PRODUCTIVITY
COMMISSION

CGE Models for Evaluating Domestic Greenhouse Policies in Australia: A Comparative Analysis

Consultancy
Report

Jack Pezzey
Ross Lambie

The views expressed in this paper are those of the authors and do not necessarily reflect those of the Productivity Commission. Appropriate citation is indicated overleaf.

April 2001

ISBN 1 74037 038 4

Publications Inquiries:
Media and Publications
Productivity Commission
Locked Bag 2 Collins Street East
Melbourne VIC 8003

Tel: (03) 9653 2244
Fax: (03) 9653 2303
Email: maps@pc.gov.au

General Inquiries:
Tel: (03) 9653 2100 or (02) 6240 3200

An appropriate citation for this paper is:

Pezzey, J.C.V. and Lambie, N.R. 2001, *Computable general equilibrium models for evaluating domestic greenhouse policies in Australia: A comparative analysis*, Report to the Productivity Commission, AusInfo, Canberra.

The Productivity Commission

The Productivity Commission, an independent Commonwealth agency, is the Government's principal review and advisory body on microeconomic policy and regulation. It conducts public inquiries and research into a broad range of economic and social issues affecting the welfare of Australians.

The Commission's independence is underpinned by an Act of Parliament. Its processes and outputs are open to public scrutiny and are driven by concern for the wellbeing of the community as a whole.

Information on the Productivity Commission, its publications and its current work program can be found on the World Wide Web at www.pc.gov.au or by contacting Media and Publications on (03) 9653 2244.

Contents

FIGURES

TABLES

Preface

Greenhouse gas emissions and how they might be abated are important issues for government, industry and the community. Economic modelling can play a role in improving our understanding of the implications of different policies for the economy. As with other types of economic models, computable general equilibrium models provide a stylised, but incomplete, picture of the real world. However, by specifying assumptions within a rigorous economic framework, they can facilitate a disciplined analysis of complex policy problems.

The Productivity Commission engaged Dr John C.V. Pezzey and Mr Ross Lambie from the Centre for Resource and Environmental Studies at the Australian National University to undertake an independent review of four main models used to assess the economic impacts of policies to reduce greenhouse gas emissions in Australia.

There has been considerable model development (for some models, largely undocumented) since a previous review in 1996 and the report provides documentation of those developments. The underlying assumptions and structure of each model (as at September 2000) are compared and contrasted. The relative strengths and weaknesses of the models for possible use in different policy scenarios are identified. Priorities for further model development to improve understanding of greenhouse policy impacts in the medium term are then considered.

A draft of this report was presented and discussed at a workshop of the modelling groups and interested parties, including model users and policy advisers, in December 2000 at the Australian National University.

About the authors

Dr John C.V. (‘Jack’) Pezzey and N. Ross Lambie are economists in the Ecological Economics Program of the Centre for Resource and Environmental Studies (CRES) at the Australian National University. CRES was established in 1973, and from its inception, its objective has been to undertake interdisciplinary research into a range of environmental and resource issues. Such studies focus primarily on Australia, and are particularly concerned with policy options and implications. Jack Pezzey is also a Visiting Fellow at the Department of Economics, at the University of Bath, U.K.

Postal address: CRES, ANU, Canberra, ACT 0200, Australia

Tel: +61 (0)2 6125 4143 Fax: +61 (0)2 6125 0757

E-mail: pezzey@cres.anu.edu.au Website: http://cres.anu.edu.au/~pezzey

Acknowledgments

The authors are grateful for helpful comments and advice generously given by the following: Neil Byron, Philippa Dee, Gavan Dwyer, Kevin Hanslow, Patrick Jomini, Anna Matysek, Deborah Peterson and Lynne Williams from the Productivity Commission; representatives of all four modelling groups; and Rod Tyers from the Australian National University. None of these bears any responsibility for the report's content or any views expressed, which are the authors' alone.

Abbreviations

ABARE	Australian Bureau of Agricultural and Resource Economics
ABS	Australian Bureau of Statistics
AEEI	autonomous energy efficiency index
AGO	Australian Greenhouse Office
ANU	Australian National University
BIE	Bureau of Industry Economics
CDE	constant differences of elasticity
CES	constant elasticity of substitution
CET	constant elasticity of transformation
CGE	computable general equilibrium (a type of economic model)
CH_4	methane (natural gas)
CO_2	carbon dioxide
CO_2-e	carbon dioxide equivalent
COP6	Sixth Conference of the Parties to the UNFCCC, which started in The Hague, Netherlands in November 2000
CoPS	Centre of Policy Studies, Monash University
CRES	Centre for Resource and Environmental Studies, Australian National University
CRESH	constant ratios of elasticity of substitution
CRS	constant returns to scale

DEST	Department of Environment, Sport and Territories (precursor to Environment Australia)
DFAT	Department of Foreign Affairs and Trade
GHG	greenhouse gases
IPCC	Intergovernmental Panel on Climate Change
LES	linear expenditure system. See appendix A
LPG	liquid petroleum gas
LNG	liquefied natural gas
N_2O	nitrous oxide
PC	Productivity Commission
OECD	Organisation of Economic Cooperation and Development
PAYE	pay as you earn
SOFT	summary of financial transactions
UNCED	United Nations Conference on Environment and Development
UNFCCC	United Nations Framework Convention on Climate Change which arose from UNCED

Key Points

Four main computable general equilibrium models (CGE) models (as at September 2000), used to assess the economy-wide and industry-specific impacts of policies to control greenhouse gas (GHG) emissions in Australia, are reviewed in this report. The models considered are: MMRF–Green developed by Monash University; MM600+ developed by Econtech; GTEM developed by the Australian Bureau of Agricultural and Resource Economics; and G-Cubed developed by the Australian National University and the University of Texas. All these models calculate the economic costs, but not the environmental benefits, of GHG control.

Each model can make a valuable contribution to greenhouse policy analysis, but the choice of model will depend upon the policy questions of interest. The range of policy analyses possible, and the distributional information provided by the models, depend on their level of product, sector, household and emission detail.

There are significant differences in model structures and disaggregation, including:

- MMRF–Green has the most regional and household detail, followed by MM600+ (both are models of Australia only). GTEM and G-Cubed are global models, with Australia represented as one zone with no domestic disaggregation.
- MM600+ has the most detailed product, sectoral and tax representation.
- MMRF–Green has the most detailed energy sector representation, while G-Cubed is the least detailed on energy.
- MM600+ and G-Cubed incorporate carbon-dioxide emissions only, while MMRF–Green and GTEM account for an extended range of GHGs.
- Only GTEM and MMRF–Green explicitly model electricity generation from renewables.

Other significant differences among the models are:

- MMRF–Green and G-Cubed are the only models to capture short-run effects (such as unemployment) arising from inflexible wages.
- G-Cubed is the only model that accounts for the short-run effects from capital adjustment costs and financial market flows between zones.

- GTEM is the only model to represent population endogenously. The other models rely on external population growth projections. Population is important in determining reference case emissions, which in turn affect the costs of implementing GHG policies.

Representation of technology affects substitution possibilities, and substitutions are very important in determining abatement costs:

- All models (except GTEM) allow capital-energy substitution at the margin even if the underlying technology is currently infeasible. However, this may be less important in the long run due to technological development.
- GTEM's technology bundle approach allows only feasible technology to be used in production, but provides as much flexibility in response to small relative price changes as the input substitution approach in the other models.

The models' emission reference levels, representations of technical change, and substitution and demand elasticities are important influences on marginal abatement cost projections. However, it is difficult to determine which other model features have significant impacts on 'bottom-line' results in abatement analysis without undertaking scenario-based comparisons.

The realism of policy analysis and the estimation of abatement costs using these models may be restricted by:

- the inability to include 'non-price' policies (for example, information campaigns, exhortation and land-use planning); and
- the representation of the rate of technical change (all current versions of the models treat technical change as exogenous to some degree).

Model comparisons require an understanding of the underlying assumptions of the models. This depends crucially upon the amount, quality and transparency of documentation. MMRF–Green and G-Cubed are currently the most thoroughly documented in terms of description, mathematical equations and source code. GTEM has dispersed documentation, while MM600+ does not have the same level of publicly available documentation as the other models.

Suggestions for future model developments include the following:

- More detail in documentation on both energy and other tax thresholds would allow better assessment of the different policy options for recycling revenue.
- Scenario-based policy runs to compare models (which were not part of this study), and validation exercises within each model (not available in current

documentation), are needed before any general conclusions can be drawn about the overall quality of the models.

- The rents (short-run or long-run profits in excess of normal levels) made by industry sectors, as a result of both overall GHG control, and the allocations of free GHG permits, should be modelled and reported. Treating rents as being passed on to a representative shareholder, no different to the representative consumer, does not fully reflect their distributional and economic impacts.
- There should be more modelling of endogenous technical progress (total factor productivity increases) in response to any increased fuel prices as a result of GHG control policy.
- Incorporating technology subsidies, energy efficiency measures in households, transaction costs, carbon sinks and land clearing are all desirable, but not necessarily easy, areas for future development.
- Disaggregating households by income level would enable better analysis of policy effects on distributional equity.
- Developing a global model to simulate external conditions, and then linking this to a national model for more detailed analysis of domestic distributional issues, would avoid the choice which currently has to be made between a national and a global model. It is not an easy choice, since sectoral detail within Australia may be desirable, yet the global economy may be important in determining a policy's effects on trade-exposed industries.

1 Introduction

Since the late 1980s, the potentially harmful effects of overall climatic warming caused by the global accumulation of greenhouse gases (GHGs) have been recognised as an important concern for public policy making. The concern is largely expressed as questions: by how much should GHG emissions be reduced, and when? What will the costs be, and which sectors of society will ultimately bear them? What will the benefits be, and who will ultimately enjoy them? These were central questions in the debate about the 1997 Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), which set overall targets for controlling emissions of six GHGs: carbon dioxide, methane or natural gas, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride. Carbon dioxide is by far the most important of these gases, followed by methane (see AGO 1999, p. 17 for details).

Greenhouse gas control has a number of key features (determined by the characteristics of carbon dioxide mainly), which together make it unique among environmental problems. Carbon dioxide has a very long residence time in the atmosphere. Any decisions taken now are bound to affect several generations to come, raising awkward questions about the valuation of events in the far future. The long residence time also means that carbon dioxide has ample time to diffuse uniformly in the global atmosphere, making its control an unavoidably global issue. Also, carbon-bearing fuels (the fossil fuels — coal, oil and natural gas) play a huge and pervasive role in most economies. Thus, GHG control inevitably has large flow-on effects on many sectors of an economy, including its trade flows. And, compared with efficiency and substitution alternatives, there is currently no economically viable ‘end of pipe’ method of abating carbon dioxide emissions. Emissions are thus proportional to carbon inputs. This means that emission taxes and tradeable emission permits are cheaper to administer (in the form of input taxes or permits), and more necessary, than those for many other pollutants where expensive emission monitoring is needed, and efficient end-of-pipe controls can be identified. Finally, the possible use of such economic instruments in such large parts of the economy raises questions of public finance, because many versions of these instruments raise significant amounts of revenue. What then should be done with this revenue? Or, should an instrument be redesigned to raise less revenue, while still creating the same marginal incentive to reduce emissions?

1.1 Computable general equilibrium (CGE) modelling of GHG policy options

This combination of features — a long time horizon, global pollution derived from a major commodity, pervasive economic effects that include impacts on trade and public finance, and a case for economic instruments — has led to the frequent use worldwide of pre-existing models of the whole economy (after appropriate development) to study GHG control. By contrast, modelling of other pollution problems (say, sulphur dioxide or water pollution) would normally use a purpose-built, partial equilibrium model to incorporate the specific, end-of-pipe abatement technologies that are available.

The main types of whole-economy or ‘top–down’ models available are macroeconomic models and computable general equilibrium (CGE) models, although both can incorporate elements of ‘bottom–up’ or ‘engineering’ descriptions of specific energy-using technologies. Further, the boundary between CGE and macroeconomic models is not rigid. So-called CGE models can, in practice, have non-equilibrium features (such as involuntary unemployment) that are more commonly associated with macroeconomic models.

CGE models are the focus of this report, because they explicitly include many different industry sectors and their interrelationships. They can examine the indirect (second-order) effects of possible GHG control policies caused by the substitutable nature of energy, and thus estimate the detailed sectoral impacts of possible GHG control policies. Such impacts are felt to be of considerable interest to policy makers, and partial economic or macroeconometric models are generally able to examine only first-order effects. A comprehensive review of the suitability of particular CGE models for specific greenhouse policies requires a comparative analysis of both inputs and outputs of each model. Inputs can include the model characteristics, data, forms of closure and modeller expertise. The purpose of this study is to understand the technical specifications (inputs) of each model and how these may be relevant to an evaluation of policy alternatives.

An evaluation of outputs would include examining the results of past simulations and considering their accuracy, which is beyond the scope of this study. A full evaluation would be an important complement to this study, including a model comparison exercise based on standardised simulations (outputs), such as those reported in Hargreaves (1994) and James (1996).

1.2 Objectives of this report

The aim of this report is to undertake a comparative review of four main, large scale, CGE models that could be used to assess the economy-wide and industry-specific impacts of policies to reduce Australian GHG emissions. The models to be evaluated are the versions available in September 2000 of:

- Monash Multi-Regional Forecasting–Green (MMRF–Green), developed by the Centre of Policy Studies (Monash University, Melbourne);
- MM600+, the 600+ version of the Murphy Model, developed by Chris Murphy (Econtech, Canberra);
- the Global Trade and Environment Model (GTEM), developed by the Australian Bureau of Agricultural and Resource Economics (ABARE, Canberra); and
- the Global General Equilibrium Growth Model (G-Cubed), developed by Warwick McKibbin (Australian National University, Canberra) and Peter Wilcoxen (University of Texas, Austin).

The first two are national models of the Australian economy, with results reported for different regions within Australia. Simplified assumptions are made about exchange rates and international flows of goods and assets. The third and fourth are models of the world economy, with no regional detail within Australia, but with endogenous calculations of exchange rates and flows between the zones into which the world is divided.[1] All these models are undergoing continual development, so some details of more recent models are bound to differ from what is reported here.

The objectives of the study are to:

- undertake a comparative analysis of the underlying assumptions and structure of each model;
- identify the relative strengths and weaknesses of the models for possible use in different policy scenarios; and
- consider priorities for broad modelling directions to improve understanding of greenhouse policy impacts in the medium term (five to ten years).

---

[1] Given the coverage here of both national and global models, common modelling uses of the word ‘region’ include both a subnational area (such as Victoria and Ontario, which are regions of Australia and Canada respectively) and a group of nations (such as the OPEC countries and the OECD, which are regions of the world). To avoid any confusion, *region* is used here to mean part of a nation, and *zone* is used to mean a nation or group of nations, even if the modellers use different terms.

The study methods have comprised:

- a study of published and unpublished literature on the selected models and on GHG control modelling in general;
- conversations and correspondence with the modellers;
- the presentation of a draft report to a half-day workshop (15 December 2000) attended by all the modellers and a wide range of potential model clients; and
- consideration of comments received during and after the workshop.

1.3 Describing and assessing model characteristics

In meeting the objectives, the study will involve describing and assessing five broad features for each model:

- the model’s basic characteristics and general strengths and weaknesses, including:
    - its sectoral (commodity and industry) coverage;
    - its regional coverage;
    - how regional results are obtained;
    - the modelling of technical progress in general;
    - key model assumptions and their expected effects on results;
    - alternative closures and the flexibility in their application; and
    - the transparency of publicly available documentation;
- the model’s incorporation of current and potential forms of GHG abatement technologies;
- the model’s current and potential level of detail about the energy sector, and its coverage of GHGs other than carbon dioxide;
- the model’s current and potential ability to give detailed results — for example, are results available by state/region/zone, income group and/or industry group?
- the model’s ability to simulate current and future GHG abatement policies, including different ways of implementing them.

