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Unifying partial and general equilibrium modelling for applied policy analysis

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Contents

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Abstract

A number of modelling frameworks have been used historically to address different policy questions. Partial equilibrium (PE) models have typically been used where engineering or industry-specific details are of particular importance. Computable General Equilibrium (CGE) models have been used where economy-wide implications and inter-industry linkages are important. However, the two frameworks have a common mathematical and conceptual origin. Recent developments in Mixed Complementary Problems (MCPs) presents an opportunity to incorporate desirable PE characteristics (engineering and policy constraints) into CGE models. This paper presents a demonstration model of an integrated MCP PE-CGE model, combining an electricity model (which includes physical laws and economic principles unique to electricity generation and transmission) with a CGE model (which includes typical CGE characteristics such as a number of industries, primary factors, taxes, inter-industry linkages and trade). The benefit of this approach is that richer insights can be gained about policy issues where the impacts depend on both the characteristics of the industry and economy-wide interactions.

1. Introduction

Economic models provide useful insights into economic policy issues. Although models are simple representations of the real world, they provide the policy analyst with a laboratory for testing ideas and policy proposals (Hazell and Norton 1986). There are many forms of economic models with strengths and weaknesses in terms of their usefulness in informing judgements about specific policy issues.

The choice of modelling framework depends on the policy questions under consideration. In selecting the modelling tool to provide the best insights into those questions, it is ideal to keep the approach as simple as possible, focussing detail on the matters that are important and relevant to the policy issues at hand. Nevertheless, complexity can be unavoidable as economic interactions are often intertwined in ways that affect outcomes. For example, policy developments in an industry that change prices for consumers, or that changes the demand for labour, can have economy-wide effects by shifting consumption patterns, or changing wages for some types of workers. The development of the MCP framework offers a way to capture some of this complexity. Specifically, the MCP modelling framework opens up greater opportunities to combine CGE frameworks and PE frameworks into single unified models.

This paper explains how we embedded a PE model of the electricity generation and transmission sector within a simplified CGE model to create a single model that is able to provide the types of insights typically only available from each model individually. This approach has the potential to make CGE models more useful for analysis of policy where both the sectoral and economy-wide details are important and there are strong economic interdependencies between the two.

The model is used to illustrate the economic principles underlying the Australian National Electricity Market (NEM) and the Renewable Energy Market by including Australia's Renewable Energy Target (RET) framework explicitly. This is a fruitful area of exploration relevant to policy makers in Australia, where recent events in the electricity market have renewed discussions about the interaction between renewable policy and electricity market design.[1]

For modelling approaches to be able to explore these policy issues, the models used for the analysis should include appropriate technology and economic principles. The model created in this paper is used to illustrate the economic principles at play at the industry level through the operation of the NEM and RET, as well as the key interactions and linkages with the rest of the economy. The PE components reflect the operation of the NEM and RET, while the CGE components feed these impacts through the rest of the economy and also provides feedback from the rest of the economy to the electricity sector.

The new model integrates the PE electricity industry model developed by Salerian, Gregan and Stevens (2000) into a CGE model (Gilbert and Tower 2013). However, the authors wish to stress that the hypothetical model presented here is to demonstrate proof of concept and it is not 'application ready' for policy analysis. The results presented in this paper are intended to illustrate the potential to apply the MCP technique to create PE CGE models for policy analysis. As such, the results should not be used to draw conclusions about the RET policy. For this reason the data used to calibrate the CGE components of the model (see section 3 below), while initially based on Australia, have been rescaled to represent a hypothetical electricity sector and an economy about the size of one of Australia's larger states. Further, the energy components of the model have realistic prices and characteristics, but the mix of technologies does not represent the generation sector of Australia or any of its states specifically.

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[1] In September 2016, extreme weather events damaged key components of South Australia's energy supply infrastructure, causing large-scale blackouts. In particular, damage to the interconnector to Victoria (an adjacent state that is able to supply large volumes of brown-coal-generated electricity to South Australia) limited South Australia's ability to import electricity. South Australia's primary means of local generation are wind, solar and gas, having shut down coal in May 2016. In particular, wind generation had to be shut down due to the high intensity winds. In the wake of the event, there were a number of discussions around the reliability of wind supply, the role of non-renewable generators in baseload, interstate trade in power, and insuring against future risks (ABC 2016).

The remainder of this paper is organised as follows. Section 2 describes MCP and the way it opens doors for integrated model development. Section 3 describes the data, PE and CGE models used for this illustration, as well as the steps that need to be taken to integrate the PE model within the CGE model using MCP. Section 4 details the way the NEM and RET operate in Australia, and how these features are incorporated into the integrated MCP model (which contains the theory from both the PE electricity and CGE economy-wide models). Section 5 presents illustrative policy results, demonstrating the economic insights that are obtained from the MCP model — insights which could not be obtained by either the original PE or CGE in isolation without reliance on more extensive subjective judgements by the analyst. Key insights and scope for research are included in Section 6.

2. MCP presents opportunities for linking PE and CGE models

PE models[2] have been used where industry-specific or technological details are fundamental to the analysis of policy issues. Well-designed PE models can incorporate a range of detailed economic, institutional and technological characteristics that provide important insights for policy analysis by creating a link between theory and empirics (Hazell and Norton 1986). Reflecting this, PE models have been applied to analyse a number of policy and resource allocation fields including electricity, natural gas, trade and urban water. Examples include Takayama and Judge (1971); Heady and Srivastava (1975); Meister, Chen and Heady (1978); Norton and Solis (1983); Hazell and Norton (1986); Labys, Takayama and Uri (1989); Heady and Vocke (1992); and Barker, Murray and Salerian (2010). However, the acknowledged limitation of PE analysis is the inability to incorporate shifts driven by simultaneous (endogenous) income changes, which are an economy-wide consequence of policies under investigation (McCarl and Spreen 1980; Hertel 1990).

