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Interfuel substitution in Australia: a way forward to achieve environmental sustainability*

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This paper examines the possibilities for interfuel substitution in Australia in view of the need to shift towards a cleaner mix of fuels and technologies to meet future energy demand and environmental goals. The translog cost function is estimated for the aggregate economy, the manufacturing sector and its subsectors, and the electricity generation subsector. The advantages of this work over previous literature relating to the Australian case are that it uses relatively recent data, focuses on energy-intensive subsectors and estimates the Morishima elasticities of substitution. The empirical evidence shown herein indicates weak-form substitutability between different energy types, and higher possibilities for substitution at lower levels of aggregation, compared with the aggregate economy. For the electricity generation subsector, which is at the centre of the CO_2 emissions problem in Australia, significant but weak substitutability exists between coal and gas when the price of coal changes. A higher substitution possibility exists between coal and oil in this subsector. The evidence for the own- and cross-price elasticities, together with the results for fuel efficiencies, indicates that a large increase in relative prices could be justified to further stimulate the market for low-emission technologies.

Key words: demand analysis, energy, environmental policy.

1. Introduction

While energy policy in Australia has been directed to reducing greenhouse gas (GHG) emissions and to attaining environmental sustainability since the early 1990s (Narayan and Smyth 2005), these efforts have received further momentum in recent years. Most recently, the Government has announced a comprehensive plan for a clean energy future in Australia. The key objective of the plan is to cut Australia's GHG emissions by at least 5 per cent compared with 2000 levels by 2020, and by 80 per cent by 2050, by introducing a price on carbon since 1 July 2012 along with other incentives (DCCEE 2011). The imposition of a carbon tax, ambitious targets for the reduction of emissions and incentives for industry assistance are expected to encourage investment in renewable energy and the use of cleaner fuels such as gas (DCCEE 2011). Australia has some of the highest-intensity emission levels in the world, mainly due to the extensive use of coal for electricity generation and generally high levels of energy intensity (ABARES 2011b).

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Burning of fossil fuels, especially that of coal, is considered to be the main driver of CO_2 emissions (IPCC 2007; DCCEE 2011; Salim and Rafiq 2012). In 2008, coal, oil and gas accounted for 56 per cent, 28 per cent and 16 per cent of Australia's energy-related CO_2 emissions, respectively (IEA 2010a).

Given the present emission target, the country is confronted with the challenge of shifting towards a cleaner mix of fuels and technologies to meet future energy demand. This mix depends largely on the proximity, relative cost, availability and flexibility of fuel use (Uri 1982). An analysis of interfuel substitution could shed light on these aspects to determine whether significant technical flexibilities exist within the current economic structure.

The objective of this paper is to investigate interfuel substitution possibilities in Australia by using data for the aggregate economy, manufacturing sector/subsectors and the electricity generation subsector. The methodological framework used in this paper is the translog cost function approach. The translog form, introduced by Christensen *et al*. (1971, 1973), allows for an individual analysis of the effects of own and relative prices for all the competing fuels (Hall 1986; Gopalakrishnan *et al*. 1989). Over the years, this approach has been implemented in a number of studies of interfuel substitution; see, for example, Halvorsen (1977) for the manufacturing sector in the United States (US), Pindyck (1979) for pooled data from 10 countries, Uri (1979, 1982) and Harvey and Marshall (1991) for the United Kingdom (UK), Hall (1986) for seven OECD countries, Vlachou and Samouilidis (1986) for several sectors in the Greek economy, Gopalakrishnan *et al*. (1989) for US agriculture, Jones (1995) for the US industrial sector, Ko and Dahl (2001) for the US electricity generation and, more recently, Cho *et al*. (2004) for Korea and Serletis *et al*. (2010) for the aggregate economy and industrial sectors in the United States.

Econometric analyses of interfuel substitution in Australia can be found in only a limited number of studies, and given the present context, these studies are rather dated. The present study uses recent data and has greater coverage because it is performed at the national level as well as for the industrial and electricity-producing sectors/subsectors. To inform the policy debate on energy conservation issues, there is a great need for such a study that uses an up-to-date analysis of data for both the aggregate and sectoral/subsectoral levels.

The remainder of this paper is organised as follows: Section 2 reviews the literature on Australia, while Section 3 describes the model and the data set used. Section 4 provides the empirical results, and finally, Section 5 concludes and discusses the policy implications.

2. Review of the literature on the Australian case[1]

Existing Australian studies on interfuel substitution are very dated. Duncan and Binswanger (1976) applied the translog cost function approach to

[1] For brevity, we focus on Australian literature on interfuel substitution. Please see Stern (2012) and Ko and Dahl (2001) for a comprehensive review of the international literature.

measure the substitution between four energy sources – coal, oil, electricity and gas – and the demand for these inputs for the manufacturing industries, for the period 1948–1949 to 1966–1967. The elasticity coefficients reported in the study showed inelastic demand for the energy categories. An elastic response in coal demand due to price rises in fuel oil was evidenced in some industries, reflecting the possibility of substitution between energy inputs. However, the study failed to satisfy the symmetry and concavity conditions in the sample. Turnovsky *et al.* (1982) updated the data from 1946–1947 to 1974–1975 for the 'manufacturing' sector. In their study, the symmetry and homogeneity conditions were rejected. The study revealed complementarity between solid fuels and gas, and oil and electricity. Solid fuels (a category that includes coal) and oil were found to be highly substitutable.

Truong (1985) used an absolute price version of the Rotterdam specification using data from 1968–1969 to 1980–1981 for the New South Wales (NSW) 'manufacturing' industry. The study also found evidence of substitutability (although small) between solid fuels and oil. A high degree of complementarity was found between electricity and gas. Using the translog cost function approach, Rushdi (1986) analysed the case for the 'residential' sector by considering electricity, oil and gas for the period 1960–1982. The study found that electricity was substitutable for both gas and oil, while gas and oil were found to be non-substitutable. Woodland (1993) used the data for NSW manufacturing establishments for the period 1977–1985 to examine the industrial energy demand. This study indicated little substitution possibility between different fuels. Creedy and Martin (2000) found little support for switching to alternative fuels in the electricity generation sector.

Our study is different from previous Australian studies in a number of ways. Firstly, we use time-series data for the recent years and dating back to the mid-1980s. Secondly, we focus on the aggregate economy, the 'manufacturing' sector and some of its subsectors, and the 'electricity generating' sector thereby providing a more comprehensive perspective. Moreover, previous studies made inferences using symmetrical Allen (or Allen/Uzawa) elasticities of substitution (AES; Allen 1938; Uzawa 1962), while our study makes use of both AES and Morishima elasticities of substitution (MES; Morishima 1967) to investigate the substitutability/complementarity between energy types. Note that the asymmetrical MES provides a correct estimate of the 'elasticities of substitution' in the case of multiple inputs (Serletis *et al.* 2011).