1.4 Previous studies

CGE models have been used in Australia since the mid-1970s to analyse a range of model use policy issues that involve economy-wide interrelationships (for surveys see Powell and Lawson (1990); Vincent (1990); Powell and Snape (1993)). The main issues analysed have included industry protection; supply shocks; macroeconomic policy; microeconomic reform; government taxes, grants, charges and regulations; and industry studies. Since the early 1990s, CGE and other whole-economy models have also been used to analyse the widespread, potential impacts of GHG control policies in Australia. Previous surveys of the use of whole-economy models to analyse Australian GHG control policy include BIE (1994), James (1996) and Hamilton and Quiggin (1997). (The latter was more a critique of the CGE modelling approach to GHG control — especially as used in informing Australia's Kyoto negotiations — than a comparative survey.) The CGE models discussed in these three reports have undergone much innovation in the past five years or so, so an update is due. Further, the objectives here differ somewhat from those of previous reviews.

BIE (1994) included MENSA (a large, dynamic linear programming model developed by ABARE) and IMP (a macro-level, dynamic model developed by the National Institute of Economic and Industry Research), as well as four CGE models (ORANI, the precursor to MMRF–Green; WEDGE; MEGABARE, the precursor to GTEM; G-Cubed). James (1996) did not include MENSA or WEDGE, which left one macroeconomic model (IMP) and the three CGE models. He compared all models' simulation of the economy's response to a standard scenario. The terms of reference of this study excluded the IMP model, added MM600+ as a fourth CGE model, and excluded any scenario-based comparisons.

The main objective here is to compare CGE model with CGE model, rather than the CGE modelling approach with other approaches. This does not mean that CGE has somehow 'won' the contest among rival modelling approaches; a recurrent theme of this report is that the best model to use depends on the type of policy question being asked. If one wishes to know about short run, economy-wide impacts (such as those on inflation), then a macroeconomic model may be best. If one wishes to know about how much of the technical potential of specific energy efficiency technologies could be achieved by targeted information campaigns, then a bottom–up model may be best.

1.5 Outline of this report

The report has been structured with a view to it being used as a reference document after initial reading. Section 2 contains a brief background and description of each model. Section 3 is an application of a common framework to summarise the detailed structure of each model in isolation, with special attention to important features for analysing GHG control policy. Section 4 is a comparison of key assumptions and features of the models, including some not included in Section 3 that are best described for all the models combined. Section 5 is a consideration of the implications for GHG policy analysis arising from each model. Finally, Section 6 is a conclusion, drawing together the main findings of the study. Appendix A lists common mathematical functions used in CGE models. Appendix B is a summary table of the models' main features (which is likely to be useful for reference purposes). Appendix C contains detailed lists of sectors, products and GHG emissions.

2 Overview of the models

This section begins by observing common features to all CGE models. It then provides a brief description of each of the models.

2.1 Common features of CGE models

It is difficult to define a computable general equilibrium (CGE) model precisely, because the boundaries of what may be called a CGE model are not altogether rigid. Nevertheless, such models usually share the following features:

- The model determines quantities and prices.
- The model's focus is on equilibrium resource allocation patterns.
- Resource allocation patterns are based (to some degree) on Walrasian general equilibrium theory.
- Product and factor markets are assumed to be perfectly competitive (including an assumption of perfect, costless information about current variables in the model, although not necessarily about future variables).
- All markets clear.
- Household product demand and factor supply functions are consistent with utility maximisation, subject to budget constraints.
- Producer product supply and factor demand functions are consistent with profit maximisation, subject to technology constraints.

All the models evaluated in this study share an additional feature that has implications for the analysis of greenhouse gas control policy: that is, they are deterministic models, so do not account for uncertainty. It is assumed that there are no surprises in important long run relationships and key exogenous parameters. This means that carbon taxes and tradeable carbon emission permits are treated identically at the domestic level in simulations, and thus have symmetrical long run efficiency properties (Pezzey 1992); however, they are not the same in terms of international trade. The free issue of some proportion of tradeable permits to some domestic agents is modelled, for example, simply by giving this proportion of carbon tax revenue as a lump sum transfer to those agents.

2.2 MMRF–Green

Monash Multi-Regional Forecasting–Green (MMRF–Green) is a dynamic, multi-regional, multi-sectoral CGE model of the Australian economy. The Centre of Policy Studies at Monash University developed MMRF–Green from the comparative static MMRF model (Peter et al. 1996) and the dynamic, single-region MONASH model (Dixon and Rimmer 1999). (These two models were developed from the ORANI model (Dixon et al. 1982).) A description of MMRF–Green is provided in Adams, Horridge and Parmenter (2000a).

MMRF–Green allows for inter-fuel substitution in electricity generation (five different types of electricity generator industry) by region, and allows the endogenous adoption of abatement measures in response to GHG control policy. The model has recently been used to analyse several GHG policies. These applications include: a simulation of the impacts of imposing an efficiency standards measure that is designed to reduce the emission of GHG per unit of electricity generated from fossil fuels (Adams, Horridge and Parmenter 2000b); a simulation of the effects on Australia's substate economies of multilateral emissions trading (Allen Consulting Group 2000b); modelling for a consultancy examining the microeconomic impacts of global emissions trading; and modelling for a project examining the national and regional impacts of various domestic trading schemes in carbon permits (Allen Consulting Group 2000a). Table 5.1 contains details of the policies analysed using MMRF–Green.

2.3 MM600+

MM600+ is a comparative static, multi-regional, multi-sectoral CGE model of the Australian economy. It is an upgraded version of Econtech's first industry model, the MM303+, which Chris Murphy developed. While some Australian CGE models are adaptations of the ORANI model, MM303/MM600+ was independently developed. It includes an extended range of economic choices and as many as 672 products. Dixon's work on the ORANI model was an important source of ideas for MM600+ in areas such as import demand and the treatment of distribution margins. A description of the MM600+ model is available on the Internet (Murphy 2000).

MM600+ has a detailed breakdown of industry sectors, products and product taxes, which allows it to distinguish many different forms of energy and energy-using industries. The breakdown also allows for substitution possibilities in production and consumption affecting GHG emissions. The model has recently been used to analyse GHG issues for the Department of Transport and Regional Services

(Econtech 2000) (see table 5.1). Previously, it was used to analyse the greenhouse implications of a proposed national gas pipeline.

2.4 GTEM

The Global Trade and Environment Model (GTEM) is a dynamic, multi-sector, multi-zone, global CGE model. The Australian Bureau of Agricultural and Resource Economics (ABARE) derived it from their dynamic MEGABARE model (ABARE 1996) and the comparative static GTAP model from the Center for Global Trade Analysis at Purdue University (Hertel 1997). GTEM is described in Brown et al. (1999) and Polidano et al. (2000). The Tablo file is available on the Internet (ABARE 2000).

The key differences between GTEM and MEGABARE are the better coverage of GHG emissions (which include methane and nitrous oxide, as well as carbon dioxide); greater allowance for inter-fuel substitution; and allowance for emission reduction responses in noncombustion GHGs in GTEM. The Australian Government used MEGABARE to provide analysis to assist negotiations on the Kyoto Protocol. GTEM has also been used in the post-Kyoto negotiating environment to undertake analysis of international emission trading, carbon sinks and the clean development mechanism. Table 5.1 presents details of some of the recent GHG policies analysed.

2.5 G-Cubed

The Global General Equilibrium Growth model (G-Cubed) is a dynamic intertemporal, global model with multiple sectors and zones. Warwick McKibbin and Peter Wilcoxen originally developed G-Cubed to analyse carbon tax issues for the US Environmental Protection Agency. It is based on the MSG2 model developed by McKibbin and Sachs (1991). Details of G-Cubed are provided in McKibbin and Wilcoxen (1999) and are available on the Internet (McKibbin Software Group 2000).

G-Cubed was constructed to analyse global warming policy issues. It stretches the definition of a CGE model, because it combines features from econometric general equilibrium modelling, international trade theory and macroeconomics. The model has complete short run and long run macroeconomic closure around a Ramsey neoclassical growth model. Annual solutions represent a transition equilibrium, which comprises the effects of short run flow and long run stock equilibriums. G-Cubed is an intertemporal model, in that annual solutions are full rational expectations equilibriums that account for the future solutions of all subsequent years. G-Cubed has been used extensively to analyse GHG issues (see table 5.1 for details) and more general trade issues.

3 Detailed features of the models

This section surveys the features of each of the four models under consideration. Each subsection begins with a structural overview of the model. This is followed by descriptions of how household, firm and government behaviour are modelled; as well as the handling of trade and financial flows, the monetary sector, labour market structure, population growth, technological change and other features relevant to greenhouse gas control policy. Finally, each subsection contains a brief description of the data sources for each model.

3.1 MMRF–Green

3.1.1 Structural overview

MMRF–Green is a multi-regional, multi-sectoral model of the Australian economy. The structure of the model is described in Adams, Horridge and Parmenter (2000a), and a detailed description of the MMRF model on which it is based is available in Peter et al. (1996). MMRF–Green models Australia as eight separate regions corresponding to the six States and two Territories. Results from each regional model can be disaggregated to produce projections of output, employment and greenhouse gas (GHG) emissions for 57 subregions. Each model represents several types of economic agent. These include domestic producers and investors by industry and region; region-specific households; regional governments; a Commonwealth government; and an aggregate foreign purchaser of exports and seller of imports. For each region there are 40 industry sectors (which are aggregates of 116 individual industries producing 118 commodities), a capital creator for each industry sector, a single household, and a foreign purchaser and seller of goods and services. Government activity is captured at the regional level through State and Territory governments, and at the national level through the Commonwealth Government.

MMRF–Green assumes that economic agents operate in fully competitive markets and engage in optimising behaviour. Apart from investor behaviour, which can be forward looking, in dynamic simulations the behaviour of other agents is myopic because they account for information concerning only the current period.

3.1.2 Households

Consumer behaviour is represented by a utility-maximising household in each region. The structure of household demand is shown in figure 3.1.

3.1.2.1 Consumption

A representative household purchases a bundle of goods and services each period that will maximise its utility from consumption while ensuring that expenditure does not exceed its available budget. Household utility is represented by a Stone-Geary utility function (see appendix A), while household expenditure is a function of regional household disposable income. This linear expenditure system distinguishes between spending on subsistence and luxury goods and services. The utility function for the 'luxury' component is modelled as a Cobb-Douglas function, which implies that the proportion of the household budget spent on luxury commodities is fixed.

3.1.2.2 Savings

Savings are not modelled at the household level.

3.1.2.3 Income

Regional household disposable income comprises employment-related income, income from other primary factors, income from government transfers (personal benefit payments) and 'other net income' that is linked to the region's nominal gross product, less any direct taxes paid.

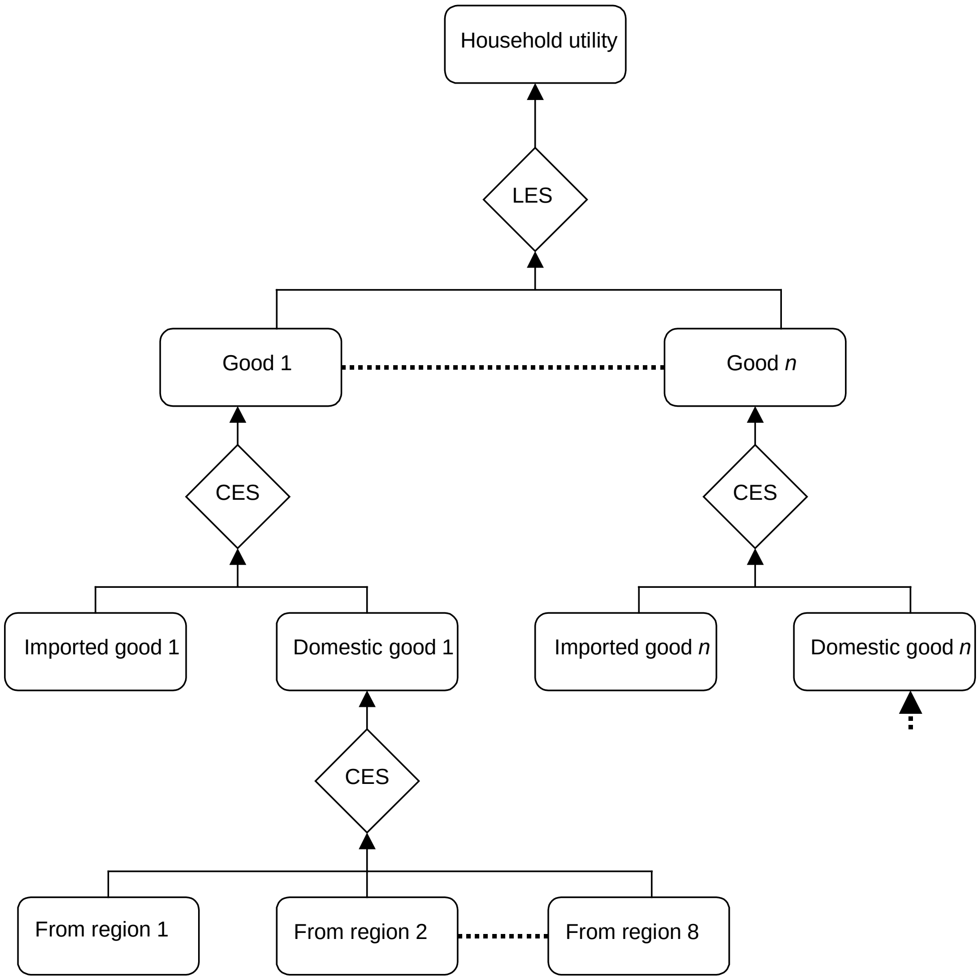
3.1.3 Firms

Firms operate in perfectly competitive markets and maximise profits using constant returns to scale technology.

3.1.3.1 Production

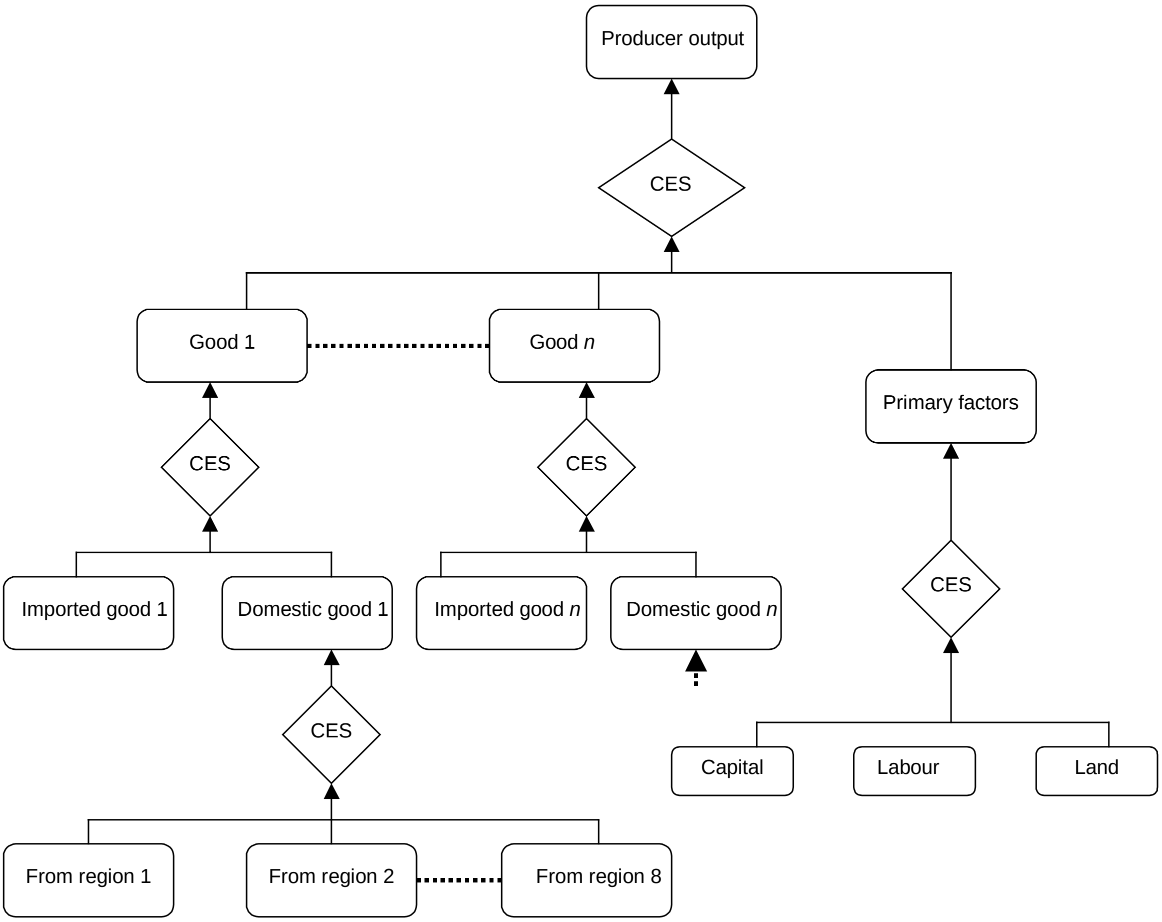
Figures 3.2 and 3.3 show how MMRF–Green treats the production of commodities. In industries other than 'electricity supply' (figure 3.2), output of goods and services is produced from inputs of intermediate commodities and primary factors. Firms are assumed to choose combinations of these inputs that minimise production costs for any given level of output. The choice of inputs is constrained by a three-level nested production technology function. At the first and highest level, a distinction is made between commodities produced from non-energy-related inputs and those produced from energy-intensive inputs. For both types of commodity, output is produced from intermediate inputs and a primary factor bundle. In the case of commodities produced from non-energy-related inputs, these are combined in fixed proportions (Leontief production technology) to produce output; therefore, the elasticity of substitution at the highest production node is zero. For commodities produced from energy-intensive inputs, the value of the elasticity is non-zero and thus a constant elasticity of substitution (CES) technology is imposed. A distinction is also made in the production of energy-intensive commodities between the input substitution possibilities for petroleum products, electricity supply and natural gas, and those for all other energy-intensive commodities. This distinction is achieved by the setting of a higher substitution elasticity for the first group of commodities than for the second.