CGE models have been used where inter-industry, inter-regional or economy-wide impacts of policy are important. While CGE models used for policy analysis today come in a variety of scales, some have evolved over time to become large-scale, recursive comparative static (dynamic) models. These are often defined as linear square systems of equations (by expressing them in percentage change form), such as the Victoria University Regional Model (VURM, Adams 2015), the United States of America General Equilibrium Model (USAGE, Dixon and Rimmer 2002), and the Global Trade Analysis Project (GTAP Hertel 1997) model. Models formulated in levels (defined as nonlinear square systems of equations) have also been used, as advances in solving nonlinear systems of equations have developed (such as those used by Rutherford 2008; Devarajan, Lewis and Robinson 1990). Although CGE models are particularly strong at highlighting linkages and economy-wide interdependencies, their stylised industry representation can be a limitation in that they do

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[2] PE models are taken to be spatial and temporal price and allocation models pioneered by Takayama and Judge, and Plesner and Heady, and which have been adapted and widely applied to study policy issues relating to trade, environment, natural resources, energy and agriculture.

not capture the economic and technological fundamentals underpinning the behaviour of agents in a specific sector.

Combining the strengths of each approach into a unified modelling framework has proved challenging. In the past, combined approaches have largely taken one of three forms. First, iterating between two pre-existing (but distinct) models (see for example Garnaut 2008). Second, integrating small bottom-up energy models with top-down macroeconomic models as a proof-of-concept (see for example Bohringer and Rutherford 2008 who combined a stylised bottom-up energy model with a small top down macroeconomic CGE model). Third, representing various elements of the energy sector (for example, load blocks) as separate commodities within the stylised structure of a CGE model (see for example Wiskich 2014).

In some areas (typically in analysing trade), a nested approach has also been adopted, where a PE model is nested within a CGE model and the PE supplements the broader CGE results (see for example, Narayan, Hertel and Horridge 2010) such that the PE components can be aggregated to form a sub-component of the CGE model, and are a refinement on the CGE approach. Grant, Hertel and Rutherford (2009) combined a detailed PE model of dairy trade (detailed in terms of the number of different products traded) with a detailed global trade model (GTAPinGAMS). However, although the PE model contains a large amount of dairy commodity detail (and the combined model they create uses inequalities), it does not include industry-specific technologies. Many of the above approaches continue to use stylised constant elasticity of transformation/constant elasticity of substitution relationships (borrowed from the CGE framework) to represent industries within the PE model without taking the next step of including a PE model with its own detailed and unique theory which sets it apart from the stylised CGE behaviour of agents in the economy.

Mostly, analysts have applied both the PE and CGE approaches separately, without completely integrating the two to solve for a consistent equilibrium. However, the evolution of MCP frameworks and algorithms have opened new possibilities in integrated economic model development.

An MCP is described in Ferris (2000):

The complementarity problem adds a combinatorial twist to the classic square system of nonlinear equations, thus enabling a broader range of situations to be modelled. In its simplest form, the combinatorial problem is to choose from 2n inequalities a subset of n that will be satisfied as equations. These problems arise in a variety of disciplines including engineering and economics where we might want to compute a Wardropian and Walrasian equilibria, and optimisation where we can model the first order optimality conditions for nonlinear programs. Other examples, such as bimatrix games and options pricing, abound.

MCPs encompass a number a special cases, including typical formulations of economic problems, as listed in table 1 (summarised from Rutherford 1995), and can include both equalities and inequalities in the system of relationships. In table 1 examples are provided of the types of CGE or PE model that would be typical of each special case. As all of the frameworks outlined in the table can be thought of as special cases of MCPs, the MCP framework provides an avenue for combining these models into a single model, provided that the MCP solver is sufficiently reliable and powerful to solve the joint model under consideration. Looking at table 1, a typical CGE model can be specified as either special cases (1) or (2), and a PE model as special cases (3) or (4), and thus MCP (general case (5)) provides an avenue for combining CGE and PE models.

Table 1 **Special cases of Mixed Complementarity Problem**

Special case	*Type of PE or CGE model*	*Examples*
(1) Linear System of Equations	Linear percentage change CGE models, system of equalities	USAGE, Dixon and Rimmer (2002); GTAP, Hertel (1997); VURM, Adams, (2015); TERM, Horridge, Madden and Wittwer (2005).
(2) Nonlinear System of Equations	Levels CGE model, system of equalities	Robinson (2005), Ballard, Shoven and Whalley (1985), Gilbert and Tower (2013).
(3) Linear programming problems	Spatial and temporal price allocation PE models in the linear form (objective function and constraints), inequality constraints	Barker, Salerian and Murray (2010), Takayama and Judge (1972).
(4) Nonlinear programming problems	Generalised spatial and temporal price allocation PE models in the nonlinear form, inequality constraints	Labys, Takayama and Uri (1989), Takayama and MacAulay (1992), Salerian, Gregan and Stevens (2000).
(5) Nonlinear system of equalities and inequalities solved as an MCP (General case).		

Throughout the 1990s and early 2000s, MCP solvers have developed to the stage of being useful for large-scale applied models (Dirkse and Ferris 1995; Billups, Dirkse and Ferris 1997; Dirkse and Ferris 1997; Ferris, Kanzow and Munson 1999; Ferris and Sinapiromsaran 2000).

The theoretical structures underlying CGE models are typically derived using classical programming sub-models regarding the behaviour of the various agents represented in the CGE model. Constraints are equations, and the theory of the Lagrangean is used to derive the first order equations for a unique solution (squared system of equality constraints). By contrast, the economic theory underlying PE models is derived using Karush–Kuhn–Tucker conditions because of inequalities associated with non-negativity and inequality constraints (Intrilligator 1971). MCP enables us to include both types of first order conditions (equalities and inequalities) in a single equilibrium model.

By deriving the first order conditions of a model where behavioural functions have desirable properties (twice differentiable and convex) the structure of the resulting MCP formulation is clear: application of the Karush–Kuhn–Tucker conditions to derive the first order conditions for a solution naturally leads to a squared system of inequality constraints and paired variables, together with associated complementary slackness conditions.