3. The model and data

We posit that the aggregate production function is weakly separable with respect to the partition of inputs – that is, capital, labour, energy and material – for the aggregate economy and each sector/subsector. Then, using the duality theory of the cost of production and following Shephard (1953), we assume that the cost functions corresponding to the production function are also weakly separable. Accordingly, the energy cost function (C_E) can be written as follows:

$$C_E = C(Q, P_{E1}, \ldots P_{En}, t) \tag{1}$$

where C is the cost of energy, Q is the aggregate energy input, and $P_{E1} \ldots P_{En}$ is the price of competing fuels in the production process, and t serves as a proxy for efficiency (fuel) gains or technological change in fuel consumption. In the case of the four major fuels considered here, namely coal (c), electricity (e), gas (g) and oil products (o), Equation (1) can be written as follows:

$$C_E = C(Q, P_\mathrm{c}, P_\mathrm{e}, P_\mathrm{g}, P_\mathrm{o}, t) \tag{2}$$

Considering the theoretical regularity conditions (i.e. the energy input function is positive, monotonic and has curvature), the energy cost function can be written as follows:

$$C_E = Q \cdot P_E(P_\mathrm{c}, P_\mathrm{e}, P_\mathrm{g}, P_\mathrm{o}, t) \tag{3}$$

where P_E is the unit cost or energy price aggregation function satisfying the regularity conditions (Diewert 1973). The unit cost of energy determined by a transcendental logarithmic (translog) unit cost function with constant return to scale can be represented as follows:

$$\ln P_E = \ln \alpha_0 + \sum_{i=1}^{n} \gamma_i \ln P_i + \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} \gamma_{ij} \ln P_i \ln P_j + \sum_{i=1}^{n} \gamma_{i\tau} t \ln P_{it} \tag{4}$$

where, i, j = c, e, g, o. P_i and P_j are the price of i and j, respectively.

Logarithmic differentiation of Equation (4) yields the demand functions:

$$\frac{\partial \ln P_E}{\partial \ln P_i} = \frac{\partial P_E}{\partial P_i} \cdot \frac{P_i}{P_E} = \beta_i + \sum_j \gamma_{ij} \ln P_j + \gamma_{i\tau} t \tag{5}$$

i, j = c, e, g, o.

Application of Shephard's Lemma results in $\partial P_E / \partial P_i = Q_i / Q$, where Q_i is the cost-minimising value of the energy input i (Diewert 1973). Substituting $\partial P_E / \partial P_i = Q_i / Q$ into Equation (5), we can write

$$\frac{Q_i}{Q} \cdot \frac{P_i}{P_E} = \beta_i + \sum_j \gamma_{ij} \ln P_j + \gamma_{i\tau} t \tag{6}$$

The left hand of Equation (6) is the cost share of the individual fuels in the total energy cost. Denoting the cost share of individual fuels as S_i, where

i = c, e, g, o, the cost share equations for each individual energy type can be rewritten as follows:

$$\begin{aligned} S_c &= \beta_c + \gamma_{cc} \ln P_c + \gamma_{ce} \ln P_e + \gamma_{cg} \ln P_g + \gamma_{co} \ln P_o + \gamma_{c\tau} t \\ S_e &= \beta_e + \gamma_{ec} \ln P_c + \gamma_{ee} \ln P_e + \gamma_{eg} \ln P_g + \gamma_{eo} \ln P_o + \gamma_{e\tau} t \\ S_g &= \beta_g + \gamma_{gc} \ln P_c + \gamma_{ge} \ln P_e + \gamma_{gg} \ln P_g + \gamma_{go} \ln P_o + \gamma_{g\tau} t \\ S_o &= \beta_o + \gamma_{oc} \ln P_c + \gamma_{oe} \ln P_e + \gamma_{og} \ln P_g + \gamma_{oo} \ln P_o + \gamma_{o\tau} t \end{aligned} \tag{7}$$

Equation (7) is the basis of our empirical estimation. Note that the cost share equations for S_i must satisfy the linear homogeneity assumption and the following parameter restrictions:

$$\sum_{i=1}^{n} \beta_i = 1, \text{and} \sum_{i=1}^{n} \gamma_{ij} = \sum_{j=1}^{n} \gamma_{ji} = 0 \tag{8}$$

In addition, the symmetry of the partial elasticity of substitution implies the following cross-equation equality restriction:

$$\gamma_{ij} = \gamma_{ji} \tag{9}$$

A well-behaved translog cost function must satisfy monotonicity and concavity conditions. Satisfying the monotonicity condition requires positive fitted cost shares; that is, the function must be an increasing function of input prices. The concavity condition is met when the Hessian matrix is negative semi-definite. This condition is evaluated at the mean cost share (Considine 1989a).

By imposing homogeneity restrictions on fuel prices by normalising the price of coal, the system of equations to be estimated can be written as:

$$\begin{aligned} S_e &= \beta_e + \gamma_{ee} \ln(P_e/P_c) + \gamma_{eg} \ln(P_g/P_c) + \gamma_{eo} \ln(P_o/P_c) + \gamma_{e\tau} t + \varepsilon_e \\ S_g &= \beta_g + \gamma_{eg} \ln(P_e/P_c) + \gamma_{gg} \ln(P_g/P_c) + \gamma_{go} \ln(P_o/P_c) + \gamma_{g\tau} t + \varepsilon_g \\ S_o &= \beta_o + \gamma_{eo} \ln(P_e/P_c) + \gamma_{go} \ln(P_g/P_c) + \gamma_{oo} \ln(P_o/P_c) + \gamma_{o\tau} t + \varepsilon_o \end{aligned} \tag{10}$$

A stochastic disturbance term (ε_i) is appended to each cost share equation to allow for random errors in the cost-minimising behaviour. One of the share equations in Equation (7) is redundant, because the sum of the cost shares is unity for all times. Thus, for estimation purposes, the system has three dimensions for four fuels (Eqn 10). Estimates of the omitted (coal) share equation can be obtained from the homogeneity restrictions. The full information maximum likelihood estimation procedure is invariant with respect to the equation omitted. We estimate the system of equations using seemingly unrelated regressions (SUR), which is equivalent to an estimation of the maximum likelihood. Following Stern (2012), the means of all of the logarithmic and trend variables are deducted before estimating the model. The elasticities are thus computed for the sample mean, where all variables are zero. Models are estimated using RATS econometric software.