Figure 3.1 **Household demand in MMRF–Green**



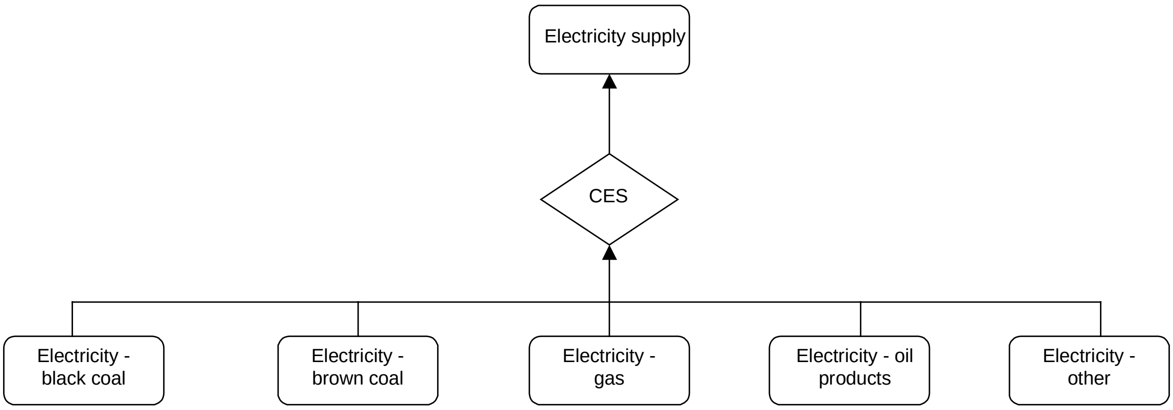
At the second level of production, the intermediate-commodity bundle is a CES combination of international imported goods and domestic goods. The primary factor bundle is a CES combination of capital, labour and land. At the third and final level, domestic goods input is formed from a CES combination of goods produced in each of the regions. The labour input is formed as a CES combination of eight different types of occupation.

Figure 3.2 **Production technology in MMRF–Green — all industries other than electricity supply**



As shown in figure 3.3, production in the ‘electricity supply’ industry is treated differently from production in the other sectors. Electricity supply industries in each State are allowed to substitute power sourced from different generators (electricity–black coal, electricity–brown coal, electricity–gas, electricity–oil products and electricity–other (mainly hydro)). Substitution between generators is price induced and represented by a CES production function. The electricity supply industry distributes electricity to industries and final users. The generator industries sell to only the electricity supply industry (although in some States they can also sell to specific aluminium and alumina refineries/smelters). The only inputs to the electricity supply industry are electricity generated by different energy sources. Electricity supply does not use primary factors or other materials and services.

Figure 3.3 **Production technology in MMRF–Green — electricity supply industry**

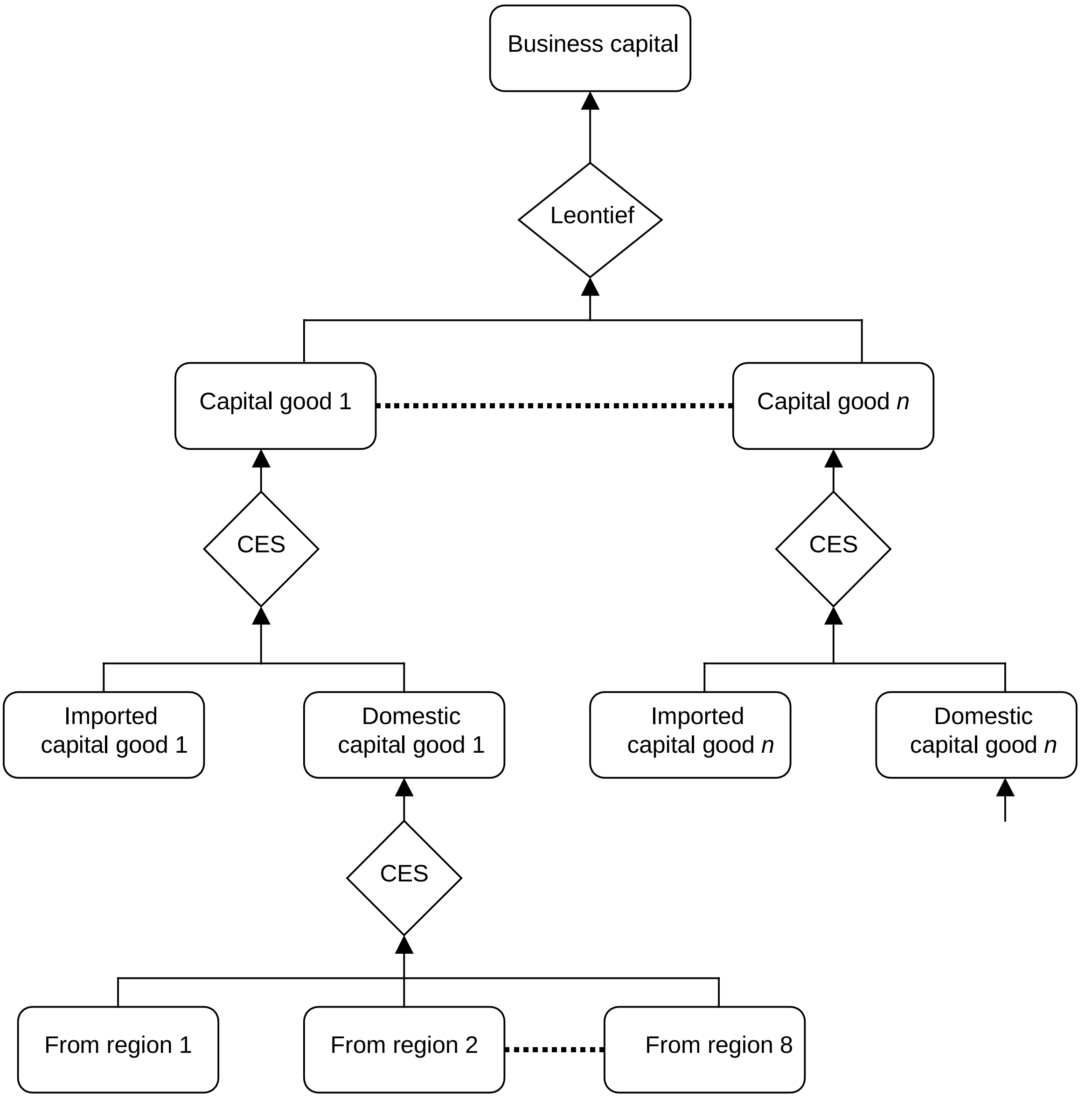


3.1.3.2 Capital creation and accumulation

MMRF–Green captures the formation of fixed capital by including industry-specific producers of capital goods in each region that are distinct from consumption goods. Capital producers choose the combination of inputs that will minimise their costs subject to the production technologies used. The production of capital uses both domestically produced and imported commodities as inputs (figure 3.4). Primary factors are not used directly as inputs into the production of capital; however, they are captured indirectly in ‘construction services’. The capital producer’s cost minimisation problem is represented using a three-level nested production structure. At the highest level, commodity composites representing individual goods are combined in fixed proportions to produce industry-specific capital. The commodity composites are formed in the second level from CES combinations of domestic and imported goods. At the lowest level, each domestic good used as an input is represented as a CES combination of that good from all domestic regions.

The demand for capital depends on the type of analysis being performed. Comparative-static analysis is possible for either the short run or long run (considered to be one to two years and more than five years, respectively). In the short run, industry stocks of capital are assumed to be fixed; therefore, capital stocks in regional industries and national aggregate investment are exogenously given. The distribution of aggregate investment between industries in each region is based on the relative rates of return on capital. In the long run, the aggregate capital stock is assumed to adjust to maintain an exogenously set rate of return for the whole economy. This is consistent with assuming that the supply of investment is perfectly elastic or that the capital market is open to international investors.

Figure 3.4 **Creation of capital goods in MMRF–Green**



For dynamic simulations, MMRF–Green uses a standard equation that assumes a one year lag between investment and capital accumulation, and other equations representing the relationship between year-to-year capital growth and rate of return expectations. Capital growth in each year, instead of being limited by rising per unit costs, is assumed to be limited by investors' perception of risk. Investors are willing to allow the rate of capital growth in an industry sector to move above its historically normal rate of capital growth only if they expect higher rates of return. The expected rates of return are treated as either static or forward looking. Under the static approach, only current rentals and asset prices are taken into account by investors when forming their expectations about rates of return. With forward looking (rational) expectations, investors are assumed to correctly anticipate actual rates of return.

3.1.4 Government

In MMRF–Green, governments affect the economy by purchasing goods and services, collecting taxes, receiving revenue from government-owned assets, and making transfer payments. Three options are available for setting both regional government and Commonwealth Government demands for goods and services. They are set endogenously by specifying a rule, endogenously as an instrument that achieves an exogenously determined target, or exogenously. Government revenue categories comprise taxes (income, sales and excise), tariffs on international imports, and income from government-owned assets. Transfers can be made from governments to households and from the Commonwealth Government to regional governments.

Commonwealth Government policy and the macroeconomic environment are determined exogenously. Government intervention in markets is modelled as an *ad valorem* sales tax on the goods or services in the market being targeted. Table 4.7 provides details of the taxes modelled.

3.1.5 Trade and financial flows

MMRF–Green does not explicitly model other world zones. International flows of goods and services are captured with export demand curves and import supply curves for each region. Domestic agents are assumed to face a perfectly elastic supply curve for imported commodities; therefore, changes in demand do not affect prices (that is, the prices of imports are exogenous). Exports are divided into two groups of commodities — traditional exports (agriculture and mining) and non-traditional exports — to account for large and small shares of total sales respectively. Exporters for both groups of commodities face downward-sloping constant elasticity demand functions.

An Armington specification (Armington 1969) is adopted for overseas trade and goods and services traded across regions. Goods and services produced in each region are therefore imperfect substitutes for the same goods and services either produced in other regions or imported from overseas. It is also assumed that the Commonwealth Government adjusts macroeconomic policies to ensure a balance of trade target. This assumption is modelled by making changes in investment and consumption proportional to changes in aggregate domestic expenditure. The implications for the way in which trade is modelled are discussed further in section 4.5. Both import and export trade elasticities are derived as weighted averages of the elasticities for the 115 commodities used in the MONASH model.

3.1.6 Monetary sector

MMRF–Green models only 'real' economic variables, so it does not contain a monetary sector.

3.1.7 Labour market

At the national level, the supply of labour is determined by either demographic factors or labour demand. The demand for labour in each region's industry sectors is derived from the producer's problem of choosing the least cost combination of occupation-specific labour inputs. Labour can move across regions to take advantage of regional employment opportunities. The model allows for regional excesses in the supply of labour. The three key variables affecting the treatment of regional labour markets are regional labour supply, unemployment rates and regional wage differentials. The model allows any two of these to be set exogenously, thereby determining the third.

When comparative static analysis is used, policy shocks are assumed to either produce an instantaneous adjustment in the national real wage rate while aggregate employment is fixed, or produce an instantaneous adjustment to aggregate employment while the national real wage rate is fixed. In dynamic simulations, real wages are assumed to be inflexible in the short run, but flexible in the long run.

3.1.8 Population growth

Regional population is determined by natural population growth, foreign migration and interregional relationships. Regional population is set either exogenously with one endogenous regional labour market variable (unemployment, participation rates or wage relativities) or endogenously with exogenous setting of all regional labour market variables.

3.1.9 Technical change

MMRF–Green allows for changes in the household's preferences for commodities, and changes in technology used in each industry to produce commodities.

Assumptions about technical change are applied at two levels. Annual rates of annual technical change are specified for the usage of commodities as intermediate inputs per unit of production in all industries, and as inputs per unit of capital creation. There is also an annual rate of change specified for primary-factor (labour, capital and agricultural land) usage per unit of output. Both preferences and technical change are exogenously imposed on all sectors, using values produced by the MONASH single-region model and applying them uniformly across the regions. These are currently average values derived from historical simulations for the period 1986-87 to 1996-97. Technical change is endogenous for the abatement of non-combustion GHG emissions in response to a carbon penalty.

3.1.10 Other features relevant to GHG control policy

MMRF–Green uses an energy and GHG module to account for emissions from:

- 37 industry sectors;
- a residential sector;
- eight States (or 57 sub-States); and
- five activities: four covering emissions from the combustion of black coal, brown coal, natural gas and petroleum products, and a single activity covering emissions from fugitive and noncombustion agricultural sources.

The commodities and GHGs covered are presented in table C.1 (appendix C). Emissions covered comprise carbon dioxide equivalents of all GHGs accounted for in the National Greenhouse Gas Inventory. Categories of emitting activities include the combustion of black coal, brown coal, natural gas and petrol, and noncombustion activities. Fuel combustion emissions are assumed to be directly proportional to fuel use. The model does not allow for inventions that may reduce the amount of emissions per unit of fuel used, but it does allow for input-saving technical progress, which is imposed exogenously. The main opportunity for emission reductions is assumed to be through price-induced substitution. The degree of input substitution in response to changes in relative prices depends on the industry sector. Input substitution is assumed to be strong for the electricity supply sector, but weak for other sectors using energy–intensive commodities.

Activity emissions from noncombustion sources such as fugitives, agriculture and other services are assumed to be directly proportional to the output of industries in which they occur. Emission abatement policies are modelled by relating the amount of abatement directly to the price or level of the policy instrument (emission permits or a carbon tax, for example). This relationship is based on constants of proportionality that are derived from point estimates of the amount of abatement likely at different tax levels. The marginal effect of abatement policy is assumed to increase the use of other inputs by the value of the tax avoided. To determine the amount of carbon sequestered by the forestry sector, it is assumed to be related to forestry activity as a whole, including logging.

3.1.11 Data

MMRF–Green uses a multi-regional input–output table generated from a disaggregation of the national input–output table used in the MONASH model. Published regional data from the Australian Bureau of Statistics are used for government revenue and expenditure, demographics, employment and the labour force. The MONASH database also provides values for primary factor and domestic–import elasticities of substitution. The disaggregation of industry sectors into subregions is achieved using base year data for the value added by each industry in each subregion.