The MCP framework is already being examined as a solution tool for PE and CGE models. Robinson has documented CGE models formulated as an MCP (see for example Hans and Robinson 1997). This paper takes one step further by combining two pre-existing models (an electricity model with technological and policy-specific relationships outlined below and a CGE model with industry, trade and macroeconomic relationships) of sufficient detail for applied policy analysis. The use of inequality constraints and complementary conditions are particularly useful for modelling real-world technological and policy details. For example, policies that can be binding or non-binding, technologies which can be on or off, and the introduction of new technologies not initially in use but induced by policies.

3. Model description

The two pre-existing models are an energy sector PE model including the economics of generation, and engineering detail for transmission (Salerian, Gregan and Stevens 2000), and a national, comparative static CGE model defined in levels (Gilbert and Tower 2013).

3.1 PE Model

The starting point for developing the integrated MCP model is a PE economic engineering mathematical programming model that captures the underlying economic theory, technology and engineering underpinning the long run equilibrium in an electricity market, such as the model described in Salerian, Gregan and Stevens (2000) (SGS-PE). The model describes an interconnected electricity generation, transmission and demand system across a number of nodes to simulate a long run market equilibrium by maximising net social welfare (in a quantity, primal formulation). Each generation plant is located at a specific node. The model includes the capital cost of building the plant, maintaining the plant, and a marginal cost of electrical generation by power stations. For electricity to be delivered to final users at the demand node, it is transmitted through the electricity transmission network. Power losses across transmission lines are governed by physical laws (Kirchhoff's law, using power flow constraints outlined in Chao and Peck 1996), which reflect the distance of transmission, phase angles of power transmitted within the network, as well as the electrical engineering parameters of the lines.

A load duration curve, used to summarise the demand across the year within the static model — is constructed by ordering all the hourly loads at a node over the course of a year (Turvey and Anderson 1977). This curve is then approximated using load blocks (for the process of this calculation, see Salerian, Gregan and Stevens 2000). Generation and transmission capacity must be constructed, and all include capacity constraints (in the case of generators, maximum output per plant reflecting plant availability and installed capacity, and in the case of transmission lines the maximum amount of power that can be transmitted). The model incorporates nodal pricing (the way prices at nodal points within a transmission network vary over time) associated with time-of-use, in which marginal transmission losses play a key role. These features of the model provide insights into the economic principles underlying the electricity system and policies that impact the generation and transmission sectors. For example, issues such the interaction of policy with merit order dispatch and the efficient procurement of supply sources can be illustrated.

The demonstration model used has been parameterised for three nodes (two generation nodes, and one demand node), five demand load blocks (with the first block being the peak high demand period, and the fifth block being the low demand off-peak period), five forms of generation (brown coal, black coal, gas combined cycle, gas open cycle and wind), and three fuel types (brown coal, black coal and natural gas). Each generation source also includes carbon emissions which can be calculated as an ex post calculation (in terms of tonnes of CO2 emitted per MWh generated), as well as marginal, operating and capital cost profiles. Optimal mix of installed capacity is based on the trade-off between fixed capital cost, variable operating cost and duration of plant operation — classical power system economics (Munasinghe 1990).

3.2 CGE Model

The CGE model used to construct the MCP model was taken from Gilbert and Tower (2013) (GT-CGE model). This comparative static, stylised, national (non-linear) CGE model defined in the levels form, contains a number of the useful features seen in typical small-open-economy CGE models used for applied policy analysis. It includes: constant elasticity relationships governing substitution between import- and domestically sourced goods and services (combined into a composite used as an intermediate input to production); primary factors (which are combined into a composite primary factor); fixed factors (land for agricultural, primary energy and mining resources; and an economy-wide labour endowment); intermediate inputs and the transformation of domestic products between domestic and export markets; market clearing conditions for all markets; zero pure economic profit conditions; downward sloping export demand functions; and horizontal import supply functions. The model also includes a number of macroeconomic identities that are used to define the macroeconomic closure, such as the balance of trade account, relationships for the share of capital owned by foreigners, government balances, and aggregate household disposable income.

Minor adaptations were made to marry the long-run equilibria described by the GT-CGE model and SGS-PE models. Specifically, an additional aggregate investment and savings relationship was added to the macro identities to produce a long-run steady-state level of new capital creation for all sectors (and not just the investment decisions coming from the sectors determined by the PE equations). This required setting domestic household savings to ensure that the foreign ownership share of capital is maintained constant. This ensures that the final equilibrium is a long run steady state with no implied changing foreign ownership in the final equilibrium result.

The model has been calibrated using a scaled Australian national IO table. It includes three primary factors (labour, land and capital), and nine industries/commodities (agriculture, mining, brown coal production, black coal production, gas production, manufactures, and services, as well as two margin services, electricity retail distribution and gas retail distribution), taxes on factor incomes, and four sources of final demands (households, investment, government and exports).

3.3 Joined through MCP

Both the SGS-PE and GT-CGE models are in a form amenable to an MCP formulation as they are initially documented. The Karush–Kuhn–Tucker first order conditions and their paired complementary variables (where each first order condition is paired with the variable used to find the derivative of the initial NLP problem) provide all that is necessary to formulate the SGS-PE model as a nonlinear mixed complementarity problem (a squared system of variables, equality and inequality constraints, Choi 2014). The GT-CGE model is already defined as a constrained nonlinear system (with pairings similarly determined by the theory associated with the Lagrangean first order conditions used to construct the CGE model). By combining paired inequalities and nonnegative variables, and equalities with variables free in sign, both sub models can be formulated and solved as a single MCP.

Completely linking the two models requires systematically replacing variables in both the SGS-PE and GT-CGE inequalities on a case by case basis. In particular, this requires replacing all the energy variables in the GT-CGE that are included in a typical CGE model with variables from the SGS-PE model: demand prices for fuel inputs (brown coal, black coal, natural gas); the supply price of electricity supplied to the demand node; the demands for inputs used in the creation of generation and transmission capital (labour and services); the demands for intermediate inputs used to generate power (fuels); and the demands for labour and manufactures used to maintain generator and transmission infrastructure (labour and manufactures). Similarly, changes need to be made to the SGS-PE components. The linear, downward sloping demand for energy needs to be replaced with the aggregated demand quantities by load block taken from the CGE model (demands from households, government and demand from other industries, each having their own load profile such that when aggregated, yield the system load duration curve). The exogenous operating costs of plant (fuel) need to be linked with the fuel supply taken from the GT-CGE. Parameters associated with the cost of building, maintaining and operating generation and transmission infrastructure have to be replaced with the supply prices taken from the GT-CGE (the price of labour, manufactures, services).