3.1. Elasticities

The estimated coefficients of the cost share equations allow the computation of the AES between input i and j as:

$$\sigma_{ii} = \frac{\gamma_{ii} + S_i^2 - S_i}{S_i^2}, i = \text{c, e, g, o} \tag{11a}$$

$$\sigma_{ij} = \frac{\gamma_{ij} + S_i S_j}{S_i S_j}, i,j = \text{c, e, g, o} \quad i \neq j \tag{11b}$$

where σ_{ij} denotes the symmetrical AES ($AES_{ij} = AES_{ji}$). If $\sigma_{ij} > 0$, inputs i and j are said to be AES substitutes, and if $\sigma_{ij} < 0$, inputs i and j are said to be AES complements. The MES can be calculated as follows:

$$\sigma_{ij}^m = S_i(\sigma_{ij} - \sigma_{jj}), i,j = \text{c, e, g, o} \tag{12}$$

where σ_{ij}^m is the asymmetrical MES ($MES_{ij} \neq MES_{ji}$). A positive value of σ_{ij}^m indicates substitutability, while a negative value of σ_{ij}^m indicates complementarity between inputs i and j. Inputs i and j are said to be good substitutes if $\sigma_{ij}^m > 1$; they are said to be weak substitutes if $\sigma_{ij}^m < 1$.

The AES measures changes in the demand for the ith quantity produced by changes in the jth price, while the MES measures the changes in the quantity ratio q_i/q_j produced by changes in the price of input j when the price of input i is held constant.

The own-price (η_{ii}) and cross-price elasticities (η_{ij}) are calculated as follows:

$$\eta_{ii} = \sigma_{ii} S_i \tag{13a}$$

$$\eta_{ij} = \sigma_{ij} S_j \quad i \neq j \tag{13b}$$

The model is estimated for the period 1986–2008 for the aggregate economy, and 1986–2009 for the sectoral and subsectoral levels. During this period, concerns were raised regarding climate change issues at both public policy and community levels, and the market-mediated system for energy pricing was strengthened. The consideration of such a sample period allows us to avoid the effects of two negative shocks in the Australian economy, namely the oil price shock of the 1970s and the business cycle recession of the early 1980s (ECRI 2012). The Australian economy remained relatively stable from the second half of the 1980s until recently.[2] The estimation horizon allows us to make reliable inferences about the energy demand and the possibility of substitution, using data for the last two and half decades.

Data on energy quantities for energy types and their prices were collected from various sources. Final energy consumption data for individual energy types were collected for the aggregate economy and the sector/subsectors from IEA (2010b) and ABARES (2009), respectively. Unit prices for gas and electricity were compiled from the Australian Bureau of Statistics (cat no. 6427) and ABARES (2010). End-user prices for diesel were used as a proxy for the price of oil products and were compiled from ABARES (2011a). Coal prices were represented by those of Australian thermal coal, which were obtained from IMF (2011).

4. Empirical Results

4.1. National-level data

Table 1 presents the estimates of the parameters for Equation (10) and the significance level (based on asymptotic standard errors) for national-level data. The cross-equation parameter symmetry is not rejected at the 1 per cent significance level for the sample 1986–2008 (Panel A). The cross-equation symmetry is, however, accepted at a higher significance level for the sample 1990–2008 (Panel B). The overall results for the coefficients are qualitatively similar in both panels. All of the estimates are found to be significant at the 1 per cent level except for $\gamma_{g\tau}$. The models perform satisfactorily in terms of other statistical criteria such as Durbin–Watson (DW) statistics and show low standard error (robust) values, reflecting a good fit of the data. Note that the DW statistics provide only a broad picture of possible misspecification and are not directly applicable to this type of model (Hall 1986). The estimated cost share equations are all found to be positive (results not reported here).

The calculated AES and MES values for the national-level data are presented in Table 2, and the own- and cross-price elasticities are presented in Table 3. The own-price elasticities of demand for each of the four energy types show the expected negative signs. The estimated models for both samples satisfy the concavity condition at the mean. The magnitude of the own- and cross-price elasticities, however, indicates the relatively low responsiveness of the energy demand to changes in the prices. The MES values are considerably lower than unity, indicating a weak substitutability among the energy types. The MES between coal and electricity (σ^m_{ce}) is negative (−0.270 and −0.493 for 1986–2008 and 1990–2008, respectively),

[2] One of the anonymous reviewers of this journal correctly points out that other events such as the Goods and Services Tax in 2000, the mild recession in 2001–2002 and the Global Financial Crisis in 2007–2008 might have placed structural breaks in the Australian economy. We considered these as exogenous or given factors and have not incorporated them in the modelling framework here; we leave this for future research.

Table 1 Parameter estimates: national

Parameter	Panel A: 1986–2008 Coefficient	Panel B: 1990–2008 Coefficient
β_g	0.05[a] (0.000)	0.05[a] (0.000)
β_e	0.267[a] (0.001)	0.267[a] (0.001)
β_o	0.677[a] (0.001)	0.677[a] (0.001)
γ_{gg}	0.046[a] (0.003)	0.047[a] (0.002)
γ_{ge}	−0.012[a] (0.003)	−0.014[a] (0.002)
γ_{go}	−0.034[a] (0.001)	−0.032[a] (0.001)
γ_{ee}	0.186[a] (0.005)	0.184[a] (0.007)
γ_{eo}	−0.170[a] (0.003)	−0.165[a] (0.005)
γ_{oo}	0.206[a] (0.004)	0.198[a] (0.005)
$\gamma_{g\tau}$	0.000 (0.000)	−0.000 (0.000)
$\gamma_{e\tau}$	0.003[a] (0.000)	0.002[a] (0.000)
$\gamma_{o\tau}$	−0.003[a] (0.000)	−0.002[a] (0.000)
Log likelihood	369.412	312.92
R^2 [DW]		
g equation	0.99 [1.53]	0.99 [1.69]
e equation	0.98 [1.02]	0.98 [1.06]
o equation	0.99 [1.08]	0.99 [1.11]
Asymmetry (significance)	11.278 (*0.0103*)	4.163 (*0.244*)

Notes: Figures in parentheses show robust standard errors, and the figures in italics in parentheses show the significance levels of the chi-squared test statistics for asymmetry restriction. The superscript ‘a’ denotes significance level at 1%.

indicating complementarity between these energy sources. These results are consistent with the AES values. According to the MES results, a significant but weak substitutability is found between coal and oil (irrespective of whether the price of coal or oil changes). The estimated value of (σ^m_{co}) is 0.616 for the period 1990–2008. The MES values between coal and oil indicate that increases in the price of oil would increase the consumption of coal and vice versa. A significant but relatively weak substitution possibility is found between coal and gas, and gas and coal for the period 1986–2008.