3.2 MM600+

3.2.1 Structural overview

MM600+ is a single zone, multi-region, multi-sector model of the Australian economy. Details of the model are available in Murphy (2000). The results for the Australian national economy can be disaggregated into eight States and Territories or 23 regions. The economic agents recognised include producers, consumers, a government, and foreign purchasers and sellers. Consumers are represented by a household, and industry is disaggregated into 108 different sectors producing 672 products that are individually identified.

MM600+ is a comparative static model that specifically analyses the economy in the long run. However, short run analyses have been done for the Australian Consumer and Competition Commission based on its price exploitation guidelines.

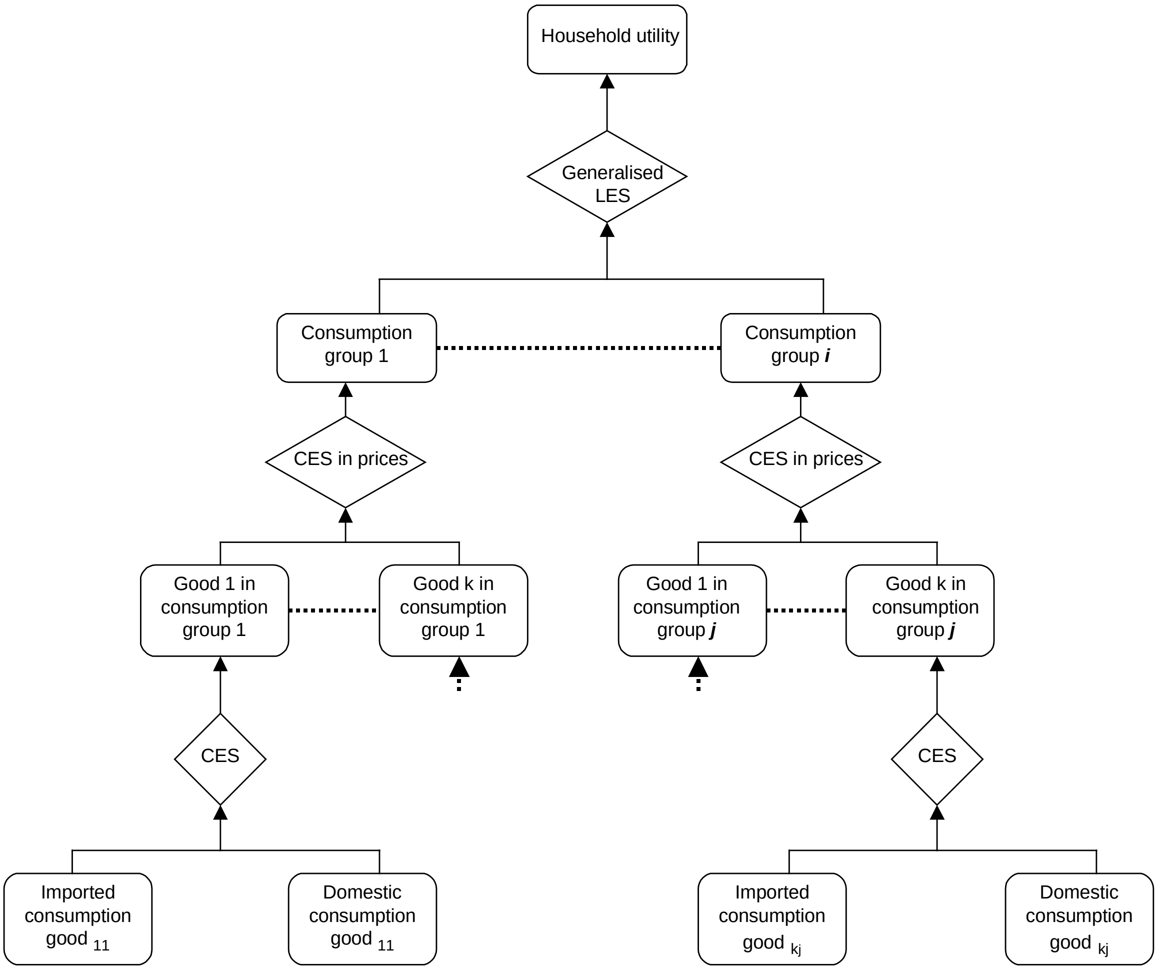
3.2.2 Households

The representative household is assumed to maximise utility subject to a budget constraint.

3.2.2.1 Consumption

MM600+ allows the representative household to substitute between and within 18 broad consumption groups (figure 3.5). The demand system that achieves this high level of substitution possibilities is obtained from an indirect utility function derived from a generalised linear expenditure system (LES). Consumption for each good is divided into both essential and non-essential components. A two-level approach captures the substitution within each of the broad consumption groups at the lowest level, while allowing substitution between the consumption groups at the top level. The within-group substitution is modelled by replacing group prices within the indirect utility function with CES price indexes for the particular group. Total expenditure on consumption goods and services is determined by household after-tax income.

Figure 3.5 **Household demand in MM600+**



3.2.2.2 Savings

Household after-tax income includes property income that is modelled as a return on a given quantity of locally owned capital. This means that changes in total capital are fully reflected in the foreign-owned portion. Holding the level of savings fixed avoids the problem in a long run model whereby an increase in savings to boost long run consumption is not recognised as involving a sacrifice of short run consumption.

3.2.2.3 Income

Household income comprises after-tax labour earnings and returns on capital.

3.2.3 Firms

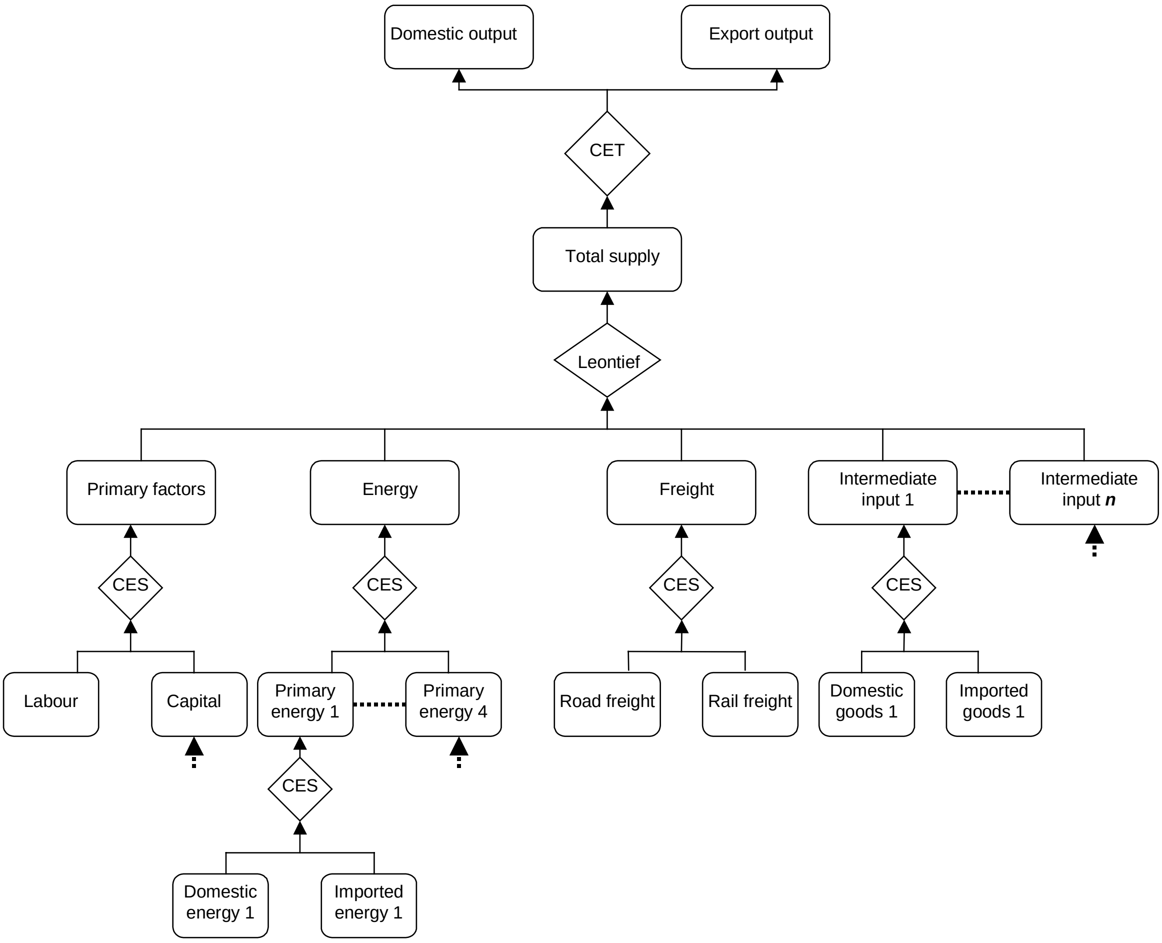
A representative firm in each industry chooses inputs and outputs to maximise profits subject to prices and a constant returns to scale (CRS) production technology.

3.2.3.1 Production

The representative firm in each industry sector produces output using the production structure shown in figure 3.6.

The firm is assumed to choose the profit-maximising combination of inputs and outputs. Total supply is a Leontief combination of a primary factor bundle, an energy bundle, a freight bundle and all other intermediate inputs. The primary factor bundle is a CES combination of labour and capital. The energy bundle comprises a CES combination of primary energy inputs (black coal, brown coal, natural gas and liquid petroleum gas). Petroleum products are not included in the energy bundle because they are used in transport mainly and thus there is limited opportunity for substitution with industrial fuels. The freight bundle is formed from a CES combination of road freight and rail freight. Each of the intermediate inputs is a CES combination of an imported good and domestic good. At the top of the production structure, a constant elasticity of transformation (CET) function determines the amount from the total supply of a good produced that will go to the domestic and export markets.

Figure 3.6 **Production technology in MM600+**



3.2.3.2 Capital creation and accumulation

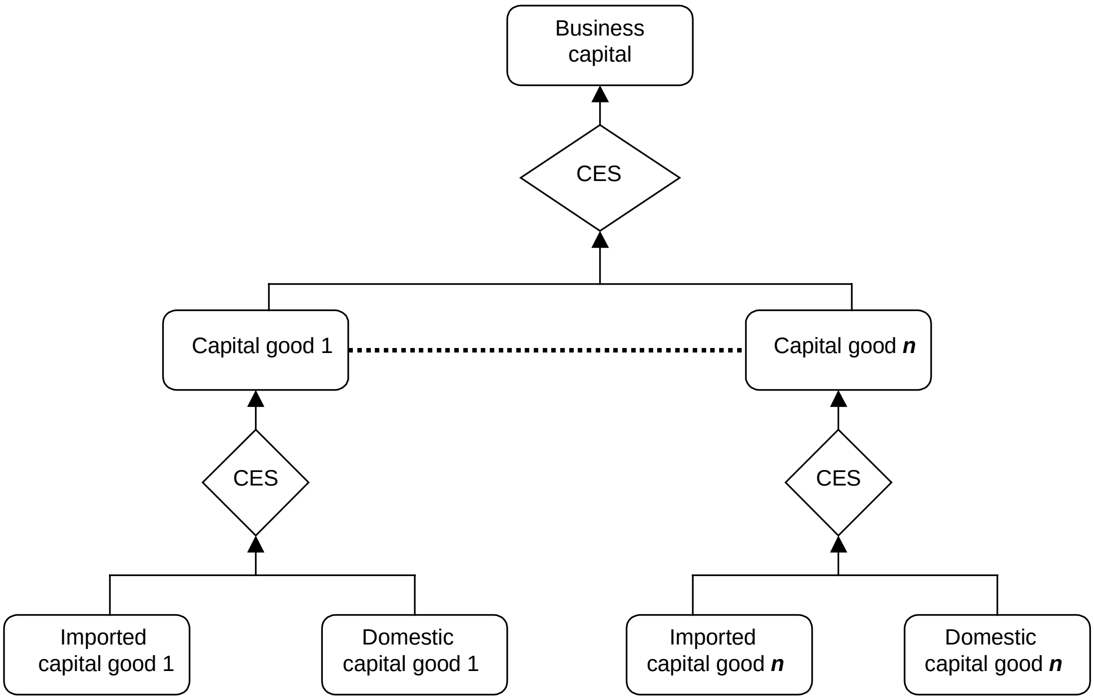
A single producer of business capital supplies each industry sector. Business capital is formed from a CES combination of different types of capital input. The capital inputs, in turn, are CES combinations of imported and domestic capital goods (figure 3.7). Demand by the capital producer for each type of capital is based on its user cost and calculated by applying a required rate of return and a capital-specific depreciation rate to the price of new investment.

The representative firm in each industry chooses a size that minimises unit costs. The long run nature of the model means the capital stock in each industry is assumed to fully adjust to any economic shock; in practice this may take five to ten years.

3.2.4 Government

The government sector consolidates all three levels of government. In the long run the government's budget is assumed to be in balance. The rate of tax on labour income is used as the adjustment mechanism (referred to as a 'swing fiscal policy instrument') that achieves this balance. MM600+ has a detailed breakdown of taxes, distinguishing 24 different indirect taxes on industry production and products, (table 4.7).

Figure 3.7 **Creation of capital goods in MM600+**



3.2.5 Trade and financial flows

Foreign-owned capital is determined as the difference between the total capital stock chosen by producers and the fixed amount of capital that is locally owned. The trade balance is set equal to the cost of servicing payments on foreign owned capital, and the model determines the required real exchange rate. The imposition of an external sector trade balance condition allows trade to be determined through foreign export supply elasticities and import demand elasticities. In the modelling of export demand and import supply, while domestic firms are assumed to face foreign demand functions with constant price elasticities, imports are fixed at world prices.

In the modelling of import demand, an Armington structure is imposed on imported commodities that both compete with domestically produced commodities and are destined to be used as recurrent inputs, business investment or other components of final demand.

In the modelling of export supply, an elasticity of transformation is set that determines the supply of commodities to the export and domestic markets. The implications for the way in which trade is modelled is discussed in section 4.5.

3.2.6 Monetary sector

The monetary sector is not modelled. Wages are used as the numeraire.

3.2.7 Labour market

The labour market is assumed to be in equilibrium in the long run, with the level of total employment set exogenously.

3.2.8 Population growth

MM600+ models long run equilibrium in a base year, which is currently 1998-99.

3.2.9 Technical change

Technical change is represented in the model as labour efficiency. The level of labour efficiency in each industry is for the base year 1998-99. Labour efficiency can be varied for any industry in model simulations.

3.2.10 Other features relevant to GHG control policy

MM600+ identifies carbon dioxide emissions from black coal, brown coal, liquid petroleum gas, natural gas, petrol, diesel fuel, aviation turbine fuel and aviation gasoline. Given that the model is so detailed in its disaggregation of industry sectors and products, a table showing all the products covered is not presented here. However, a breakdown of industry sectors and products releasing carbon dioxide on combustion that are covered by the model is provided in appendix C (table C.2).

Firms are allowed to substitute between different forms of primary energy, which comprise black coal, brown coal, liquid petroleum gas, and natural gas. They can also respond to changing energy prices affecting the demand for diesel fuel by substituting between road and rail freight transport. The model distinguishes between freight and passenger transport: freight transport includes road, rail, pipeline, water and air, while passenger transport includes bus, taxi, rail, water and air.

The model accounts for differences in diesel fuel tax across qualifying and non-qualifying road use, rail and marine transport, agriculture and fishing use, mining use, and other non-transport use.

Household responses to changes in energy prices arising from GHG control policy are captured through several specific consumption categories:

- substitution between different types of household energy within the ‘gas, electricity and fuel’ consumption group;
- substitution between different forms of passenger transport within the ‘fares’ consumption group; and
- substitution between expenditure on running a motor vehicle (‘operation of motor vehicles’ consumption group) and other consumption groups.

GHG control policy is modelled as being budget neutral. Any effects on the government budget (for example, via revenue from a carbon dioxide tax) are balanced by an adjustment to the rate of labour income tax. The application of the goods and services tax (10 per cent) on top of GHG taxes levied is also captured.