In CGE models, prices are relative to a numeraire and the choice of numeraire is arbitrary. For ease of exposition in our levels model, the nominal exchange rate is used as the numeraire.

3.4 Model data

The first step to integrating the models is creating consistent datasets so that the base case solution is in initial equilibrium for all theory and agents represented in the integrated MCP model.

The aggregated IO table is shown in table 2. This database represents a rebalanced version of an Australian national IO table calibrated to ensure all costs columns and sales rows relevant to the energy sector exactly fit the partial equilibrium energy data, which is shown in a more disaggregated form in table 3. As the power demand levels data were calibrated on the Australian state of Victoria, the national IO database has been scaled down for the purposes of the illustrative exercise in this paper, so that the relative sizes of the electricity sector and the economy as a whole are reasonable. It is worth noting that for the purposes of the illustrative exercise in this paper, wind does not appear in the initial IO table for the base case — it only becomes economically desirable when the RET policy is operational in the policy simulation.

The model has 668 constraints and variables with source code written in the General Algebraic Modelling System (GAMS), and is available from the Productivity Commission website ([to be inserted]). The model, being written via the combination of the optimality conditions for both the SGS-PE and GT-CGE models is fully self-documented in the GAMS code, describing all first order conditions and the economics of both component models, as well as the linking constraints.

Table 2 **Aggregated Input–Output table used for the CGE model ($ million, AUD)**

	Agriculture	*Mining*	*Manufacturing*	*ElecRet*	*GasRet*	*Serv*	*BrownCoalGen*	*BlackCoalGen*	*z GasCombCycGen*	*GasOpenCycGen*
Agriculture	1556.47	7.74	5175.36	0.00	0.00	779.40	0.00	0.00	0.00	0.00
Mining	0.51	1848.82	9742.32	0.00	0.00	192.55	0.00	0.00	0.00	0.00
Manufacture	1630.54	1465.68	21280.39	239.48	26.85	35042.18	28.00	1.97	2.31	0.58
ElecRetailDistn	35.91	188.11	1211.51	1035.15	2.75	2236.66	0.00	0.00	0.00	0.00
GasRetailDistn	2.12	2.29	375.60	0.00	0.06	128.46	0.00	0.00	0.00	0.00
Services	2070.56	3043.54	19711.15	570.84	291.33	126543.92	49.77	3.51	4.11	1.03
BrownCoalGen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BlackCoalGen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GasCombCycGen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GasOpenCycGen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WindGen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BulkElectSupplyB1	3.55	11.74	79.82	264.16	0.18	176.83	0.00	0.00	0.00	0.00
BulkElectSupplyB2	1.24	4.12	27.99	92.65	0.06	62.02	0.00	0.00	0.00	0.00
BulkElectSupplyB3	6.03	25.33	168.89	579.04	0.39	325.71	0.00	0.00	0.00	0.00
BulkElectSupplyB4	1.99	13.27	86.24	291.88	0.20	145.94	0.00	0.00	0.00	0.00
BulkElectSupplyB5	0.03	0.28	1.74	5.80	0.00	2.90	0.00	0.00	0.00	0.00
BrownCoalProd	0.00	0.00	0.00	0.00	0.00	0.00	200.38	0.00	0.00	0.00
BlackCoalProd	0.00	7.18	180.39	0.00	1.73	141.73	0.00	73.28	0.00	0.00
GasProd	5.07	16.94	909.10	0.00	0.39	347.61	0.00	0.00	314.72	33.98
Labour	3350.79	1950.12	15313.83	98.86	24.30	110842.58	233.30	16.45	19.28	4.81
Capital	3276.49	6000.06	9855.93	3418.22	340.39	72244.45	1630.49	99.39	147.73	76.19
Land	1728.24	2426.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(continued next page)

Table 2 (continued)

	WindGen	*ElecTrans*	*BrownCoalProd*	*BlackCoalProd*	*GasProd*	*Households*	*Government*	*Investment*	*Imports*	*Exports*
Agriculture	0.00	0.00	0.00	0.00	0.00	2423.86	82.14	0.00	-295.03	3939.61
Mining	0.00	0.00	14.72	449.97	113.63	1528.00	26.06	683.46	-4119.13	6530.46
Manufacture	0.00	16.86	18.69	571.42	114.64	37330.69	788.25	14697.60	-40507.14	11371.26
ElecRetailDistn	0.00	0.00	0.67	20.57	5.22	1853.74	5.80	0.00	0.00	0.00
GasRetailDistn	0.00	0.00	0.00	0.00	0.00	117.69	0.00	0.00	0.00	62.41
Services	0.00	25.29	31.19	953.64	262.83	79879.14	42369.63	49836.58	-4447.09	28011.97
BrownCoalGen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BlackCoalGen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GasCombCycGen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GasOpenCycGen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WindGen	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BulkElectSupplyB1	0.00	0.00	0.16	4.97	1.26	237.38	2.42	0.00	0.00	0.00
BulkElectSupplyB2	0.00	0.00	0.06	1.74	0.44	83.26	0.85	0.00	0.00	0.00
BulkElectSupplyB3	0.00	0.00	0.35	10.67	2.73	329.81	3.23	0.00	0.00	0.00
BulkElectSupplyB4	0.00	0.00	0.18	5.59	1.46	150.85	1.51	0.00	0.00	0.00
BulkElectSupplyB5	0.00	0.00	0.00	0.12	0.03	3.10	0.02	0.00	0.00	0.00
BrownCoalProd	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BlackCoalProd	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5722.61
GasProd	0.00	0.00	0.00	0.00	309.63	371.10	0.00	0.00	0.00	950.71
Labour	0.00	42.14	22.80	697.02	206.14	0.00	0.00	0.00	0.00	0.00
Capital	0.00	196.67	78.09	2387.83	1568.88	0.00	0.00	0.00	0.00	0.00
Land	0.00	0.00	33.47	1023.36	672.38	0.00	0.00	0.00	0.00	0.00

