, and overall system.

The cointegration analysis in the study shows that energy consumption and real GDP are cointegrated and a bidirectional causality exists between energy consumption and real GDP in Australia in the long-run. Results from the VEC models suggest the existence of bidirectional causality between energy consumption and real GDP in Australia in both the short- and long-run. While there is a strong evidence of long-run causality between energy consumption and capital accumulation, energy consumption does not Granger cause capital accumulation, but capital accumulation Granger causes energy consumption in the short-run. Tests for the joint significance of the lagged dynamic terms of an explanatory variable and error-correction terms suggested the existence of Granger endogeneity in the system.

Being a high per capita carbon dioxide emitter, as well as prevailing hot and dry weather conditions and enduring vulnerability to climate variation, Australia has great interest in emissions control at both national and global levels. However, carbon emissions are largely attributed to energy consumption. Given the long-run relationship and the direction of causality between energy consumption and real GDP, as found in this study, drastic measures of carbon reductions by placing constraints on the energy sector seem to pose significant economic costs for the Australian economy.

In a country like Australia, where energy consumption appears to be an important determinant of long-run growth, direct measures to reduce carbon from energy related sources pose a significant threat to the country's economic growth. Presently, the fossil fuel energy consumption accounts for about 95% of the total energy consumption in Australia, and coal alone accounts for about 80% of the total electricity production (World Bank, 2009). Conversely, clean energy consumption is only 1% of total energy consumption. It is, therefore, necessary to focus on the diversification of energy sources, particularly towards the clean energy sources (natural gas, nuclear power, solar, and wind) to attain the target of carbon reduction while maintaining a sustainable output growth.

REFERENCES

Akaike, H. (1969), Fitting autoregressive models for regression. *Annals of the Institute of Statistical Mathematics, 21*, 243-247.

Akinlo, A. (2008). Energy consumption and economic growth: Evidence from 11 Sub-Sahara African countries. *Energy Economics, 30*(5), 2391-2400.

Belloumi, M. (2009). Energy consumption and GDP in Tunisia: Cointegration and causality analysis. *Energy Policy, 37*(7), 2745-2753.

Chiou-Wei, S., Chen, C., & Zhu, Z. (2008). Economic growth and energy consumption revisited—Evidence from linear and nonlinear Granger causality. *Energy Economics, 30*(6), 3063-3076.

Department of Climate Change (2008). *Australia's National Greenhouse Accounts, National Greenhouse Gas Inventory 2006* Commonwealth of Australia.

Elliott, G., Thomas, J., & Stock, J. (1996). Efficient tests for an autoregressive unit root. *Econometrica, 64:4*, 813-826.

Enders, W. (2004). *Applied econometric time series* (2nd ed.): John Wiley & Sons (ASIA) Pte Ltd.

Engle, R., & Granger, C. (1987). Co-integration and error correction: representation, estimation, and testing. *Econometrica: Journal of the Econometric Society*, 251-276.

Erdal, G., Erdal, H., & Esengün, K. (2008). The causality between energy consumption and economic growth in Turkey. *Energy Policy, 36*(10), 3838-3842.

Fatai, K., Oxley, L., & Scrimgeour, F. G. (2004). Modelling the causal relationship between energy consumption and GDP in New Zealand, Australia, India, Indonesia, The Philippines and Thailand. *Mathematics and Computers in Simulation, 64*(3-4), 431-445.

Garnaut, R. (2008). *The Garnaut climate change review*: Cambridge University Press.

Ghali, K., & El-Sakka, M. (2004). Energy use and output growth in Canada: a multivariate cointegration analysis. *Energy Economics, 26*(2), 225-238.

Granger, C. (1988). Causality, cointegration, and control. *Journal of Economic Dynamics and Control, 12*(2/3), 551–559.

IPCC (2007a). *Climate Change 2007: Synthesis Report*. Geneva, Switzerland: Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

IPCC (2007b). *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Jobert, T., & Karanfil, F. (2007). Sectoral energy consumption by source and economic growth in Turkey. *Energy Policy, 35*(11), 5447-5456.

Johansen, S. (1988). Statistical analysis of cointegration vectors. *Journal of Economic Dynamics and Control, 12*(2-3), 231-254.

Johansen, S. (1991). Estimation and hypothesis testing of cointegration vectors in Gaussian vector autoregressive models. *Econometrica: Journal of the Econometric Society*, 1551-1580.

Johansen, S. (1995). *Likelihood-based inference in cointegrated vector autoregressive models*: Oxford University Press, USA.

Karanfil, F. (2009). How many times again will we examine the energy-income nexus using a limited range of traditional econometric tools? *Energy Policy, 37*(4), 1191-1194.

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

Lee, C., & Chang, C. (2005). Structural breaks, energy consumption, and economic growth revisited: Evidence from Taiwan. *Energy Economics, 27*(6), 857-872.

Lise, W., & Van Montfort, K. (2007). Energy consumption and GDP in Turkey: Is there a co integration relationship? *Energy Economics, 29*(6), 1166-1178.

Mackinnon, J. (1991). Critical Values for Cointegration Tests. In R. Engle & C. Granger (Eds.), *Long-run Economic Relationships*. New York, United States: Oxford University Press.

McKibbin, W., & Wilcoxen, P. (2002). The role of economics in climate change policy. *Journal of Economic Perspectives*, 107-129.

Narayan, P. K., & Prasad, A. (2008). Electricity consumption-real GDP causality nexus: Evidence from a bootstrapped causality test for 30 OECD countries. *Energy Policy, 36*(2), 910-918.

Narayan, P. K., & Smyth, R. (2005). The residential demand for electricity in Australia: an application of the bounds testing approach to cointegration. *Energy Policy, 33*(4), 467-474.

Pickering, K., & Owen, L. (1997). *An introduction to global environmental issues* (2nd ed.): Routledge.

Soytas, U., & Sari, R. (2003). Energy consumption and GDP: causality relationship in G-7 countries and emerging markets. *Energy Economics, 25*(1), 33-37.

Soytas, U., & Sari, R. (2009). Energy consumption, economic growth, and carbon emissions: Challenges faced by an EU candidate member. *Ecological Economics, 68*(6), 1667-1675.

Soytas, U., Sari, R., & Ewing, B. T. (2007). Energy consumption, income, and carbon emissions in the United States. *Ecological Economics, 62*(3-4), 482-489.

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

Stern, D., & Cleveland, C. (2004). *Energy and Economic Growth*, Department of Economics**,** Rensselaer Polytechnic Institute.

Stern, N. (2008). The economics of climate change. *American Economic Review, 98*(2), 1-37.

Thompson, P., & Taylor, T. (1995). The capital-energy substitutability debate: A new look. *The Review of Economics and Statistics, 77*(3), 565-569.

Wills, I. (2006). *Economics and the environment: a signalling and incentives approach* (2nd ed.): Allen & Unwin.

World Bank (2009). World Development Indicators CD-ROM.

Yuan, J., Kang, J., Zhao, C., & Hu, Z. (2008). Energy consumption and economic growth: Evidence from China at both aggregated and disaggregated levels. *Energy Economics, 30*(6), 3077-3094.