3.2.11 Data

MM600+ uses an unpublished special series of input–output tables from the Australian Bureau of Statistics, which contains information on 107 industries producing about 1000 products, as well as extra detail on indirect taxes. Currently, the 1993-94 database is used; however, the 1996-97 database is due for release towards the end of 2000. The Australian Bureau of Statistics data are adjusted to ensure economic concepts are correctly measured.

3.3 GTEM

3.3.1 Structural overview

GTEM is a multi-sector, multi-zone, global model. Various parts of its structure are described in ABARE/DFAT (1995), ABARE (1996), Brown et al. (1999) and Polidano et al. (2000). It divides the world economy into a maximum of 45 zones representing groups of countries and individual countries (including Australia). The economic agents represented in each zone comprise consumers, producers, investors and the government. Each zone can be disaggregated into a maximum of 50 different sectors. The model assumes that markets are perfectly competitive, and that economic agents engage in myopic decision making.

3.3.2 Households

A household, also referred to as a ‘super household’, is modelled for each zone. This household is assumed to reflect the preferences of society in each zone, and decides how national income is allocated between expenditure on private and government goods and services, and savings.

Expenditure on consumption and savings must equal income in each period. The household effectively acts as an ‘income pool’ for each zone.

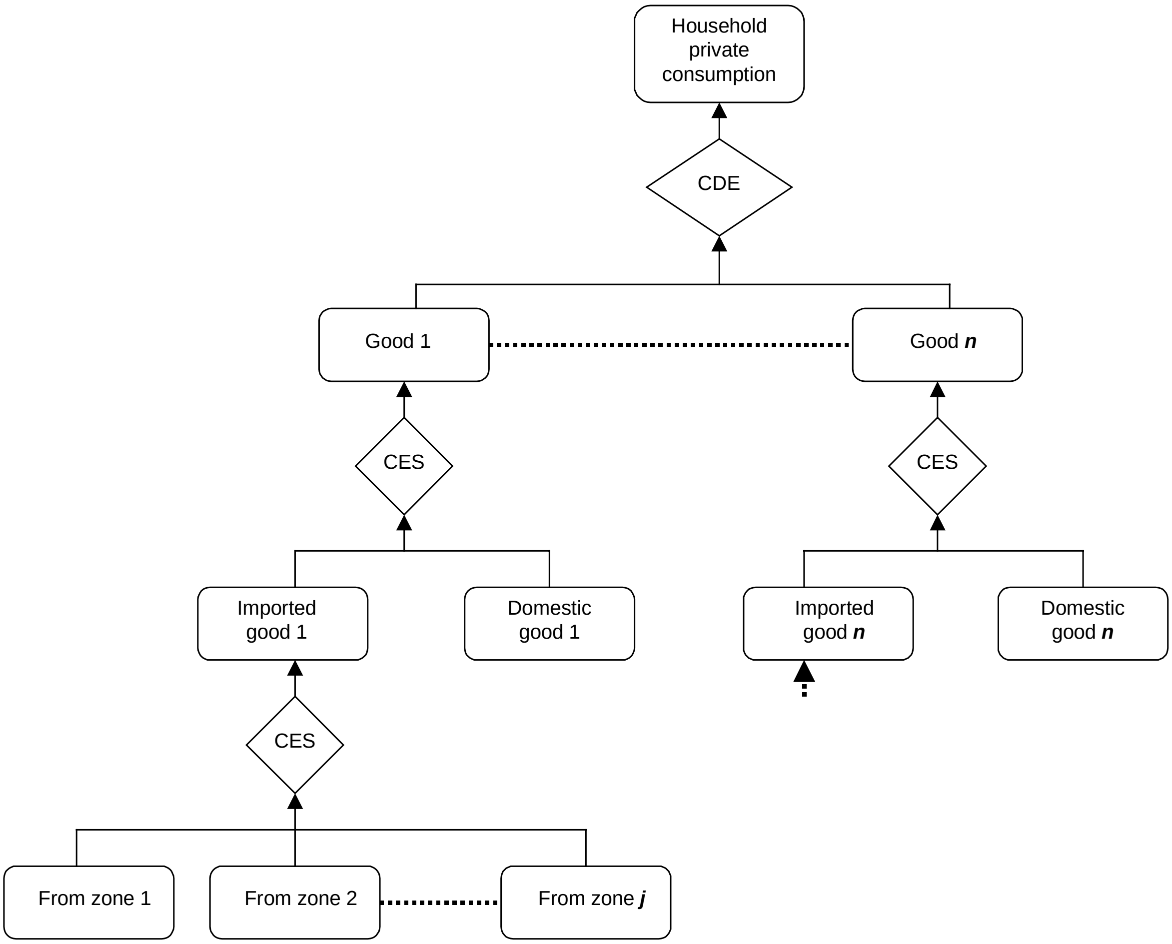
3.3.2.1 Consumption

The household’s share of total consumption expenditure (private and government) in each period is equal to the difference between household income and savings. Consumption expenditure is divided between private and government expenditure by an exogenously given ratio. The allocation of private consumption expenditure among goods and services is the result of the household maximising current period utility subject to an income constraint. As shown in figure 3.8, this myopic behaviour is modelled for the household in each zone using a constant differences of elasticities (CDE) expenditure function (see appendix A). A feature of the CDE functional form is that it allows marginal shares of expenditure on goods and services to vary as total expenditure changes. Figure 3.8 identifies household demand for each commodity by zone-specific source. This can be justified as representing the structure of household demand in GTEM. However, in the actual implementation of the model, no single user distinguishes imported commodities by source; rather, the zone does as a whole (or the zonal importer). This means that the preference of all agents for the sources of imports supply is identical.

3.3.2.2 Savings

The division of income into consumption and savings is treated in two ways in GTEM. First, a life cycle model (detailed in ABARE/DFAT 1995) determines the share of national savings attributable to each age group of the population. Savings behaviour and consumption are connected through a demographic module. The life cycle hypothesis of savings assumes that levels of saving change as people move through different stages of life. A life cycle model determines age-specific savings rates for the population of each zone, which are then combined with outputs from a demographic module to determine the savings rate for the household. The second treatment assumes that the zonal household has a Cobb-Douglas preference for private consumption, government consumption and savings. This means that the shares of national income going to private consumption, government consumption and savings remain fixed over time.

Figure 3.8 **Household demand in GTEM**



3.3.2.3 *Income*

In GTEM, households receive all factor incomes (net of taxes) and all tax revenue and net interzonal income transfers. These incomes include foreign income (payments) on international lending (borrowing) and income (payments) resulting from the sales (purchases) of international emission quota. The net income comprising these receipts and all net intergenerational income transfers is allocated between private and government consumption and savings each period.

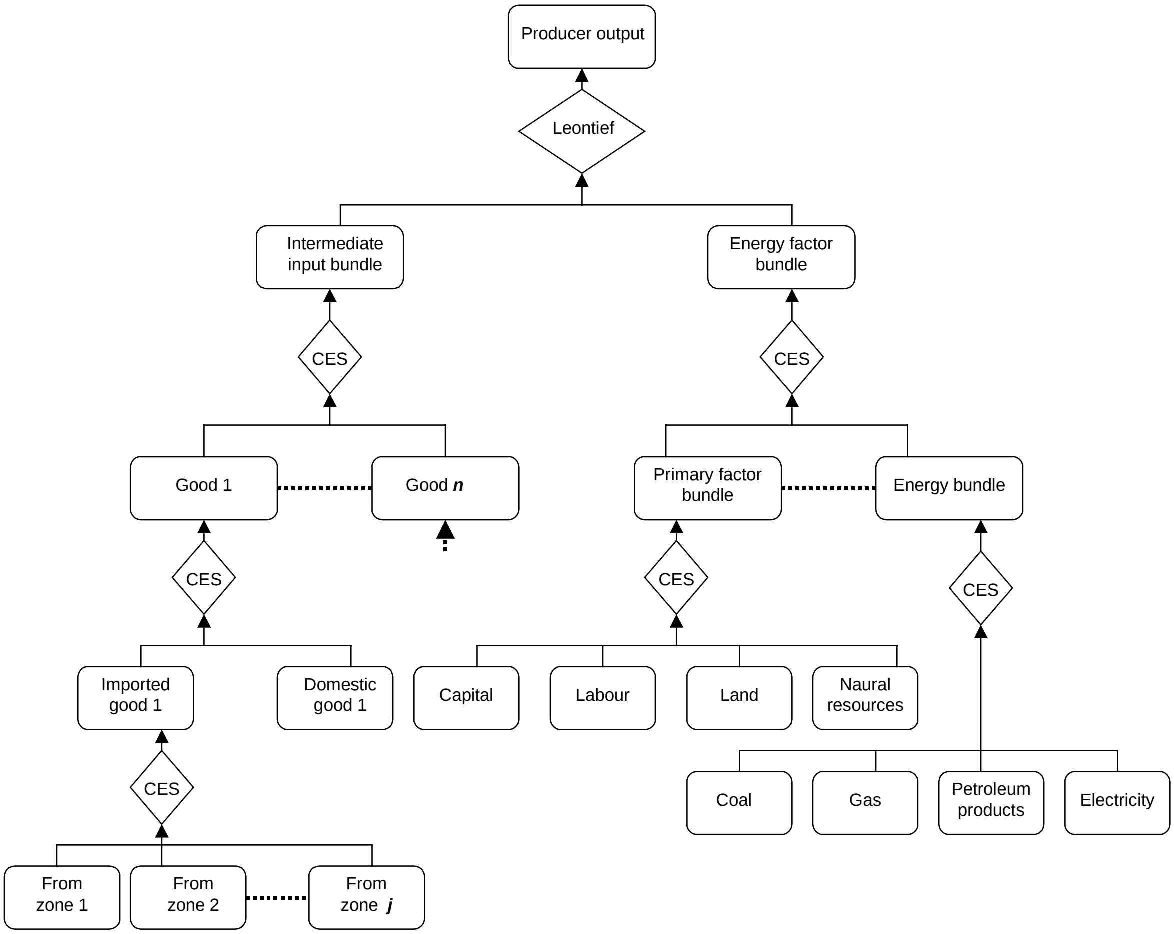
3.3.3 Firms

A representative firm in each industry sector is assumed to use CRS technologies, and to choose input combinations that minimise costs subject to given input prices.

3.3.3.1 Production

In GTEM, production in all industries (except electricity, and iron and steel) is assumed to involve only one technology that combines inputs in fixed proportions (figure 3.9).

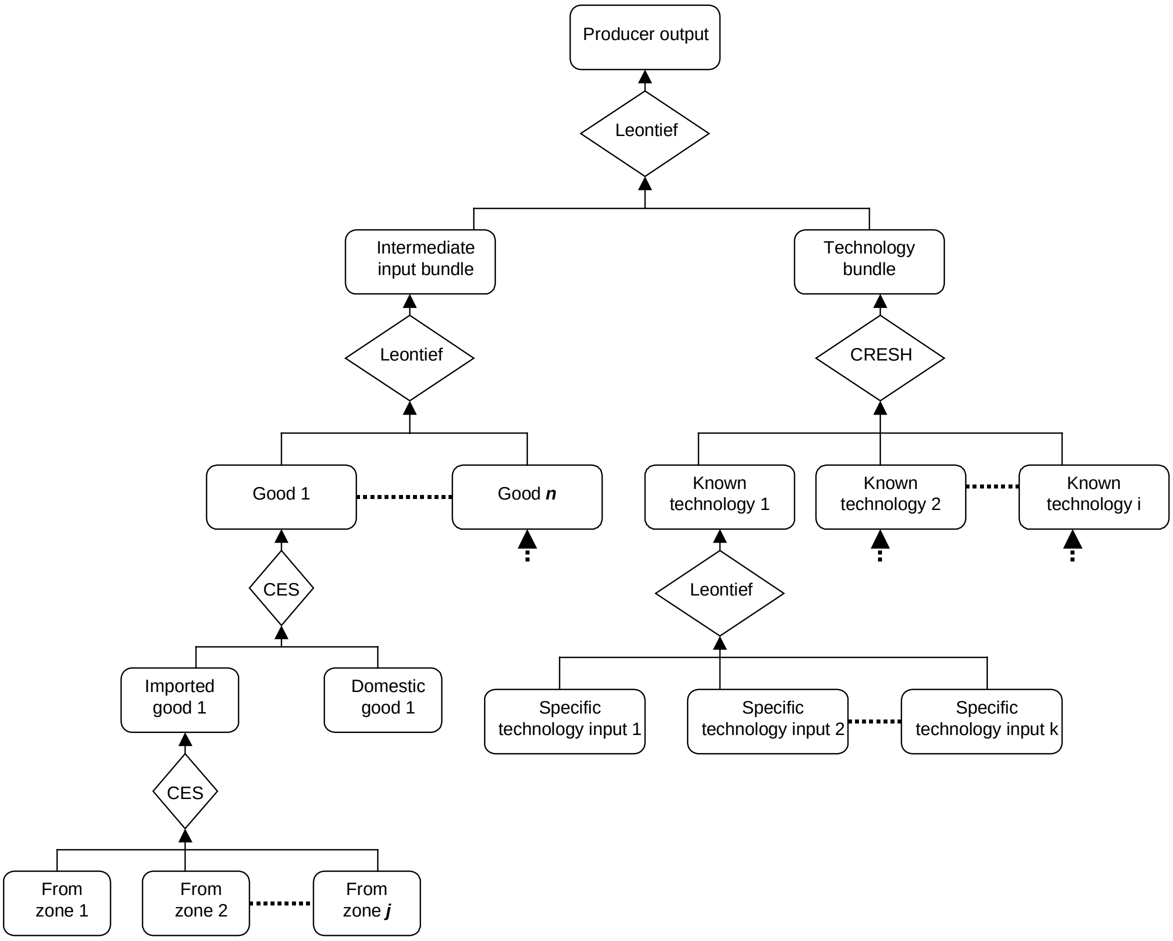
Figure 3.9 **Production technology in GTEM — all industries (excluding electricity, and iron and steel)**



In these general industries, a Leontief technology is used to produce output from an intermediate-input bundle and an energy-factor bundle. The intermediate inputs are assumed to involve Leontief technologies. The energy-factor bundle is formed by a CES technology that uses an energy bundle and a primary-factor bundle as inputs. The energy-input bundle is obtained from a least cost combination of four energy commodities (coal, gas, petroleum products and electricity) using CES technology. CES technology is also used for the primary-factor bundle, which is obtained from a least cost combination of the primary factors (capital, labour, land and natural resources). All industries use capital and labour, while agriculture is the only sector that uses land, and resource sectors (coal mining, oil and gas extraction, other minerals and forestry and fishing) use natural resources.

A 'technological tree' (branched) approach, instead of the usual nesting procedure, is used to represent production in the electricity, and iron and steel industries (figure 3.10).

Figure 3.10 **Production technology in GTEM — electricity, and iron and steel industries**



Production technology in these sectors is modelled using a technology bundle — that is, a combination of a discrete number of known production techniques (a range of real world technologies) that generate a homogeneous output in each of the two sectors. Industries can substitute between known technologies in response to changes in relative costs. Each specified technology uses inputs in fixed proportions (the inputs being consistent with known technologies). The range of technologies that comprise an industry's technology bundle are represented by a constant ratio of elasticities of substitution, homothetic (CRESH) production function (see appendix A). This formulation relaxes the assumption implied by CES functions that the elasticity of substitution between all pairs of inputs must be the same. Output is given by a Leontief production function combining the technology bundle and an intermediate-input bundle. The intermediate-input bundle, in turn, is a fixed proportion combination of commodities not in the technology bundle.

3.3.3.2 Capital creation and accumulation

The allocation of investible funds across zones is based on investment in a zone being an increasing function of the real rate of return in the next year and the growth rate of real gross domestic product. Rates of return for each zone are assumed to equalise in the long run. Investment is allocated within a zone to ensure that the rates of return on physical capital in all sectors are equal.