There have been no similar studies for Australia at the aggregate level, so we cannot compare our estimates with previous results.[3] However, there have been multiple international studies incorporating recent time-series data for developed countries, and it is useful to assess the agreement between our results and those from other countries. In a recent study, Serletis *et al.* (2011) estimated the aggregate elasticities of substitution for a number of OECD and non-OECD countries, using data from the 1980s to 2006. Among the OECD countries in the sample, the study found that coal and oil were Morishima substitutes for the United States, Japan and France. Gas and coal were also found to be Morishima substitutes in the United States and the UK, irrespective of whether the price of gas or coal changed. The estimated Morishima elasticities were lower than unity and were consistent

[3] One exception would be a meta-analysis on interfuel substitution by Stern (2012), which considered symmetric shadow elasticity and found evidence of little or no substitutability among different fuels for high-income countries including Australia.

Table 2 Estimated elasticities of substitution: national

Elasticities	Panel C: 1986–2008 Value	Panel D: 1990–2008 Value
Allen elasticities of substitution		
σ_{gg}	−0.704 (1.11)	−0.290 (0.823)
σ_{ee}	−0.133[c] (0.071)	−0.152[c] (0.824)
σ_{oo}	−0.028[a] (0.009)	−0.043[a] (0.012)
σ_{cc}	−12.49[a] (3.795)	−14.38[a] (0.001)
σ_{ge}	0.079 (0.258)	−0.07 (0.189)
σ_{go}	0.003 (0.032)	0.042 (0.035)
σ_{gc}	1.77 (1.312)	0.693 (1.114)
σ_{eo}	0.058[a] (0.017)	0.082[a] (0.030)
σ_{ec}	−1.142[a] (0.341)	−2.007[a] (0.416)
σ_{oc}	0.445[a] (0.111)	0.865[a] (0.147)
Morishima elasticities of substitution		
σ^m_{ge}	0.057 (0.084)	0.022 (0.068)
σ^m_{eg}	0.039 (0.068)	0.011 (0.05)
σ^m_{go}	0.021 (0.026)	0.058[b] (0.026)
σ^m_{og}	0.035 (0.055)	0.017 (0.041)
σ^m_{gc}	0.096[a] (0.026)	0.092[a] (0.030)
σ^m_{cg}	0.123[b] (0.057)	0.049 (0.047)
σ^m_{eo}	0.058[a] (0.018)	0.085[a] (0.028)
σ^m_{oe}	0.051[b] (0.022)	0.062[c] (0.033)
σ^m_{ec}	0.076[a] (0.026)	0.076[a] (0.026)
σ^m_{ce}	−0.270[a] (0.100)	−0.493[a] (0.12)
σ^m_{oc}	0.087[a] (0.026)	0.093[a] (0.028)
σ^m_{co}	0.320[a] (0.079)	0.616[a] (0.101)

Notes: Figures in parentheses show robust standard errors. Superscripts a, b and c denote significance levels at 1%, 5% and 10% level, respectively.

Table 3 Estimated own- and cross-price elasticities: national

Elasticities	Panel E: 1986–2008	Panel F: 1990–2008
η_{gg}	−0.014 (0.041)	−0.014 (0.041)
η_{ee}	−0.04 (0.025)	−0.04 (0.025)
η_{oo}	−0.029[a] (0.008)	−0.029[a] (0.008)
η_{cc}	−0.088[a] (0.288)	−0.088[a] (0.288)
η_{ge}	0.021 (0.069)	−0.019 (0.050)
η_{eg}	0.004 (0.012)	−0.003 (0.009)
η_{go}	0.002 (0.021)	0.029 (0.024)
η_{og}	0.0001 (0.002)	0.002 (0.002)
η_{gc}	0.012 (0.009)	0.004 (0.007)
η_{cg}	0.088 (0.065)	0.034 (0.055)
η_{eo}	−0.039[a] (0.012)	0.056[a] (0.020)
η_{oe}	0.016[a] (0.005)	0.022[a] (0.008)
η_{ec}	−0.008[a] (0.002)	−0.012[a] (0.003)
η_{ce}	−0.305[a] (0.091)	−0.533[a] (0.110)
η_{oc}	0.003[a] (0.001)	0.005[a] (0.001)
η_{co}	0.301[a] (0.075)	0.587[a] (0.100)

Notes: Refer to Table 2.

with the results of this study. The results from Serletis *et al.* (2011) are consistent with those from Serletis *et al.* (2010); the latter considered the case for the United States alone. Table 4 presents the estimates for the MES from

Serletis *et al*. (2011) for the United States, and those obtained here for Australia.

4.2. Sector-level analysis

In this section, we repeat the foregoing estimation procedure to obtain the elasticities of fuel substitution in different industrial and energy-producing sectors in Australia. The estimates for the parameters in Equation (10) – along with their significance levels – are reported in Table 5 for the 'manufacturing' sector (Division C) and some of its subsectors. The subsectors concerned are 'food, beverage and tobacco' (subsector 21), 'metal' (subsector 27), 'petroleum coal and chemical' (subsector 25), and 'non-metallic mineral products' (subsector 26). Together, these four subsectors account for approximately 95 per cent of the total coal consumption in the aggregate 'manufacturing' sector.

As shown in Table 5, most of the coefficients are highly significant. Consistent with the results for the aggregate economy, the estimated cost share equations are found to be positive, and fit well with the actual data (results not reported here). The estimated models strongly satisfy the cross-equation parameter symmetry for the aggregate 'manufacturing' sector and the 'food, beverage and tobacco' subsector. For the 'metal' and 'petroleum, coal and chemical' subsectors, the cross-equation symmetry of the parameters is not rejected at the 1 per cent significance level. The asymmetry of the parameters, however, is not rejected for the 'non-metallic mineral' subsector. Remarkably, the sign and significance of the γ_{ij} coefficients are consistent across the sectors, with some rational variations in magnitudes. The DW statistics for each estimated equation are satisfactory, compared with the existing literature (Hall 1986). The models for the sectors and subsectors

Table 4 International evidence of the elasticities of interfuel substitution (σ_{ij}^{m}): national

	Serletis *et al*. (2011) United States (1980–2006)	This study Australia (1990–2008)
Morishima elasticities of substitution		
σ_{ge}^{m}	−0.003	0.022
σ_{eg}^{m}	0.029[a]	0.011
σ_{go}^{m}	0.042[a]	0.058[b]
σ_{og}^{m}	0.044[a]	0.017
σ_{gc}^{m}	0.366[a]	0.092[a]
σ_{cg}^{m}	0.175	0.049
σ_{eo}^{m}	0.016[a]	0.085[a]
σ_{oe}^{m}	0.001	0.062[c]
σ_{ec}^{m}	0.362[a]	0.076[a]
σ_{ce}^{m}	0.128	−0.493[a]
σ_{oc}^{m}	0.361[a]	0.093[a]
σ_{co}^{m}	0.087	0.616[a]

Notes: The superscripts a and b denote significance levels at 1% and 5%, respectively.