Table 3 **Aggregated Input–Output table used for the CGE model ($ million, AUD)[a]**

		Coal generation		*Gas generation*		
	Units	*Brown*	*Black*	*Combined cycle*	*Open cycle*	*Wind*
Capital Cost	$m/MW	4.2	2.8	1.1	0.85	2.4
Fuel Cost	$/GJ	0.4	2.25	7	7	
Fixed Operating Costs	$/MW	65500	50500	17000	6000	45000
of which						
Labour	share	0.75	0.75	0.75	0.75	0.75
Manufacturing	share	0.09	0.09	0.09	0.09	0.09
Services	share	0.16	0.16	0.16	0.16	0.16
Plant Availability	% of time	97	97	99	99	25
Minimum Plant Size	MW	300	300			
Maximum Plant Size	MW	750	750	349	530	100
Life of Plant	Years	50	50	30	40	25
Thermal Efficiency	GJ electricity generated per GJ fuel	0.29	0.39	0.50	0.35	1.00
Carbon Emissions	tCO2e/MWh	1.126	0.743	0.349	0.515	0.000

[a] In the combined model, the capital cost, fuel cost, and fixed operating cost are endogenously linked to the CGE result, and so change with the economy-wide impact of the policy simulation.

4. Illustrative policy application: Renewable Energy Target

4.1 Operation of the RET

For a decade and a half Australia has had a renewable energy target of some form (Department of the Environment and Energy, 2016). The current version of the scheme, the Large-Scale Renewable Energy Target (RET), last adjusted in 2015, sets a target such that in the year 2020, 33 000 GWh of Australia's generated electricity will come from renewable supply sources. Renewables include supply sources such as wind, hydroelectric, solar and geothermal generation, among others, which is projected to account for over 20% of Australia's generated electricity.

The RET facilitates the production of renewable energy by creating a market for Large scale Generation Certificates (LGCs). For each megawatt-hour of energy generated from a renewable supply source, one tradeable LGC is assigned to that generator. LGCs can then be sold to electricity retailers, who surrender them to the government (through the Clean Energy Regulator). Retailers recover the cost of purchasing LGCs by applying a uniform surcharge on sales of electricity to their consumers, which is on top of the price that customers pay for electricity purchased through the electricity market. The revenue from the sale of the LGCs accrues to the owner of the renewable generator, which is in addition to the revenue they gain from the sale of the electricity into Australia's NEM. In this way, electricity users subsidise renewable electricity supplies.

4.2 RET implementation in the model

The RET is implemented in the MCP model by the creation of two new inequality constraints and their associated complementary (price) variables.

The first constraint (equation 1) specifies that GWh generated by wind generators (renewables) must be greater than or equal to the RET. The associated complementary variable is the price of the tradeable LGC (the price of renewable energy certificates PREC in the model). The target GWh in the policy model is set to be 20% of the total GWh generated in the base case model.[3]

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[3] The symbol $\perp$ is read to mean that at least one of either the right-hand-side or left-hand-side inequalities must hold with equality. PREC is the price of renewable energy certificates in \$m per GWh. AggDuration(b) is the electricity system aggregate duration in hours by load block b. QGO(b,reps) is the level of generation output in GW of renewable plant reps in load block b. RetTargetBar is the level of the renewable energy target (GWh).

$$PREC \geq 0 \perp \sum_{b,reps} AggDuration(b) * QGO(b,reps) - RetTargetBar \geq 0 \quad (1)$$

The second constraint requires that retailers recover the cost of purchasing renewable energy certificates by imposing a unit surcharge (PRESUR) on their electricity sales. The surcharge revenue raised by retailers from sales to end users (i.e. the surcharge PRESUR multiplied by total final sales) must be greater than or equal to the cost to retailers for purchasing LGCs from renewable electricity generators (i.e. PREC multiplied by the RET).[4]

$$PRESUR \geq 0 \perp PRESUR * \sum_{b} AggDuration(b) * QD(b,'n2') - PREC *$$

$$RetTargetBar \geq 0 \quad (2)$$

The introduction of the two new constraints and associated complementary price variables also requires adjustments to other first order conditions in the base case model to incorporate the flow on consequences. The surcharge PRESUR is required in all constraints which determine the price of electricity, the zero pure profit inequalities, such that it forms a wedge between the supply price (cost of production from the national electricity market) and demand price faced by wind generators. The price of certificates PREC is a source of unit revenue for renewable generators in addition to the revenue from sales of generated electricity. PREC is added as a wedge between the cost of generating power (the cost inputs plus a return on capital) and the price of power supplied to the electricity retail industry via the national electricity market.

Both models (base case and policy simulation) meet all the requirements to be valid CGE models (Dixon and Rimmer 2015). The models are homogeneous of degree zero with respect to price and the input–output structures balance in equilibrium.

5. Simulation results

This section outlines some key results, showing both the consequences of the policy, as well as the economy-wide CGE interactions.

5.1 Generation mix and total electricity supply

The optimal generation mix (installed capacity for all five generator types), as well as their level of supply in each load-block, for both the base case and the RET policy simulation is shown in figure 1. The results are intuitive. There is an overall reduction in electricity consumption and generation due to the increased price of electricity and reduced demand by

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[4] PRESUR is the price of the renewable energy surcharge on electricity sold to end users, measured in $m per GWh. QD(b,n) is the electricity demanded at the node n (where ‘n2’ is the demand node) in each load block b, measured in GW.

end users as a result of more expensive generation to meet the RET. In the base case brown coal is the marginal source of electricity generation for base load as it has the lowest marginal cost. However, wind has an even lower marginal cost, even though the capital cost (and availability factor) mean it is not built in the absence of a RET. With the imposition of the RET and given its low operating cost, wind displaces some brown coal. However, the installed capacity of wind is insufficient to displace brown coal entirely. Consequently, brown coal remains the marginal generation source during the base load period. As brown coal is only used for domestic electricity generation, the reduction in demand reduces the price of brown coal. So the price of generation is lower in block 5 under the RET.