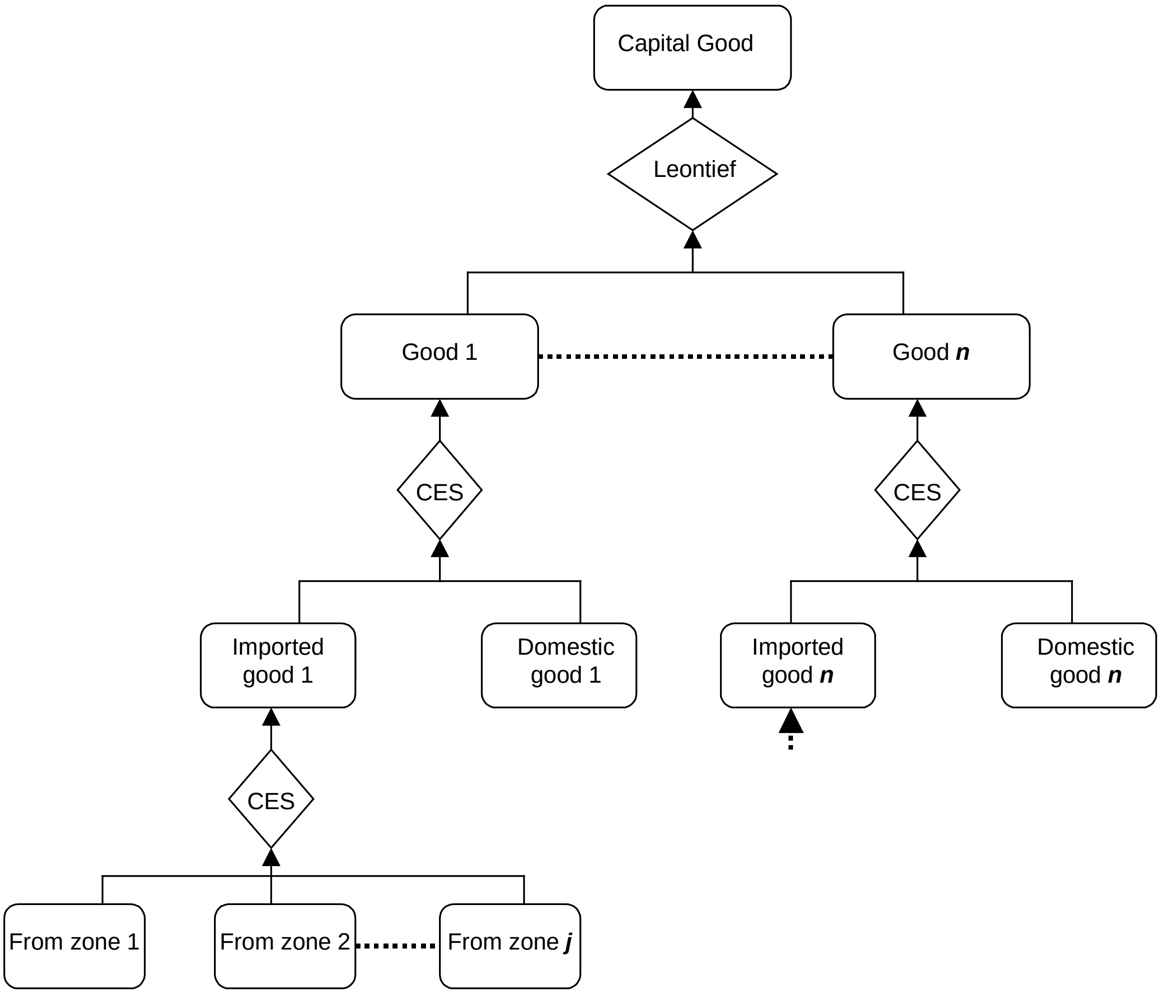
The resulting demand for investment goods in each zone is met locally. One of the production sectors (the capital goods industry) in each zone specialises in meeting this demand. This sector simply assembles various composite commodities into capital goods using a Leontief production function without using any primary factors (figure 3.11). The input demands of the capital goods sector are then allocated to various domestic and foreign sources using the standard Armington assumption.

The accumulation of capital stock takes place over time. It takes one period to install new capital stock. Therefore, net investment undertaken over the current period leads to an accumulation of the capital stock in the next period.

3.3.4 Government

All incomes and expenditures of the government form part of the zonal household incomes and expenditures. This means that all incomes of the government (tax revenues from instruments listed in table 4.7) are included in household income, and that the household also funds the expenditure of the government (implicitly via an income tax levied to keep the government budget in balance). The zonal household, therefore, simultaneously chooses private consumption, government consumption and saving of the gross national income. The allocation of the government consumption expenditure across goods and services is modelled using a Cobb-Douglas function. This results in fixed shares of government spending on goods and services over time.

Figure 3.11 **Creation of capital goods in GTEM**



3.3.5 Trade and financial flows

Bilateral trade flows are modelled for all goods and services between all zones. An equilibrium condition requires that the amount of a good exported from each zone must equal the total imports of that good by all other zones. An Armington preference structure is assumed, so a good or service produced in another zone is an imperfect substitute for the same one produced in the consumer's zone. An international transport industry is specified to capture the cost of transporting goods between zones, and it is included in each zone's cost of imports.

In the case of investment, Walras's law clears the global financial market. Equality between global investment and global savings is not explicitly forced, but is achieved as an equilibrium outcome. (This property of the model is always used as a routine check that the experiment has been correctly implemented and that the model has converged to an equilibrium solution.) The allocation of investment across zones does not assume an equilibrating mechanism. It allows the current rates of return to differ across zones, thus allowing imperfections in the international capital market.

Any imbalances in the current account each period are compensated for by changes to the capital account to maintain the balance of payments. This compensatory process is achieved by a flexible exchange rate, which is the price of converting a zone’s currency into global currency. Movements in the exchange rate affect the zone’s producers of exports and import substitutes, as well as the international transfers of interest on financial assets. The implications for the way in which trade is modelled are discussed in section 4.5.

3.3.6 Monetary sector

Although GTEM does not explicitly model a monetary sector, the monetary policy in each zone always targets some sort of price index (which determines the zonal numeraire). In a standard GTEM run, monetary policy in each zone is assumed to target the zonal consumer price index. As a result, changes in the nominal exchange rates between any two currencies reflect the underlying relative change in the consumer price indexes of the two zones. They thus reflect the changes in the real exchange rates between the numeraire commodities of the zones.

3.3.7 Labour market

Unemployment in each zone is assumed to remain at its natural rate, leading the labour market to remain at full employment at all times. To achieve full employment, real wages adjust fully to compensate for any changes in the demand for labour. This implies that policy changes are implemented in a way that allows the labour market plenty of time to adjust to the new conditions.

The supply of labour is determined by the model over time using a demographic module. It is assumed to grow at the same rate as the rate of growth of the working population. Wage rates can differ across zones because net migration between zones, while allowed for in GTEM, is not based on wage rates. Labour, however, is mobile across sectors within the same zone, and each sector is assumed to pay the same wage rate.

3.3.8 Population growth

Population growth for each zone is endogenously determined using equations for births, deaths and net migration on an age and gender basis, and the movement between age groups. The key relationship of the module is the link between the level of per person income and the rates of population growth. Key parameters for the relationship between per capita gross national product and both birth rates and life expectancy are econometrically estimated for different income groups. Each zone's birth rate and life expectancy are a weighted average of the estimates for its low, middle and high income groups. The weights are determined by the relative difference between a zone's income in each of these three groups, and the level of income used to classify the group for all zones.

Global net migration is restricted to zero for each age cohort and gender. The net migration rate of each zone for each age and sex is derived from the initial zonal net migration rate, subject to the global net migration rate for a sex and age being zero. This rate, together with the age- and sex-specific populations at the beginning of the period in each zone, generates the net migration of the zone. This migratory pattern is endogenous as far as the change in the population is dynamically endogenous. It does not, however, respond to changes in the economic incentives (such as changes in the difference in the real wage rates).

3.3.9 Technical change

Technical change is set exogenously for all industry sectors. Technical change leading to reductions in noncombustion GHG emissions is also modelled for relevant industries. The driver of this change is the size of the carbon penalty (amount of carbon emissions tax or the price of carbon permits) along with electricity and gas prices in some industries.

3.3.10 Other features relevant to GHG control policy (including AUSTEM)

GTEM accounts for emissions of carbon dioxide, methane and nitrous oxide. The commodities and GHGs covered are presented in appendix C (table C.3). Carbon dioxide emissions are linked to (a) activities that are directly related to the combustion of commodities (coal, petroleum and natural gas) and (b) noncombustion activities (fugitive emissions from oil and natural gas systems, emissions from aluminium production and emissions from cement manufacture). Carbon dioxide sequestration from afforestation and reforestation activities in Annex B zones are also included.

The model accounts for methane emissions from livestock production, paddy rice cultivation and fugitive emissions (coal mining, oil extraction and natural gas systems). It does not include emissions from burning agricultural residues or savannas, the disposal of solid waste, wastewater handling and waste incineration. (An explicit waste industry is not currently included.) Nitrous oxide emissions include those from the transport sector, chemical industries, livestock waste and nitrogenous fertilisers used in agricultural industries.

It follows from the structure of GTEM that industries can reduce emissions not only by reducing their activity levels, but also by energy substitution and/or by using different production practices or technologies. Inter-fuel substitution and the substitution between fuel and primary factors are captured by the energy-factor composite in the technology tree. An emission response function simulates the introduction of technologies or practices that reduce emissions from industries that emit methane, nitrous oxide and noncombustion carbon dioxide. The function applies only to industry sectors that can reduce their emissions without reducing inputs. It reflects each of these industry sectors' ability to reduce emissions per unit of output in response to emission costs. Adjustment is assumed to take time, so is modelled as a lagged process.

To improve analysis of the impacts of climate change policy on the Australian economy, there are plans to develop a dynamic CGE model of the Australian economy (AUSTEM) and link it to GTEM. AUSTEM will be based on the comparative static ORANI-E model. (Details of ORANI-E are available in McDougal 1993 and James 1996.) Proposed developments of AUSTEM include:

- incorporating stock flow dynamics in investment, labour force growth and population growth, similar to those employed in GTEM;
- using the 123 industry sectors in ORANI-E which include detailed representations of the fossil fuel, electricity, transport and agricultural sectors;
- improving the representation of the fossil fuel and electricity sectors by applying the technology bundle approach;
- allowing for inter-fuel and energy–capital substitution over a range of different technologies in the remaining sectors;
- using the detailed treatment of margins in ORANI-E;
- incorporating the eight occupations accounted for in ORANI-E;
- including a specific treatment of the government sector based on the detailed government accounts contained in ORANI-E; and
- incorporating a system of emission accounts that covers all the gases, sources and sinks mandated in the Kyoto Protocol.

3.3.11 Data

GTEM uses the GTAP 4.0e database, which is based on 1995 production and trade data. This database is substantially modified in areas such as the energy sector, and data on energy, emissions and population are added.

Emissions of carbon dioxide, methane and nitrous oxide are represented as carbon dioxide equivalents, using global warming potentials of 1, 21 and 310 respectively. Data on carbon dioxide emissions from fossil fuel combustion are sourced from the International Energy Agency. Obtaining data on noncombustion emissions is problematic, so relevant data are either estimated or compiled from the United Nations Framework Convention on Climate Change's (UNFCCC) national inventory figures for individual countries. Estimates are produced by multiplying output for each zone by an emission coefficient, representing the zone's emissions per unit of output. Data on emission coefficients are sourced from the Intergovernmental Panel on Climate Change (IPCC), the National Greenhouse Gas Inventory Committee or ABARE estimates. Output data are sourced from the International Energy Agency for coal production, the Food and Agriculture Organisation for agricultural production, the United Nations for cement production and the World Bureau of Metal Statistics for aluminium production. Emission response data are based on estimates for the US and Canadian industries and adjusted according to local conditions for each region.

3.4 G-Cubed

3.4.1 Structural overview

G-Cubed is a multi-sector, multi-zone, global model (see McKibbin and Wilcoxen 1999). The model divides the world into eight zones: the United States, Japan, Australia, the rest of the OECD, eastern Europe and the former Soviet Union, China, oil-exporting developing countries and other developing countries. The economic agents represented in the model are consumers, producers, financial markets and governments. Each zone has twelve industry sectors, a capital goods producer, a representative household, a financial sector and a government. G-Cubed assumes that consumers, producers and investors all engage, to some degree, in forward-looking optimising behaviour. It combines this rational-expectations behaviour with liquidity-constrained behaviour to reflect that some agents make their decisions by accounting for all future periods, while others are myopic.

3.4.2 Households

Household behaviour in each zone is captured using a model of a representative household. In each period households consume goods and services, supply labour and save; by doing so, they demand labour, consumer durables and residential housing. When making their decisions, households are assumed to maximise an intertemporal utility function while facing a lifetime budget constraint.

3.4.2.1 Consumption

Household total consumption expenditure is determined by combining two types of consumer behaviour. The first is forward-looking behaviour, whereby the consumer seeks to maximise the value of both their current and all future consumption subject to a private wealth constraint that comprises both human and financial wealth (where human wealth is defined as the expected present value of the future stream of after-tax income plus transfers). The second behaviour is myopic — that is, the consumer responds to a constraint imposed by liquidity in the current period and, therefore, bases each period's consumption spending on their after-tax income. This approach results in total consumption expenditure being the sum of a constant proportion of private wealth and a constant proportion of after-tax income.

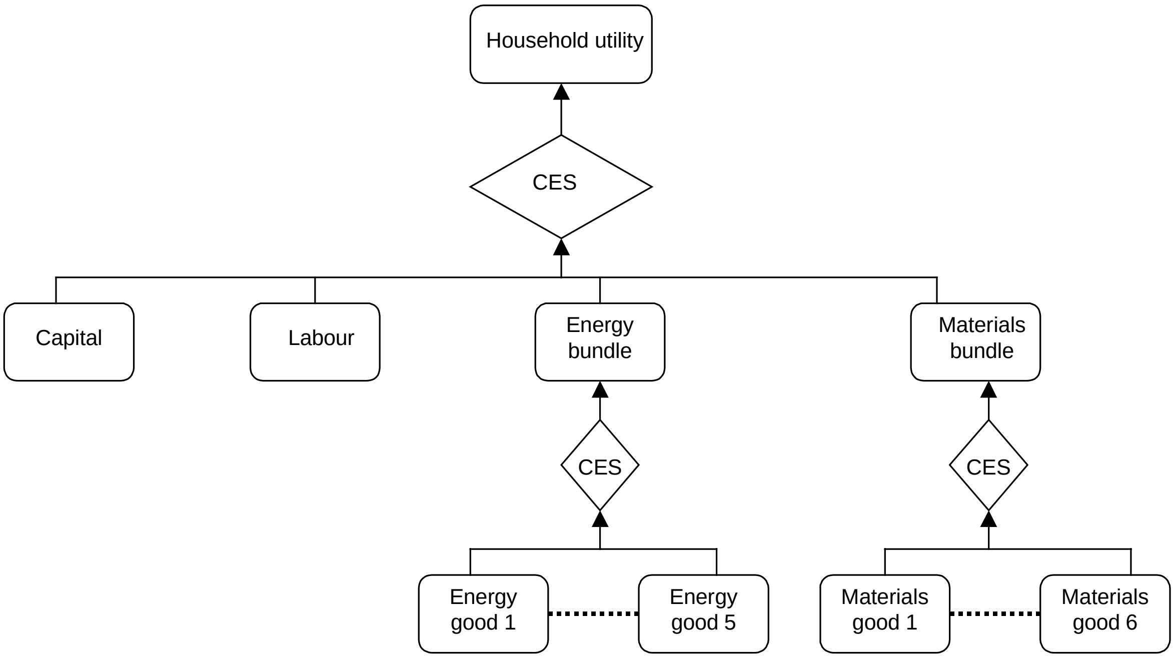
Total consumption expenditure is allocated across goods and services by a two-tier CES utility function (figure 3.12). The top tier allocates expenditure among capital services, labour services and two composite goods categories represented by energy and materials inputs. The second tier allocates the expenditure on the energy goods and materials goods composites among their respective components.