Table 5 Estimates of parameters: 'Manufacturing' sector and selected subsectors

Parameter	MFC	FB&T	MTL	P&C	NMM
β_g	0.143[a] (0.001)	0.20[a] (0.001)	0.132[a] (0.001)	0.108[a] (0.003)	0.363[a] (0.002)
β_e	0.391[a] (0.003)	0.571[a] (0.005)	0.54[a] (0.002)	0.101[a] (0.001)	0.357[a] (0.002)
β_o	0.414[a] (0.004)	0.185[a] (0.005)	0.237[a] (0.002)	0.783[a] (0.004)	0.196[a] (0.003)
γ_{gg}	0.103[a] (0.009)	0.147[a] (0.01)	0.074[a] (0.021)	0.102[a] (0.017)	0.207[a] (0.03)
γ_{ge}	−0.027[b] (0.013)	−0.117[a] (0.01)	−0.008 (0.024)	−0.012 (0.023)	−0.10[a] (0.034)
γ_{go}	−0.066[a] (0.008)	−0.026[a] (0.005)	−0.054[a] (0.009)	−0.09[a] (0.014)	−0.089[a] (0.015)
γ_{ee}	0.248[a] (0.018)	0.157[a] (0.026)	0.212[a] (0.029)	0.125[a] (0.030)	0.288[a] (0.038)
γ_{eo}	−0.204[a] (0.016)	−0.018 (0.024)	−0.157[a] (0.009)	−0.109[a] (0.013)	−0.125[a] (0.012)
γ_{oo}	0.286[a] (0.026)	0.052[b] (0.027)	0.227[a] (0.012)	0.202[a] (0.023)	0.209[a] (0.023)
$\gamma_{g\tau}$	0.001[a] (0.000)	0.001 (0.000)	0.001[b] (0.000)	0.003[a] (0.000)	−0.004[a] (0.001)
$\gamma_{e\tau}$	0.006[a] (0.001)	0.007[a] (0.001)	0.007[a] (0.000)	0.002[a] (0.001)	0.005[a] (0.000)
$\gamma_{o\tau}$	−0.006[a] (0.000)	−0.007[a] (0.001)	−0.005[a] (0.000)	−0.005[a] (0.001)	0.001 (0.000)
Log L	268.118	249.94	250.171	269.035	226.573
R^2 [DW]					
g equation	0.85 [1.65]	0.92 [2.29]	0.78 [0.86]	0.61 [1.38]	0.95 [1.26]
e equation	0.89 [1.93]	0.65 [1.19]	0.95 [1.15]	0.84 [1.32]	0.93 [1.36]
o equation	0.85 [2.02]	0.69 [1.37]	0.91 [1.34]	0.71 [1.60]	0.94 [1.73]
Asymmetry	5.253	6.020	10.129	8.22	11.971
(*significance*)	(0.*154*)	(0.*111*)	(0.*018*)	(0.*042*)	(0.*007*)

Notes: Refer to Table 2. In addition, MFC stands for the 'Manufacturing' sector, FB & T stands for the 'Food, beverage and tobacco' subsector, MTL stands for the 'Metal' subsector, P&C stands for the 'Petroleum and coal' subsector, and NMM stands for the 'Non-metallic mineral' subsector.

satisfy the monotonicity regularity at the local level. Only the 'food, beverage and tobacco' subsector satisfies the concavity regularity condition, checked at the mean.

Table 6 shows the estimated elasticities of substitution corresponding to the estimated parameters shown in Table 5. The asymmetrical MES values are all positive in the 'food, beverage and tobacco' subsector, indicating some weak substitutability between all of the energy types. Similar to the results for the aggregate economy, oil and coal are found to be Morishima substitutes, irrespective of changes in the price of coal or oil in the 'food, beverage and tobacco' and 'petroleum and coal' subsectors. The MES values between coal and gas are all positive – although smaller – in the 'manufacturing' sector and all the subsectors, suggesting substitutability between them. Furthermore, significant substitution possibilities exist between gas and electricity in the 'metal' subsector, which is presently responsible for approximately 74 per cent of the total coal consumption by the 'manufacturing' sector. We found consistently negative coefficients for the own-price elasticities for all energy types in the 'food, beverage and tobacco' subsector (Table 7). Positive own-price elasticities are found in some instances, but the estimated coefficients are typically not significant; they are found to be marginally significant in only a few cases. Overall, the demand for fuels is found to be price inelastic. The inelastic demand for electricity and oil is often observed in the empirical literature due to their uniqueness in terms of doing useful economic work as compared to other energy categories (Jones 1995). Previous studies that found positive own-price elasticities using the translog model include that of Vlachou and Samouilidis (1986) for intermediaries and the 'transport' sector in Greece, that of Hall (1986) for the industrial sector in the United States, Italy and Canada, that of Harvey and Marshall (1991) for several sectors of the UK economy and that of Ma *et al.* (2009) for Region 6 in China. This problem could be avoided by imposing concavity conditions at the outset (Ryan and Wales 2000). However, as discussed by Ogawa (2008, p. 557), 'If some of the firms are incapable of minimising production costs due to extraneous circumstances, then imposing concavity conditions on the cost function misspecifies the model and therefore yields inconsistent estimates of the cost function parameters'. There could be an array of other factors – including the high level of aggregation of the quantity and price data (Considine 1989b; Serletis *et al.* 2010) and/or difficulties in finding alternative energy sources in a limited sample period (Vlachou and Samouilidis 1986) – that could explain the positive own-price elasticities.