It is also interesting to note that there is an increase in open-cycle gas turbine generation in the blocks in which it supplies (blocks 1 and 2) despite its higher marginal supply cost than in the basecase (gas prices rise). With the removal of baseload coal and its supplementation with wind (with its low availability factor) it is most economical to meet peak and intermediate load using generation from additional gas turbines.

Figure 1 **Power station generation by load block (GW)**

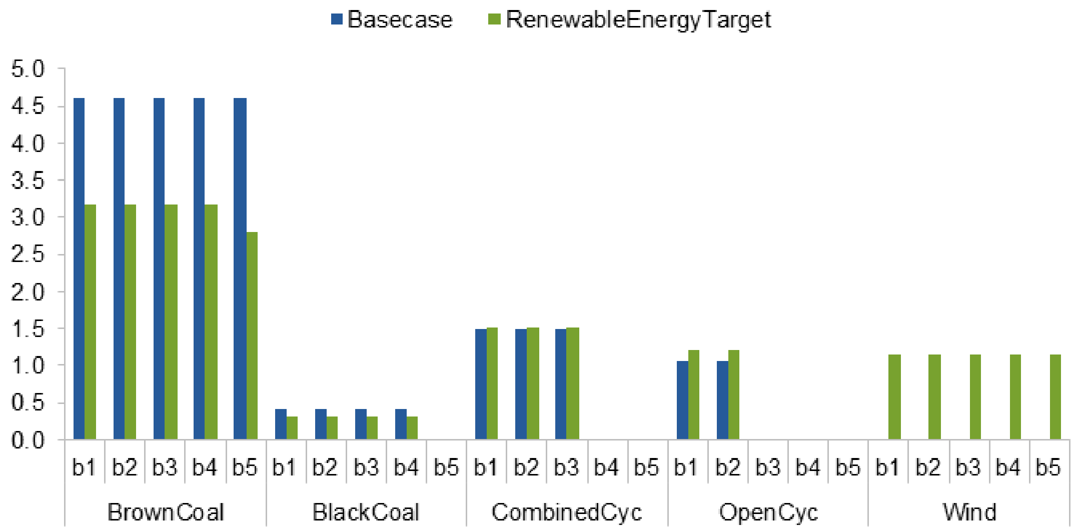
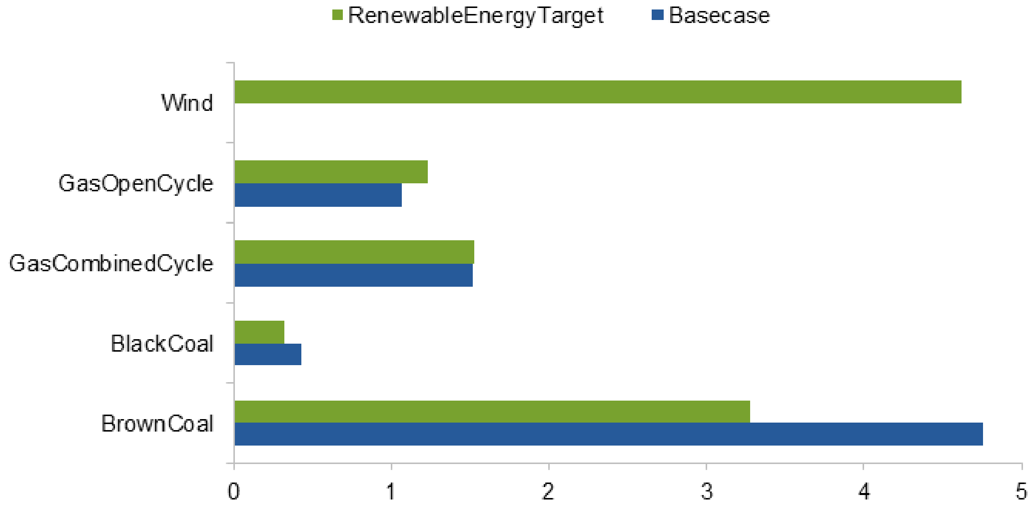


Figure 2 shows the total installed capacity of each generation type under the basecase and RET scenarios. Due to the lower availability factor of wind generation, the increase in wind capacity is much larger than the reduction in brown coal capacity that it is displacing.

Figure 2 **Total installed generation capacity (GW)**



5.2 Time-of-use and nodal pricing

Table 4 shows the time-of-use and nodal prices at the bulk or wholesale (NEM) level for both the base case and RET policy scenarios. The net impact on the nodal price of power in each block varies in sign and magnitude. In some blocks the price increases (peak, block 1). In others there is a marginal decrease in the supply price (blocks 2 through 5). Note from figure 1 that although wind displaces some brown coal in the baseload, the marginal generation source remains the same in each block (brown coal in b5; black coal in b4, combined-cycle gas in b3, open-cycle gas in b1-b2). Thus, the changes in price in each block reflect changes in the cost of production of the marginal source, due to general equilibrium impacts on the costs of fuels. Where the price decreases (b1 b4) this is because the operating cost of the marginal plant has declined due to the decreased demand for fuels. This is why the largest price reduction is in b5. The marginal plant is brown coal, and brown coal prices are most severely impacted (as brown coal has no export market, see below). On the other hand, the price has increased (by a small degree) in b1, due to the increased operating cost of open-cycle gas turbines resulting from the increase in demand for gas as well as the capital cost associated with open-cycle gas turbines.

Note that final user demand for power is all located in node 2. The non-renewable generation is at node 1, and wind generation is at node 3. The end user prices are shown in table 5, as well as the endogenous renewable energy surcharge paid by end users. There is a price decrease in some nodes and time blocks. However, with the inclusion of the surcharge, the final demand nodal time-of-use price increases under the RET policy for all load blocks.