3.4.2.2 Savings

Households hold financial wealth in the form of real money balances, real government bonds that have been publicly issued, net holdings of claims against foreign residents, physical capital held in each sector, and holdings of emission permits.

Households invest in household capital (which comprises consumer durables and residential housing) and in return receive a flow of services. The demand for investment in capital is formulated as an intertemporal optimisation problem. As with firm investment, household investment is restrained by adjustment costs that are incurred when the capital stock changes. An accumulation equation ensures that household investment in capital satisfies the household's demand for capital services at all times.

Figure 3.12 **Household demand in G-Cubed**



3.4.2.3 Income

Households receive income from their supply of labour to firms and the government, their investment in financial assets, and transfers from the government. Households also receive imputed income from owning durables and housing.

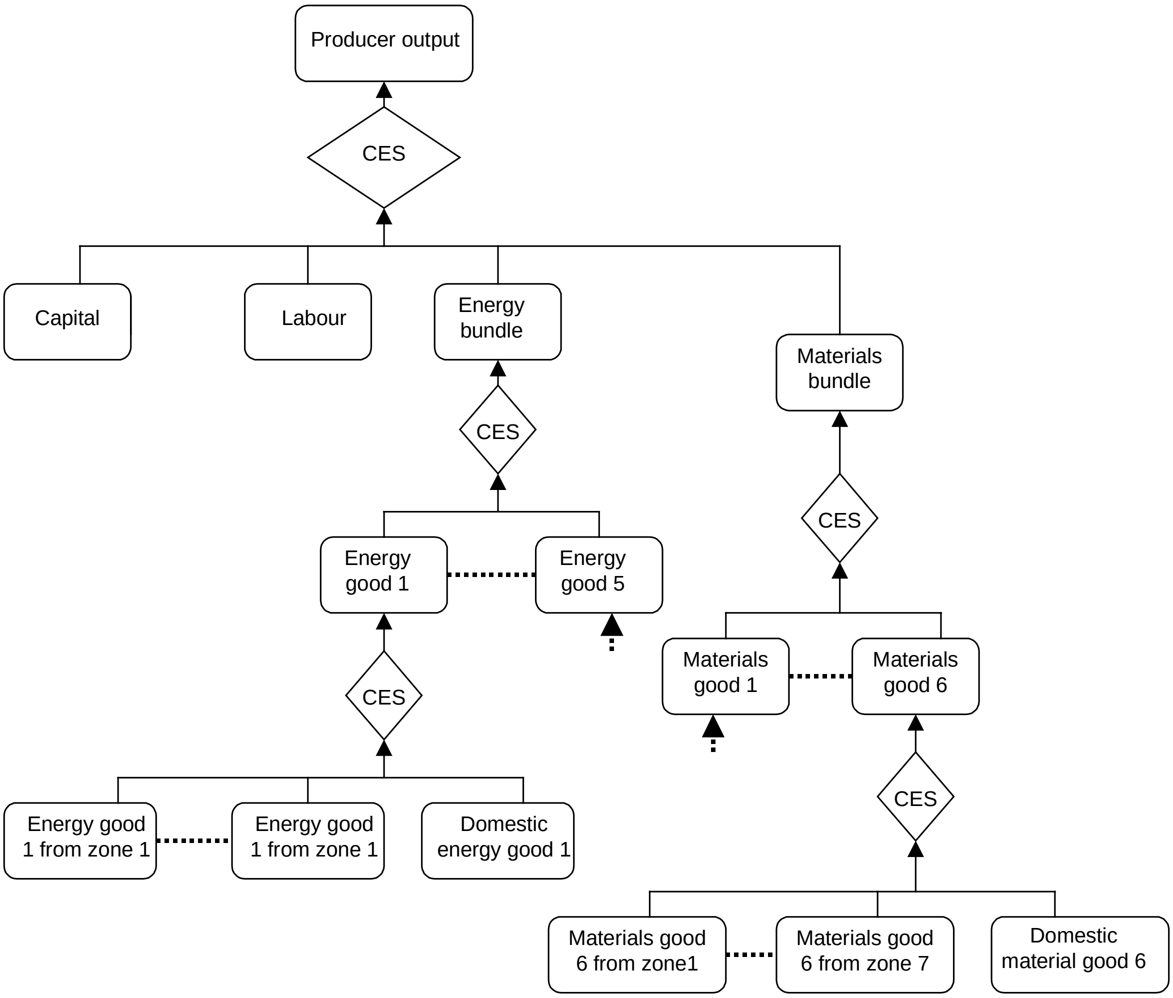
3.4.3 Firms

G-Cubed disaggregates each zone into twelve production sectors, and models a representative producer for each sector. The representative producer is assumed to be a price taker who chooses the levels of inputs and investment that maximise the firm's stock market value, subject to a production technology and a set of given prices.

3.4.3.1 Production

The optimisation model adopts a three-tier, nested production technology which is a CES function that combines capital, labour, energy and materials at the top tier to produce output (figure 3.13). If there is a natural resource that is specific to a particular sector (for example, coal reserves or agricultural land), then it too may be included in the production function at this level. At the second tier, inputs of both the energy and materials composites are formed from CES aggregates of goods and services. The energy composite includes output from electricity utilities, gas utilities, petroleum refining and crude oil and gas extraction. The lowest tier represents the production of goods and services purchased by the firm. These are CES aggregates of imported and domestic inputs. It is assumed that imported inputs for a given commodity are an imperfect substitute for domestic inputs, so an Armington structure is imposed. Further, products imported from all other zones are imperfect substitutes for each other.

Figure 3.13 **Production technology in G-Cubed**



3.4.3.2 *Capital creation and accumulation.*

The firm's stock of capital changes according to the rate of capital formation and the rate of geometric depreciation. The firm is assumed to incur adjustment costs; therefore, investment is subject to rising marginal costs of installation. The demand for investment goods is derived from the solution to the firm's intertemporal optimisation problem. It is formulated as a function of an after-tax, marginal version of Tobin's *q* and the firm's current cash flows.

Capital goods are supplied by a thirteenth industry, which combines labour and the outputs of other industry sectors to produce raw capital goods. The same nested CES production technology as that used in the other production sectors is adopted, along with the assumption of adjustment costs (figure 3.14).

Government spending is exogenously determined and is allocated among the inputs into goods and services in fixed proportions based on historical values. Categories of expenditure include the purchase of goods and services, interest payments on government debt, investment tax credits and transfers to households. Revenue is generated from taxes (see table 4.7) and sales of new government bonds. Taxes on externalities are also allowed.

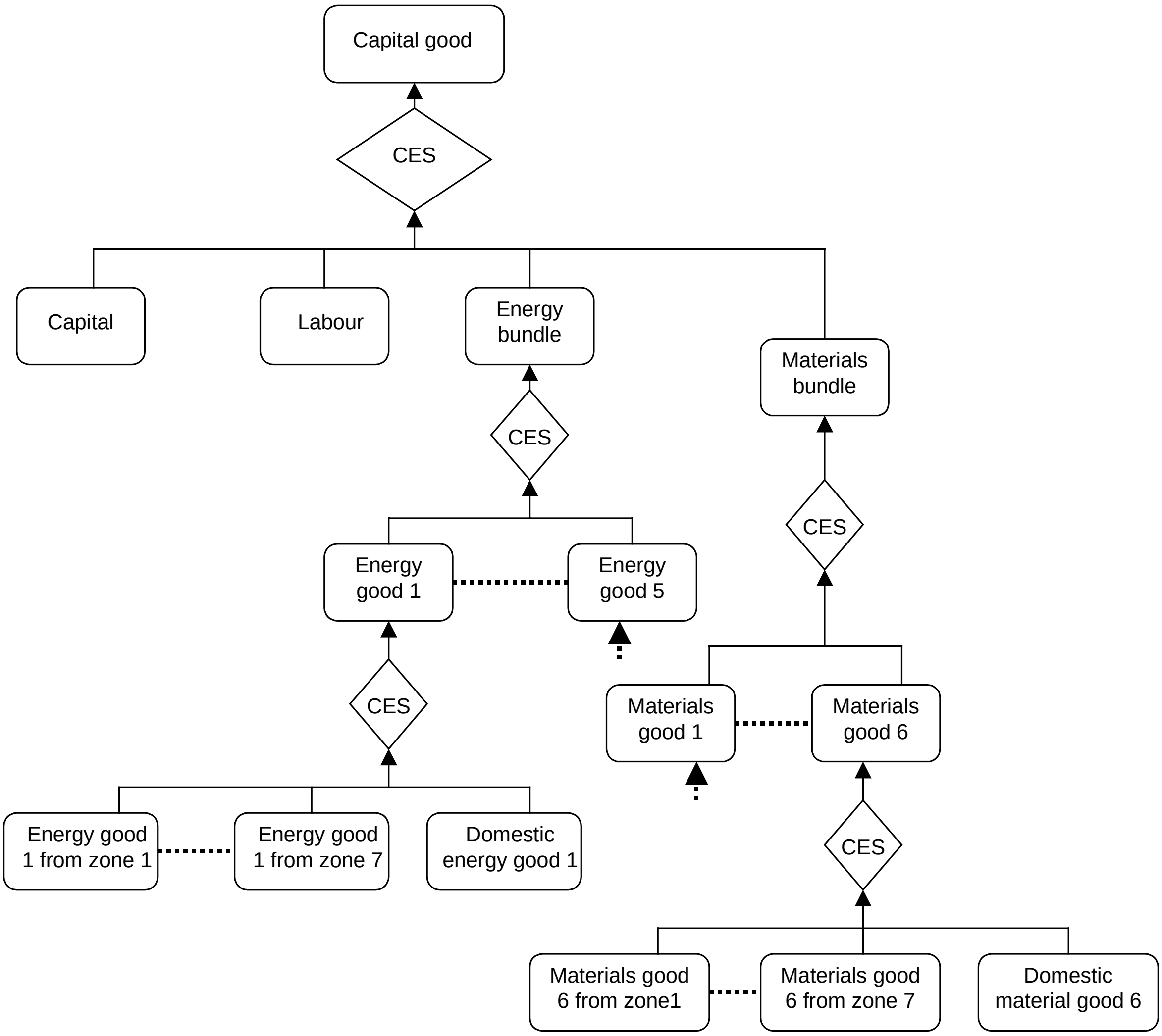
The government's budget deficit/surplus is the difference between revenues and expenditure. If deficits arise, then the government borrows to cover them by issuing bonds. The government faces an intertemporal budget constraint that requires the current level of public debt to equal the present value of all future budget surpluses. The time path of future budget surpluses is obtained by assuming in each period that an amount equal to the interest payments on outstanding government debt is included in tax revenue. This is modelled as a lump sum tax. The model also allows for other fiscal closure rules.

3.4.5 Trade and financial flows

The trade in goods and services between zones is determined by each zone's demand for imports. G-Cubed requires any trade imbalance in a zone to be offset by the movement of financial capital between that zone and the other zones, thereby restoring the balance of payments.

Financial capital is assumed to be perfectly mobile. Flows of financial capital between zones are subject to an interest arbitrage relation, which equalises (through changes in each zone's interest rate) the expected returns on loans across all the zones each period. Capital gains and losses are possible on financial capital that is invested in physical capital, because adjustment costs cause large differences in *ex post* returns between zones. The implications for the way in which trade is modelled are discussed in section 4.5.

Figure 3.14 **Creation of capital goods in G-Cubed**



3.4.6 Monetary sector

Transactions within a zone are constrained by the amount of money available in it. The demand for real money balances is determined by the value of a zone's aggregate output (gross domestic product) and short run interest rates. The supply of money is exogenously set and obtained from each central bank's balance sheet.

3.4.7 Labour market

G-Cubed assumes that labour is perfectly mobile among all the sectors in each zone, but immobile between zones. Labour supply exhibits both long run and short run characteristics. In the long run, labour supply is perfectly inelastic and determined by the population growth rate; therefore, wages are assumed to adjust completely to ensure full employment in each zone. In the short run, nominal wages are assumed to adjust slowly. This slow adjustment is determined by an overlapping contracts model that bases wages on current and expected inflation and on labour demand relative to supply. A feature of this specification is that labour in the short run may be at levels either lower or higher than the long run full employment level, as a result of adverse or beneficial unexpected shocks respectively.

3.4.8 Population growth

The population growth rate for each zone is determined exogenously.

3.4.9 Technical change

G-Cubed distinguishes technological change in the energy and non-energy sectors in each zone. The rates of technological change applying to these two sector groups are exogenously set. For the energy sectors, a global constant energy efficiency growth rate is assumed, along with zone-specific productivity growth rates. For the non-energy sector in each zone, a zone-specific productivity growth rate is applied.

3.4.10 Other features relevant to GHG control policy

The model directly incorporates policy instruments such as a carbon tax or carbon emission permits. Only carbon from fossil fuel combustion is modelled. The commodities and GHGs covered are presented in appendix C (table C.4). Emission permits are owned by households but needed by firms as an additional input for production if they use primary fossil fuels (coal and crude oil and gas). The number of permits required for production depends on the average carbon content per physical unit of each fuel used, and is set as a fixed proportion. The model assumes a competitive market for permits, in which the price of permits is determined by the total number of permits available.

G-Cubed includes five energy sectors (electricity utilities, gas utilities, petroleum refining, crude oil extraction and gas extraction) and allows for inter-fuel substitution between them. Energy sectors are nested in consumption, production and capital formation relationships, enabling the model to capture the substitution between different forms of energy in all major areas of economic activity.

3.4.11 Data

G-Cubed uses a constructed time series of input–output tables for the United States (based on data from the Bureau of Economic Analysis and the Bureau of Labor Statistics) to estimate production and final demand parameters econometrically for the United States. The top-tier production parameters account for capital being fixed in the short run. The estimates of the substitution elasticities of each industry sector in the United States are assumed to be the same for all zones. However, estimates of the share parameters (the weighting given to each input in production) for the United States are not applied to other zones. Instead, share parameters for the other zones are obtained from either each zone's input–output data or adjusted US estimates (where the adjustment is based on final demand data from the zone's national accounts). The procedure for estimating final demand parameters is similar to that used for obtaining the production parameters, in that estimates for elasticities are obtained from US data, and share parameters are obtained from each zone's input–output tables.

4 Technical comparison of the models

This section provides a comparison of the model features that were summarised by the survey in Section 3. First, levels of disaggregation across various areas, households and industries are examined. Next, the structures of household demand are compared. Then, production technologies are compared, with a focus on energy sectors. The models' treatments of government taxes and transfers, and of closure and dynamics are also compared. Finally, the 'level of transparency' of the models (which depends on how well the models are documented) is discussed. Unless otherwise stated, the technical details in this section are obtained either from recent versions of the models (Adams, Horridge and Parmenter 2000a; Murphy 2000; Polidano et al. 2000; McKibbin and Wilcoxen 1999) or from the modellers.

4.1 Levels of disaggregation

4.1.1 Regional and zonal disaggregation

Two of the models are national and two are global. Table 4.1 shows how coverage of regions varies within the national models, and how coverage of zones varies within the global models.

Table 4.1 **Levels of regional and zonal disaggregation**

Model	*Zones*	*Australian regions*
MMRF–Green	1	8 and 57
MM600+	1	23
GTEM	45	1
G-Cubed	8	1

MMRF–Green and MM600+ focus on the Australian economy specifically, while allowing for trade with the rest of the world. MMRF–Green produces results for the six States and two Territories, then uses a top–down approach to disaggregate the results for output, employment and GHG emissions into 57 subregions, which is its maximum level of regional disaggregation. It disaggregates by using an approach similar to that normally taken in disaggregating national input–output tables into regional tables. Industries are classified as either State, Territory or local, and output from a State industry is assumed to change in line with changes in the output of the State in which it is located. Output from local industries depends on mainly the level of local (subregional) demand, while demand from the State in which they are located is assumed to have only a small effect.

MM600+ is a single-zone model of Australia that also disaggregates results using a top–down method. Results can be derived for a maximum of 23 regions. The regional module divides industries into those producing either traded or non-traded products. The regional output from industries producing traded products is based on shares of national output. Regional output is achieved by a direct relationship between employment in each industry and its output. In the industries producing non-traded products, regional employment is proportional to total employment in the traded product industries. Changes to employment in traded product industries therefore exhibit a multiplier effect while changes to employment in non-traded product industries do not affect employment in traded product industries.