It would be instructive to compare the elasticity estimates determined here for the 'manufacturing' sector and some of its subsectors with the results from existing studies performed in Australia and elsewhere. Since none of the comparable studies for Australia use recent data, we refer to two earlier studies, one on the aggregate 'manufacturing' sector by Turnovsky *et al.* (1982) and another on the NSW 'manufacturing' by Truong (1985). The studies are based on the AES and/or the own- and cross-price elasticities. As

Table 6 Estimated elasticities of substitution: 'Manufacturing' sector and selected subsectors

Elasticities	MNF	FB&T	MTL	P&C	NMM
Allen elasticities of substitution					
σ_{gg}	−0.941^{b} (0.470)	−0.312 (0.239)	−2.31^{b} (1.17)	0.466 (1.51)	−0.185 (0.226)
σ_{ee}	0.068 (0.114)	−0.271^{a} (0.083)	−0.126 (0.101)	3.36 (2.94)	0.460 (0.294)
σ_{oo}	0.255^{c} (0.154)	−2.91^{a} (0.769)	0.812^{a} (0.210)	0.053 (0.037)	1.31^{b} (0.584)
σ_{cc}	−1.96^{a} (0.598)	−4.31 (0.554)	−1.05^{a} (0.004)	−21.7^{a} (9.17)	−0.30 (0.511)
σ_{ge}	0.508^{b} (0.235)	−0.027 (0.107)	0.891^{a} (0.341)	−0.072 (2.13)	0.228 (0.265)
σ_{go}	−0.115 (0.124)	0.304^{b} (0.139)	−0.73^{a} (0.279)	−0.064 (0.169)	−0.253 (0.204)
σ_{gc}	−0.315 (0.293)	0.479^{a} (0.185)	−0.019 (0.340)	0.795 (3.51)	0.426^{a} (0.165)
σ_{eo}	0.258^{b} (0.101)	0.828^{a} (0.225)	−0.229^{a} (0.068)	−0.387^{b} (0.164)	−0.786^{a} (0.17)
σ_{ec}	0.145 (0.169)	0.153 (0.163)	0.048 (0.070)	−3.40 (3.63)	−1.12^{a} (0.223)
σ_{oc}	0.221 (0.214)	0.058 (0.555)	0.307 (0.230)	0.558^{b} (0.263)	1.38^{a} (0.432)
Morishima elasticities of substitution					
σ^{m}_{ge}	0.172 (0.123)	0.139^{c} (0.084)	0.549^{b} (0.236)	−0.346 (0.501)	−0.082 (0.198)
σ^{m}_{eg}	0.207^{b} (0.098)	0.057 (0.068)	0.424^{b} (0.199)	−0.058 (0.374)	0.150 (0.174)
σ^{m}_{go}	−0.153 (0.011)	0.592^{a} (0.168)	−0.366^{a} (0.109)	−0.091 (0.157)	−0.308^{b} (0.146)
σ^{m}_{og}	0.118^{c} (0.067)	0.123^{b} (0.054)	0.210 (0.160)	−0.057 (0.165)	−0.025 (0.117)
σ^{m}_{gc}	0.086^{b} (0.037)	0.215^{a} (0.021)	0.094^{b} (0.041)	0.190^{a} (0.067)	0.060 (0.039)
σ^{m}_{cg}	0.089 (0.061)	0.158^{a} (0.03)	0.304^{b} (0.132)	0.036 (0.299)	0.222^{a} (0.060)
σ^{m}_{eo}	−0.213^{b} (0.105)	0.689^{a} (0.187)	−0.247^{a} (0.058)	−0.344^{b} (0.153)	−0.412^{a} (0.137)
σ^{m}_{oe}	−0.127^{c} (0.075)	0.627^{a} (0.168)	−0.056 (0.078)	−0.378 (0.307)	−0.445^{a} (0.121)
σ^{m}_{ec}	0.110^{a} (0.033)	0.20^{a} (0.026)	0.100^{a} (0.036)	0.155 (0.099)	−0.068 (0.048)
σ^{m}_{ce}	0.030 (0.078)	0.242^{c} (0.129)	0.094 (0.085)	−0.678 (0.571)	−0.567^{a} (0.169)
σ^{m}_{oc}	0.114^{a} (0.037)	0.196^{a} (0.043)	0.124^{a} (0.048)	0.188^{a} (0.078)	0.139^{b} (0.072)
σ^{m}_{co}	−0.014 (0.149)	0.547^{a} (0.172)	−0.120 (0.083)	0.396^{c} (0.230)	0.013 (0.185)

Notes: Refer to Tables 2 and 5.

Table 7 Estimated own-price and cross-price elasticities: 'Manufacturing' sector and selected subsectors

Elasticities	MNF	FB&T	MTL	P&C	NMM
η_{gg}	−0.134[b] (0.067)	−0.062 (0.048)	−0.306[b] (0.155)	0.05 (0.163)	−0.067 (0.082)
η_{ee}	0.027 (0.045)	−0.154[a] (0.046)	−0.068 (0.054)	0.339 (0.297)	0.164 (0.105)
η_{oo}	0.106[c] (0.064)	−0.536[a] (0.145)	0.192[a] (0.049)	0.041 (0.029)	0.258[b] (0.114)
η_{cc}	−0.103[a] (0.031)	−0.194[a] (0.025)	−0.096[a] (0.034)	−0.183[b] (0.077)	−0.025 (0.045)
η_{ge}	0.199[b] (0.091)	−0.015 (0.061)	0.481[a] (0.184)	−0.007 (0.214)	0.082 (0.095)
η_{eg}	0.073[b] (0.034)	−0.005 (0.021)	0.118[a] (0.045)	−0.008 (0.230)	0.983 (0.096)
η_{go}	−0.048 (0.052)	0.056[b] (0.026)	−0.173[a] (0.066)	−0.050 (0.132)	−0.05 (0.04)
η_{og}	−0.016 (0.018)	0.061[b] (0.028)	−0.097[a] (0.037)	−0.007 (0.018)	−0.092 (0.074)
η_{gc}	−0.017 (0.015)	0.021[a] (0.008)	−0.002 (0.031)	0.007 (0.03)	0.035[a] (0.014)
η_{cg}	−0.045 (0.042)	0.096[a] (0.037)	−0.003 (0.045)	0.086 (0.381)	0.155[b] (0.060)
η_{eo}	0.053[b] (0.025)	0.153[a] (0.044)	−0.054[a] (0.016)	0.042 (0.023)	−0.154[a] (0.033)
η_{oe}	−0.101[b] (0.039)	0.473[a] (0.126)	−0.124[a] (0.037)	−0.303[b] (0.128)	−0.281[a] (0.062)
η_{ec}	0.008 (0.009)	0.007 (0.007)	0.004 (0.006)	−0.028 (0.031)	−0.093[a] (0.018)
η_{ce}	0.056 (0.066)	0.087 (0.093)	0.026 (0.038)	−0.34 (0.366)	−0.402[a] (0.079)
η_{oc}	0.012 (0.011)	0.003 (0.025)	0.028 (0.021)	0.005[b] (0.002)	0.114[a] (0.036)
η_{co}	0.091 (0.089)	0.011 (0.102)	0.073 (0.055)	0.467[b] (0.206)	0.272[a] (0.086)