Table 4 **Time-of-use and nodal price of transmitted electricity by load block and simulation ($/MWh)**

	Basecase			Renewable Energy Target		
	n1	*n2*	*n3*	*n1*	*n2*	*n3*
	Generation	*Demand*	*Wind*	*Generation*	*Demand*	*Wind*
b1	5648	7633		5649	8030	7775
b2	72	87		72	77	75
b3	58	62		58	61	59
b4	32	34		32	33	32
b5	8	9		5	5	5

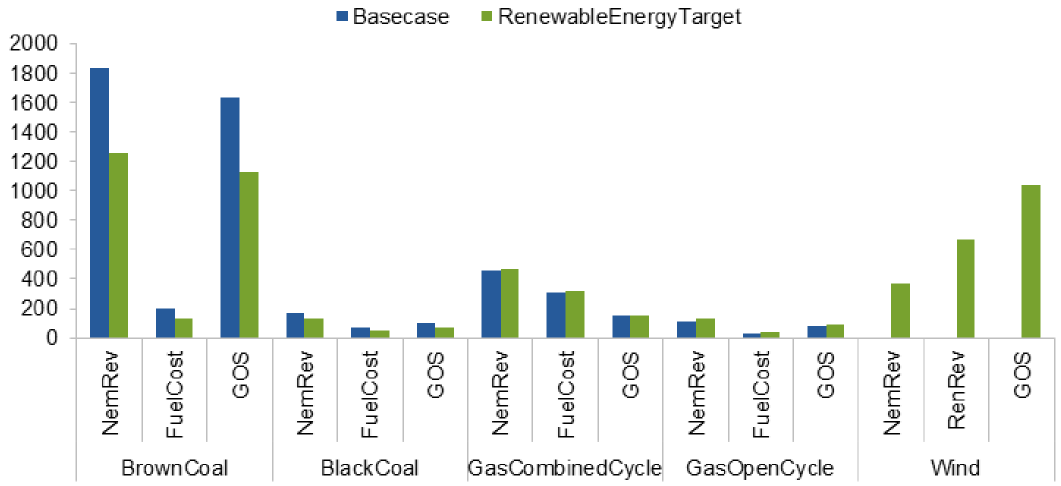
Table 5 **End-user (n2) electricity prices by load block and simulation ($ per MWh)**

		Basecase	Renewable Energy Target
b1	Electricity Market Price	7633	8030
b1	Renewable Energy Surcharge		15
b1	**Total**	**7633**	**8044**
b2	Electricity Market Price	87	77
b2	Renewable Energy Surcharge		15
b2	**Total**	**87**	**92**
b3	Electricity Market Price	62	61
b3	Renewable Energy Surcharge		15
b3	**Total**	**62**	**76**
b4	Electricity Market Price	34	33
b4	Renewable Energy Surcharge		15
b4	**Total**	**34**	**48**
b5	Electricity Market Price	8	5
b5	Renewable Energy Surcharge		15
b5	**Total**	**8**	**19**

5.3 Sales revenue, costs and net returns to generators

Total annual revenue and costs, as well as gross operating surplus (GOS), for each power station are shown in figure 3. Non-renewable generating technologies have a decrease in revenues and costs. This is driven by the reduction in installed capacity and production, with further cost reductions brought about by the reduction in the price of fuel due to decreased demand (see next section). Under the RET, wind generation has NEM revenue, as well as revenues from renewable energy certificates, which sum to GOS (given zero fuel costs for wind generation).

Figure 3 **Power station revenue and costs ($m)**



5.4 Impacts on fuel producing industries

Changes in the generation mix also impacts the CGE industries, most immediately and directly the fuel extraction industries: black coal, brown coal, black coal, and natural gas. Coal is most strongly impacted, due to the large decrease in demand from generators. Table 6 shows the price and output impacts on the fuel industries. Brown coal has the largest output (-31%) and price (-7%) reduction relative to the base case, as brown coal is used exclusively for domestic electricity generation with no alternative market. Although the black coal industry has a significant reduction in production (-25%), its price adjustment is more muted (-1%), because its price is linked to export markets. Reduced domestic use lowers the domestic supply price of black coal, but the price decrease is conditioned by the opportunity to export. Doing so has a small impact on the world price. Finally, natural gas production experiences a small increase in both output and price, and benefits from the labour, capital and land shed by the contracting fuel industries.

Table 6 **Price and quantity of fuels ($ per GJ, and PJ)**

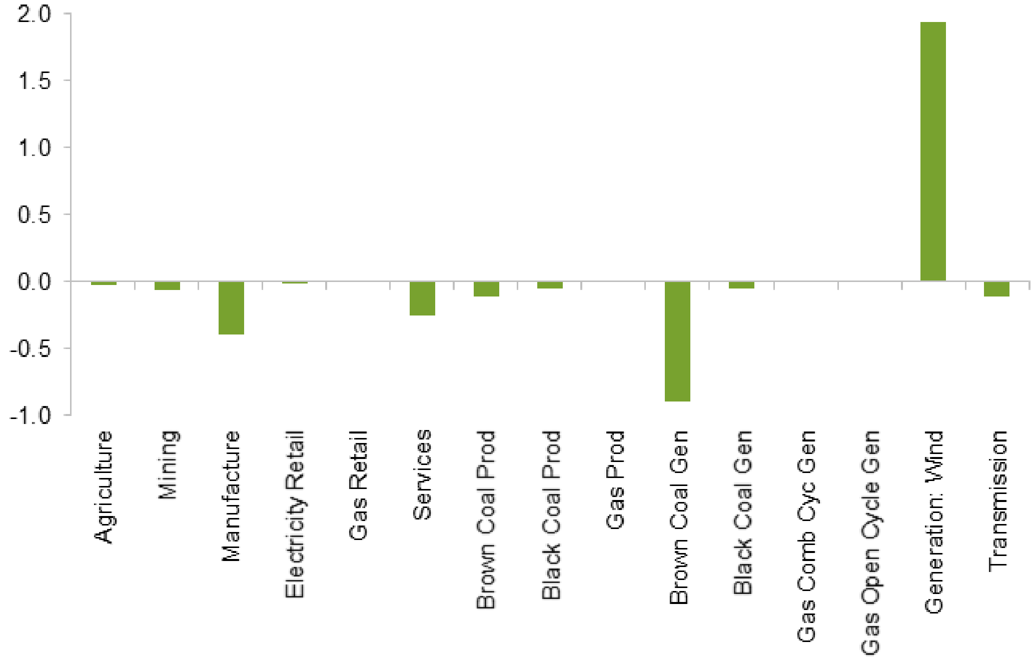
			Basecase	Renewable Energy Target
Domestic supply				
Price	$ per GJ	Brown Coal	0.4000	0.3713
		Black Coal	2.2500	2.2254
		Natural Gas	7.0000	7.0082
Quantity	PJ	Brown Coal	501	344
		Black Coal	33	24
		Natural Gas	50	51
Export supply				
Price	$ per GJ	Black Coal	2.2500	2.2414
		Natural Gas	7.0000	7.0025
Quantity	PJ	Black Coal	2543	2545
		Natural Gas	136	136

5.5 Economy-wide impacts, interindustry impacts and impacts on emissions

As discussed above, the introduction of the RET causes a reduction in aggregate energy sector activity (despite an increase in renewable energy activity), and an increase in the end user price of power. This increase in the cost of power impacts most industries throughout the economy, increasing the cost of production. Figure 4 shows that employment contracts in most industries, with (aside from in the coal generation sector) the strongest decreases in manufacturing, services and mining, all industries that are relatively energy intensive and trade exposed (either through exports in the case of mining and services, and import competition in the case of manufacturing). The services contraction is tempered by the fact that it supplies services used for the construction and maintenance of wind generation and energy transmission between nodes 3 and 2.

Almost all of the labour shed by other industries is absorbed by the newly created wind generation sector. In part, this is driven by the CGE closure: being a long-run comparative static steady state, the employment level is fixed. It is worth noting though, that the increase in wind generation employment is larger than the reduction in coal generation employment. This is because (as discussed earlier), a much greater capacity of wind generation has to be installed than the brown coal generation it displaces, due to the lower availability factor of wind generation.

Figure 4 **Change in industry employment (persons, ‘000s), base case to RET policy scenario**



The increase in the cost of power drives a CPI increase (0.24%) and a nominal wage decrease (-0.25%) resulting in a net fall in the real wage. Real household income is reduced by $743 million. The fall in real household income causes a significant reduction in real household consumption of $652 million which is also a primary driver of the reduction in imports of $94 million. Increased production costs also reduce exports, down $149 million. Aggregate investment experiences a small real increase of $10 million, where the increase is driven almost exclusively by installation of wind generation capacity (as well as new transmission line infrastructure, and a small increase in gas extraction investment). There is an overall GDP contraction of $885 million, summarised in table 7.

The contraction in imports in particular requires further explanation, but is intuitive. The import demand reduction is proportionately much smaller than the total consumption demand reduction. This is because there are two effects pulling imports in opposite directions. The household income effect would (on first glance, in the absence of price effects) be expected to reduce import demand by approximately $200 million. However, due to the domestic price increase there is a corresponding substitution in favour of imports, increasing imports by just over $106 million. The net reduction in imports of $94 million mentioned above reflects the net effect of these two influences.

Table 1.7 **Real GDP summary ($m)**

	Deviation	Percentage change
Consumption	-652	-0.52
Investment	10	0.02
Government	0	0.00
Exports	-149	-0.26
Imports	-94	-0.25
GDP	-885	-0.27

Table 8 **Carbon emissions from power stations by simulation (Mt CO2 equivalent)**

	Basecase	Renewable Energy Target
Brown Coal	45.4	31.2
Black Coal	2.6	2.0
Gas Combined Cycle	2.2	2.2
Gas Open Cycle	0.2	0.3
Total	50.5	35.6

6. Conclusions

This paper presents an illustration of the opportunities created by MCP for merging PE models with applied CGE models. Specifically, the integrated MCP model is able to illustrate the impacts on merit order dispatch, capacity mix, time-of-use prices and nodal supply prices — insights typically drawn from PE models, while at the same time providing insights into the extent and distribution of impacts on other industries in the economy, as well as aggregate impacts on Australian households and trade (insights typically drawn from CGE models).

The model also provides important CGE insights which could not be obtained from the PE model in isolation. Income effects could not be included endogenously in a PE model, except through exogenous parameterisation. The important CGE insight that the black coal extraction industry — through its exposure to export markets — does not proportionately contract as much as the non-traded brown coal extraction industry, is an insight that would not necessarily be immediately obvious prior to the simulation.

The approach of embedded PE and CGE models into a single modelling framework opens the door to richer applied analysis in the future, particularly in areas where exposition of the economic impacts at the micro-level are important at the same time as macroeconomic flow-on effects, or where micro-level or technical policy details need to be represented in a precise way to capture the underlying economic principles relevant to policy analysis. This approach will not be appropriate for every exercise. For some analyses, the cost of the additional efforts and time required to build a complete, integrated model can exceed the benefits gained from the additional insights. In those situations, it is likely that a single PE or CGE model would provide a large share of the necessary insights. However, there are likely to be some policy issues where the unified PE-GE approach presents valuable opportunities to contribute to the policy debate in ways that were not previously possible.

Further work could explore the extent to which fully integrated models formulated as MCPs produce different results to models solved iteratively and separately. It would also be useful to see if simply expanding the detail for the industries of interest in the CGE model (i.e. take the initial IO table for the PE-CGE MCP model and use it to generate a standard CGE model used for the policy experiment where all industries including generation and transmission have the usual stylised CGE representation) implies different results. The MCP model approach applied also has potential limitations on model size. These might be able to be overcome if the model can be decomposed and solved efficiently. This could provide insights into the situations where it would be justified incurring the additional time costs required to construct a full MCP model.

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