Notes: Refer to Tables 2 and 5.

mentioned in Section 2, Turnovsky *et al.* (1982) analysed Australian time-series data from 1946–1947 to 1974–1975. The study found a very high own-price elasticity for gas (−1.47). Truong (1985) found an own-price elasticity for gas that was slightly lower than unity (−0.917) for data covering the period 1968–1969 to 1980–1981 for Australia. While the significance levels for the interfuel elasticities were not reported, the study found that solid fuels and gas were complementary, as were oil and electricity. The fuels were found to be substitutes for all other cases in the four fuels (solid fuel, oil, electricity and gas) model, and very high substitution elasticities were found (e.g. $\sigma_{og} = 4.50$, $\sigma_{eg} = 3.18$). In contrast, we found that the own-price elasticity for gas is considerably lower than unity (i.e. inelastic demand) and varies across sectors. The elasticity coefficient for gas is found to be higher in the 'metal' subsector than in the aggregate 'manufacturing' sector. In the recent study by Serletis *et al.* (2010), the own- and cross-price elasticities were found to be considerably lower than unity for the economic sectors in the United States. We found little evidence of the complementarity between gas and coal evidenced in the studies on Australia; instead, these two fuel types appeared to be weakly substitutable with each other in some subsectors. With coal being the inferior fuel, it is reasonable that a higher price for coal would propel demand for gas or other alternative fuels. The low energy demand elasticity values reflect short-term phenomena and may be a reflection of the underlying assumption of the translog cost model, which holds the total energy usage constant. The elasticities shown here can therefore be interpreted as conditional elasticities.

Having considered the results for the 'manufacturing' sector, we now analyse the substitution possibilities in the 'electricity generation' subsector (subsector 361) in Australia. Approximately 89 per cent of the total domestic primary coal consumption in Australia can be attributed to this subsector, placing it at the centre of emissions reduction debate (ABARES 2009). Table 8 presents the estimates for the parameters of the system-of-cost-share equations, which consider three fuels; coal, gas and petrol. The petrol equation is estimated from the homogeneity restriction. Electricity is excluded because this is an output of the sector, not an input. The cross-equation asymmetry is not rejected for the sample 1986–2009 (Panel G). The model satisfies the concavity condition evaluated at the mean. The estimated cost share equations are all found to be positive at each point (results not shown here). The cross-equation symmetry, however, is accepted for the sample 1988–1909 (Panel H). It can be observed from the estimation results that all the coefficients are highly significant, except for the trend in the coal equation.

Table 9 reports the estimated elasticities corresponding to Table 8. The own-price elasticities have the expected negative signs. The MES values indicate significant but weak substitution possibilities among the different energy types. Gas and coal are found to be Morishima substitutes (weak) only when the price of coal changes. A higher substitution coefficient is found between coal and oil, irrespective of changes in the price of coal or

Table 8 Estimates of parameters: 'electricity' subsector

Parameter	Coefficient Panel G: 1986–2009	Coefficient Panel H: 1988–2009
β_g	0.181[a] (0.004)	0.183[a] (0.000)
β_c	0.693[a] (0.004)	0.693[a] (0.004)
γ_{gg}	0.137[a] (0.014)	0.146[b] (0.028)
γ_{gc}	−0.105[a] (0.011)	−0.107[a] (0.011)
γ_{cc}	0.148[a] (0.01)	0.146[a] (0.009)
$\gamma_{g\tau}$	0.003[a] (0.001)	0.004[a] (0.002)
$\gamma_{c\tau}$	0.0003 (0.001)	−0.001 (0.001)
Log likelihood	144.487	112.936
R^2 [Durbin–Watson]		
g equation	0.88 [0.59]	0.88 [0.70]
c equation	0.90 [1.03]	0.92 [1.39]
Asymmetry	10.84	2.39
(significance)	(*0.001*)	(*0.122*)

Notes: Refer to Table 1. In addition, superscript b denotes significance levels at 5% level.

Table 9 Estimated elasticities: 'electricity' subsector

Elasticities	Panel I: 1986–2009	Panel J: 1988–2009
Allen elasticities of substitution		
σ_{cc}	−0.134[a] (0.023)	−0.139[a] (0.022)
σ_{gg}	−0.344 (0.414)	−0.101 (0.846)
σ_{oo}	−2.26[c] (1.39)	−1.95 (2.416)
σ_{gc}	0.158[c] (0.086)	0.16[c] (0.084)
σ_{go}	−0.373 (0.675)	−0.747 (1.413)
σ_{co}	0.509[a] (0.132)	0.545[a] (0.112)
Morishima elasticities of substitution		
σ^m_{oc}	0.446[a] (0.099)	0.475[a] (0.083)
σ^m_{co}	0.35[c] (0.189)	0.308 (0.304)
σ^m_{go}	0.239 (0.254)	0.149 (0.469)
σ^m_{og}	−0.005 (0.184)	−0.119 (0.407)
σ^m_{gc}	0.202[a] (0.066)	0.208[a] (0.067)
σ^m_{cg}	0.091 (0.079)	0.048 (0.153)
Own- and cross-price elasticities		
η_{cc}	−0.093[a] (0.031)	−0.097[a] (0.015)
η_{gg}	−0.062[b] (0.075)	−0.018 (0.155)
η_{oo}	−0.286[c] (0.176)	−0.241 (0.296)
η_{gc}	0.109[c] (0.059)	0.111[b] (0.058)
η_{cg}	0.028[c] (0.015)	0.029[b] (0.015)
η_{go}	−0.047 (0.086)	−0.092 (0.176)
η_{og}	−0.067 (0.122)	−0.137 (0.595)
η_{co}	0.064[a] (0.018)	0.067[a] (0.015)
η_{oc}	0.353[a] (0.091)	0.378[a] (0.076)

Notes: Refer to Table 2.

oil. The substitution possibilities are therefore higher between oil and coal (σ^m_{oc} = 0.48) than between gas and coal (σ^m_{gc} = 0.21), but they reflect weak substitutability overall. The substitution possibility can be further affirmed by observing the cross-price elasticities. Demand for all fuels is found to be inelastic, but the elasticity coefficient is relatively higher in the case of oil.

Most studies of interfuel substitution have focused on the possibility of substitution between oil and other fuels in the post-oil-crisis period, considering mainly the 'manufacturing' and other non-energy-producing sectors. Climate change policies to reduce GHGs, particularly CO_2, have received considerable attention since the early 1990s. Given the severity of the CO_2 problem in the 'electricity generation' sector, which relies particularly heavily on coal, elasticity estimates for the aggregate economy and the non-energy-producing sectors cannot be readily applied to the energy-producing sectors. In any case, there are few elasticity estimates for the substitution possibilities among different fuels in the empirical literature in recent years for the 'electricity generation' sector. The only recent study is that of Serletis *et al.* (2010); they consider the case for the 'electricity generation' sector, along with some other sectors and the aggregate economy for the United States. The MES results determined in this study for the 'electricity generation' sector are consistent with Serletis *et al.* (2010), but the substitution coefficients between coal and gas, and coal and oil are lower in magnitude in the Australian case.

4.3. Fuel efficiency bias

The sign, significance and magnitude of the individual $\gamma_{i\tau}$ in each cost share equation in Equation (10) can provide some indication of the partial fuel efficiency (Hall 1986). A negative and significant value of $\gamma_{i\tau}$, that is, $\gamma_{i\tau} < 0$ reflects a fuel-saving bias. Similarly, if $\gamma_{i\tau} > 0$ and is significant, a fuel-using bias is reflected; $\gamma_{i\tau} = 0$ represents neutral fuel efficiency.

The estimates of $\gamma_{i\tau}$ are smaller in magnitude for each share equation for the aggregate economy (Table 1), the 'manufacturing' sector and its selected subsectors (Table 5) and the 'electricity generation' subsector (Table 8), but this is consistent with empirical evidence (Duncan and Binswanger 1976; Hall 1986). At the national level, a fuel-saving bias is observed for oil, and a fuel-using bias is observed for electricity. The results are similar at the sectoral and subsectoral levels in the 'manufacturing' industry. Given the higher prices of oil compared with other fuels, some efficiency gain in this fuel type could be expected. On the other hand, the electricity prices in Australia – while they remain well above the prices for coal and gas – are relatively low compared with most OECD and European countries (ABARES 2011b). Neutral fuel efficiency is observed for gas in the national data, since the estimated coefficient is not different from zero. A fuel-using bias is observed in the aggregate 'manufacturing' sector, and in most of the subsectors analysed here. The fuel efficiency results are consistent with those of Turnovsky *et al.* (1982) and Duncan and Binswanger (1976) for the Australian 'manufacturing' sector. For the 'electricity generation' subsector, a fuel-using bias and neutral fuel efficiency are observed for gas and coal, respectively, even though coal appears to become fuel-saving (but not significantly) during the period 1988–2009.

5. Conclusions and policy implications

The objective of this study was to investigate the interfuel substitution possibilities in Australia in the context of the country's recent move towards a cleaner energy future. For the first time in the literature, we estimated the translog cost function for the national economy and the electricity-producing subsector in Australia. In contrast with most previous studies of the Australian case, we calculated the MES, as well as the Allen elasticities of substitution and the own- and cross-price elasticities, providing a more comprehensive picture of the elasticity of substitution among different energy vectors. The data analysed here cover the period from the mid-1980s to 2008 for the aggregate analysis and from the mid-1980s to 2009 for the sectoral and subsectoral analysis. Previous empirical evidence of this kind in Australia is mostly based on samples from the 1970s to 1980s. The use of relatively recent data and the focus on CO_2-intensive subsectors allowed us to provide valuable guidance for the move towards a cleaner mix of fuels and technologies in Australia envisaged by the most recent policies for the achievement of environmental sustainability.

The cost functions estimated herein for the aggregate economy and the 'electricity generation' subsector satisfied the cross-equation symmetry for a well-behaved cost function. For the 'manufacturing' sector and some of the selected subsectors, the performance of the translog cost function varied in terms of the degree to which it satisfied the concavity condition. The standard errors (robust) of the regressions were found to be fairly small for all of the estimations.

The empirical evidence presented herein indicates complementarity between coal and electricity, and this complementarity has increased since the 1990s. In line with the results for the aggregate economy, oil and coal were found to be Morishima substitutes, but weak in magnitude, irrespective of price changes for coal or oil in the 'food, beverage and tobacco' and 'petroleum and coal' subsectors. The Morishima elasticities between coal and gas were all positive and smaller than one in the 'manufacturing' sector and its subsectors, suggesting weak substitutability between these energy sources. Furthermore, significant but weak substitution possibilities were found between gas and electricity in the 'metal' subsector, which is presently responsible for approximately 74 per cent of the total coal consumption by the 'manufacturing' sector. For the 'electricity generation' subsector, gas and coal were found to be Morishima substitutes (weak form) only when the price of coal changes. A relatively higher but weak substitution possibility was found between coal and oil, irrespective of changes in the price of coal or oil. Overall, we found that the substitution coefficients were higher between oil and coal than between gas and coal. This could indicate that production technologies exist in an environment similar to that in the post-oil-crisis period, when policies were more concerned with accommodating the higher costs of petroleum than with low-cost fuels such as coal.

In view of current climate change policies, a significant technological breakthrough towards cleaner fuels is clearly essential in the Australian context. The results from this study indicate that the relative price hypothesis has been instrumental in Australia, given that oil is found to demonstrate a fuel-saving bias throughout the estimations. For all other energy types, notably coal, a fuel-using bias is observed. The small coefficients for the own-price elasticities of coal indicate that a large increase in relative prices is required to stimulate the market to adopt low-emission technologies.

Overall, this study provides some guidance regarding the price elasticities and substitution possibilities in Australia, at both the aggregated and disaggregated levels. We find considerable variations in the results from the aggregate economy to the 'electricity generation' and industrial sectors of the economy. In line with Stern (2012), this study finds that the substitution possibilities are higher at the lower levels of aggregation, compared with the national level, but the results from the sectoral/subsectoral levels are not encouraging in the context of the switch to low-emission fuels. While electricity generation in Australia produces the majority of CO_2 emissions, the possibility of switching fuels is likely to be constrained by the high costs and long lifetimes of the machinery concerned (Creedy and Martin 2000). The relevance of the results is critical for emission reduction policies. This confirms that a high carbon price is essential for encouraging abatement measures. The elasticity estimates in this paper should, however, be considered as short-term elasticities.

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