GTEM and G-Cubed have a global coverage but differ in the number of zones into which they divide the world. GTEM uses the GTAP 4.0e database, which covers 45 zones. Recent applications of GTEM to GHG issues have divided the world into 23 zones (Polidano et al. 2000) and 18 zones (Brown et al. 1999), with Australia alone as one zone. G-Cubed divides the world into eight zones, also with Australia alone as one zone.

4.1.2 Household disaggregation

All four models use a representative household to capture private consumption and, in the case of GTEM and G-Cubed, savings behaviour too. MMRF–Green models a different household for each of its eight regions, while the other models use only a single household for Australia. The ‘super’ household used in GTEM is a concept first adopted in the GTAP model. It is different from the representative households in the other models because it receives all factor incomes (net of taxes) and all tax revenue and net interzonal income transfers.

4.1.3 Industry sector and product disaggregation

As shown in tables 4.2 and 4.3, the level to which industry sectors and products are broken down is significantly different across the models, leading to differences in the amount of detail captured on energy sectors and products.

Table 4.2 **Industry sector and product disaggregation**

Model	*Industry sectors per region/zone*	*Products*	*Energy sectors/products*
MMRF–Green	40	45	15
MM600+	10	672	12
GTEM	50	50	11
G-Cubed	12	12	5

MM600+ is the most disaggregated model, having 108 industry sectors and 672 products. It identifies 12 energy products. MMRF–Green distinguishes 40 industry sectors producing 45 products for each of its regions. It also has a detailed representation of energy industries, identifying 15 different products. The GTAP database allows GTEM to identify up to 50 industry sectors producing 50 products for each zone, although fewer industry sectors have been used in recent greenhouse gas analyses. Production in each zone was disaggregated into 19 and 23 tradeable goods respectively by Polidano et al. (2000) and Brown et al. (1999). Energy production is represented in GTEM by 11 sectors. G-Cubed is the least disaggregated model, covering 12 industry sectors for each zone (of which five represent energy production).

4.2 Specification of household demand

4.2.1 Demand structure

Figure 3.2 showed that G-Cubed has the simplest household demand structure, in the form of a two-tier nested utility function. The top tier is represented by a KLEM (capital, labour, energy and materials) function. Constant elasticity of substitution (CES) functions in the utility function combine both primary inputs and intermediate inputs. (Appendix A lists the mathematical functions for CES and all other specific functional forms mentioned in this section.) MMRF–Green, MM600+ and GTEM adopt a three-tier nested system. Unlike in G-Cubed, actual goods are combined at the node for the first and highest tier, using functional forms other than CES.

The functional form used at the highest node depends on the demand system that is modelled and, therefore, has implications for how the household responds to changes in prices and its income. Table 4.3 highlights some implications. MMRF–Green and MM600+ model household demand as a linear expenditure system (LES). The household is assumed to first purchase its subsistence needs of each good and then spread the remaining ‘luxury’ expenditure over the goods in fixed proportions. MM600+ extends the household substitution possibilities to allow substitution between and within broad consumption groups. Substitution within each consumption group is achieved by replacing prices in the indirect utility function with a CES price index for the goods in the group. The level of within-group substitution in the CES price index is determined by an intra-group substitution parameter. Household expenditure is allocated across goods in G-Cubed using a CES system. By contrast, GTEM uses a constant difference of elasticity (CDE) expenditure system. In both these cases, the models do not distinguish expenditure on the subsistence component of goods and expenditure on the luxury component. Each of these demand systems imply certain assumptions about how demand for goods responds to changes in income and relative prices.

Table 4.3 **Specification of household final demand**

		Implied elasticity characteristics		
Model	*Utility/expenditure function*	*Income*	*Own-price*	*Cross-price*
MMRF–Green	LES: Stone-Geary	Value may vary; fixed marginal budget shares	Value = 1 for luxury goods	Value = 1; constant between all pairs of ‘luxury’ goods
MM600+	LES: generalised	Value may vary; fixed marginal budget shares	Value may vary	Value does vary between groups
GTEM	CDE	Value may vary; variable marginal budget shares	Value may vary	Value may vary; constant difference in elasticity of substitution between all pairs of goods
G-Cubed	CES	Value = 1; fixed marginal budget shares	Value may vary	Value may vary; constant between all pairs of goods

4.2.2 Income elasticities

G-Cubed has the most restrictive assumption about the household’s demand for goods in response to changes in income. The two-tier CES utility function implies that the value of the income elasticities of demand for goods is one. Thus, as household income changes, the demand for each good will change by the same percentage. The linear expenditure systems in MMRF–Green and MM600+ relax the requirement of unitary income elasticities. However, the marginal amount spent on each luxury good as income increases remains a fixed proportion. The CDE expenditure system used in GTEM also assumes that income elasticities are not restricted to one, but it further relaxes the requirement of fixed marginal budget shares by allowing them to vary with changes in income.

4.2.3 Own-price elasticities

The LES in MMRF–Green implies that the own-price elasticities for the luxury component of goods are always equal to one. Luxury goods are defined as the amount of each good purchased in excess of a subsistence amount. The percentage change in demand for each good’s luxury component will therefore be equal to the percentage change in the price of that good. This restriction on the demand response by the household to price changes is relaxed for the luxury component of goods by the generalised LES used in MM600+, and for all goods by the CDE and CES expenditure systems adopted in GTEM and G-Cubed respectively.

4.2.4 Cross-price elasticities

The demand for goods by households is affected by changes in relative prices as well as own-prices of goods. All the models assume the elasticity of substitution between pairs of goods is constant. The LES used in MMRF–Green requires this elasticity to always equal unity for the luxury component of goods. MM600+ is the most general in that it allows the cross-price elasticities to vary between broad consumption groups. Both GTEM and G-Cubed assume that the elasticity of substitution can vary from a value of one. However, in G-Cubed the value of the cross-price elasticity is constant between all pairs of goods. The CDE used in GTEM implies that the cross-price elasticities for pairs of goods can vary, but that the difference in these elasticities between pairs of goods in which one good is the same is constant for the choice of the pairs.

4.3 Specification of production technology

4.3.1 Production functions and substitution possibilities

Various approaches are used to represent production technology (see the production technology figures for each model in section 3). Some implications of these approaches are summarised in table 4.4.

Table 4.4 **Specification of producer technology**

Model	*Production function at highest tier*	*Characteristics of substitution elasticities*	*Production function for energy bundle*	*Characteristics of substitution elasticities*
MMRF–Green: All sectors using non-energy-intensive inputs	Leontief	Value = 0 ; no substitution	CES for electricity supply (no explicit energy bundle used)	Value >0 and <1; constant between all pairs of inputs
MMRF–Green: Electricity supply and all sectors using energy-intensive inputs	CES	Value >0 and <1; constant between all pairs of inputs	CES for electricity supply (no explicit energy bundle used)	Value >0 and <1; constant between all pairs of inputs
MM600+	Leontief	Value = 0; no substitution	CES	Value >0 and <1; constant between all pairs of inputs
GTEM: All industries except Electricity, and iron and steel	Leontief	Value = 0; no substitution	CES	Value >0 and <1; constant between all pairs of inputs
GTEM: Electricity, and iron and steel industries	Leontief	Value = 0; no substitution	CRESH	Value >0; may differ between pairs of inputs
G-Cubed	CES	Value > 0 and < 1; constant between all pairs of inputs	CES	Value >0 and <1; constant between all pairs of inputs

All the models employ CES functions at some level(s) of their production structure. CES technology assumes factor inputs are substitutes for one another, depending on the value of the elasticity of substitution. It implies that the elasticity of substitution between all pairs of inputs is the same and remains constant. Leontief (fixed proportions) technology is used at the highest node of the production structures in MMRF–Green (for the electricity supply sector), MM600+ and GTEM, and at various nodes in the production tree for the electricity, and iron and steel industries in GTEM. It assumes there are no substitution possibilities among the factor inputs. GTEM’s technology bundles in the electricity, and iron and steel industries are formed using a constant ratio of elasticities of substitution, homothetic (CRESH) production function. It relaxes the assumption of uniform elasticities of substitution imposed by the CES function, and allows elasticities to differ between given pairs of inputs.

The technology bundle approach to modelling production in GTEM’s electricity, and iron and steel industries is significantly different from the other production structures. The technology bundles constrain the use of inputs to combinations that are consistent with a finite number of known technologies, and thereby will produce different output responses compared with the usual nesting approach using a CES function. Technology bundles are treated as imperfect substitutes on similar grounds to those used when applying the Armington assumption to domestically produced and imported goods. The main implication is that input substitution, unlike the CES approach, cannot occur if the underlying technology is currently infeasible.

4.3.2 Energy substitution possibilities

The relationship between the combustion of fossil fuels and the release of carbon dioxide emissions makes the treatment of energy products in the models very important. Table 4.5 lists the energy sectors and products covered by the models. The disaggregation of energy is varied. Only MMRF–Green and GTEM explicitly model the generation of electricity from renewables.

G-Cubed accounts for energy generation from renewables implicitly, by including them in the capital stock. It implies that if more capital is used to produce more energy, then the energy is produced from renewable sources. For convenience, table 4.5 also lists the coverage of noncombustion GHGs in each model.

The way in which the models form bundles of energy products also varies, as do the assumptions that apply to them. Table 4.6 provides a comparison of different possibilities for energy substitution within energy bundles, and between energy bundles and other inputs.

G-Cubed allows the greatest flexibility for the substitution between energy and other production inputs in its KLEM production structure. The energy bundle comprises electricity, gas, petroleum, coal and extracted crude oil and gas. The extent to which energy can be substituted in each industry sector depends on the values of the elasticities for the output tier and the energy bundle for the sector. G-Cubed uses econometric estimates for its elasticities and, therefore, bases them on historical relationships. An implication of using nested CES functions is that where the elasticity at the node of the output tier is larger than the elasticity at the energy bundle node, the energy inputs will be treated as complements rather than as substitutes for one another.

The other models use more complex treatments of energy inputs. MMRF–Green uses similar production structures for both energy-intensive and non-energy-intensive industries (except electricity supply). The main difference between energy-intensive and non-energy-intensive industries is that the former are given a non-zero elasticity of substitution at the output node, while Leontief production technology (zero elasticity of substitution) is imposed on the latter. This approach allows for possible input substitution between energy-intensive commodities, primary factors and other intermediate inputs. A further distinction is made within energy-intensive commodities. Petrol products, electricity supply and natural gas are given a higher substitution elasticity than the other energy-intensive inputs. The model adopts a separate production structure for the electricity supply sector. Electricity generators using different energy types (black coal, brown coal, gas, oil products and other renewable energy such as hydro) are the only inputs recognised, and substitution is allowed.

Table 4.5 **Energy sectors/products and GHGs covered by the models**

	Energy sector/product group					
Model	*Coal*	*Oil*	*Gas*	*Petroleum products*	*Electricity generation*	*GHGs covered*
MMRF–Green	Black Brown	Crude oil	Natural gas	Automotive Aviation Gasoline Aviation Turbine Diesel LPG Other	Black coal Brown coal Gas Oil Renewables	All GHGs accounted for in the National GHG Inventory
MM600+	Black Brown	Crude oil	Natural gas LNG/LPG	Petrol Aviation Gasoline Aviation Turbine Diesel Kerosene LPG Other	Electricity generation	Carbon dioxide
GTEM	Coal	Oil	Gas	Petroleum products	Coal fired Gas fired Oil fired Nuclear Hydro Renewables Other	Carbon dioxide Methane Nitrous oxide
G–Cubed	Coal production	Crude oil/ gas extract	Gas production	Petroleum refining	Electricity generation	Carbon

MM600+ takes a different approach. It combines a primary-factor bundle (labour and capital), an energy bundle (black coal, brown coal, natural gas and liquid petroleum gas), a freight bundle (road freight and rail freight) and other intermediate inputs in fixed proportions. The model does not allow for any direct substitution between energy and these other inputs. While substitution is permitted between the inputs in the energy bundle, petroleum products are not included because there is a relatively lower opportunity for substituting them with other industrial fuels. Energy substitution is indirectly captured between road and rail freight transport (which have different energy intensities).

Table 4.6 **Energy substitution possibilities**

	1st tier above the energy bundle/inputs		*Energy bundle*	
Model	*Substitution possibilities*	*Elasticity of substitution*	*Substitution possibilities*	*Elasticity of substitution*
MMRF–Green: All sectors using non-energy-intensive inputs	Primary-factor bundle All other intermediate inputs	0	Electricity supply — black coal, brown coal, gas, oil products and renewables	5.0
MMRF–Green: All sectors using energy-intensive inputs except petroleum, natural gas and electricity supply	Primary-factor bundle All other intermediate inputs	0.10	Electricity supply — black coal, brown coal, gas, oil products and renewables	5.0
MMRF–Green: All sectors using inputs of petroleum, natural gas and electricity supply	Primary-factor bundle, All other intermediate inputs	0.25	Electricity supply — black coal, brown coal, gas, oil products and renewables	5.0
MM600+	None	0	Black coal, brown coal, natural gas, LPG	0.9
GTEM [a]	Primary-factor bundle Energy bundle	0.4	Petroleum products, coal, gas, electricity	0.2
G-Cubed	Capital, labour, energy bundle Materials bundle	0.2556–1.703	Coal, petroleum, electricity, gas, crude oil	0.2–1.594

[a] All goods except electricity, and iron and steel

As in MMRF–Green, GTEM distinguishes between sectors requiring energy-intensive inputs and non-energy-intensive inputs. The model contains two production structures — one for all industries, excluding electricity, and iron and steel, and the other for electricity, and iron and steel. In the first of these industry sector groups, products in each of the energy bundle (coal, gas, petroleum products and electricity), primary-factor bundle and intermediate-input bundle are combined using CES technology. The energy-factor bundle is formed from a CES combination of the primary-factor bundle and the energy bundle, and is combined in fixed proportions with the intermediate input bundle. Depending on the value of the substitution elasticities at the various production nodes for an industry sector, substitution is possible between the four energy inputs and then between the energy bundle and the primary-factor bundle. The structure does not, however, permit substitution between intermediate inputs and either the other primary factors or the four energy inputs.

As mentioned in section 4.3.1, GTEM uses a separate production structure for the electricity, and iron and steel industry sectors. It replaces the energy-factor bundle with a technology bundle. While each technology in the bundle uses inputs in fixed proportions to output, there can be a smooth substitution between technologies. In other words, the technology bundle restricts combinations of inputs to a convex combination of existing (or possible) technologies. For the electricity sector, the generation technologies are coal fired, oil fired, gas fired, nuclear, hydro and renewables. Two significant differences between the technology-bundle approach and the other production structures discussed in this review are (a) the technology bundle does not allow energy inputs to be directly substitutable for either one another or other production inputs (instead, energy is embedded with in a specific technology that is substitutable for other technologies) and (b) this approach does not allow output to be produced from currently infeasible technologies.

4.3.3 Technical change in energy industries and industries with noncombustion emissions

CGE models need to include technical change — changes of the production possibilities frontier, rather than moves along an unchanged frontier — if they are to capture the effects of new technologies and new products on carbon emissions over the 10–20 years for which projections are commonly made. Technical change can be treated as either exogenous — where no policy choices make any difference to the rate of change, no matter how big a shift they cause in the price of one good compared with the price of another — or endogenous. All the current versions of the models treat technical change as exogenous to some degree. However, technical change biased by relative prices has been modelled in GTEM in experimental simulations (Hanslow, Hinchy and Fisher 1998).

MMRF–Green allows for annual changes to be set exogenously for the amounts of both intermediate and primary-factor inputs used per unit of output in industry sectors. It can therefore capture input-saving technical progress which may occur in the energy sectors. These autonomous technology improvements are applied uniformly across all regions. MM600+ models technical change using exogenous efficiency of labour and capital parameters. The GTEM approach is different: it finds technical change by initially setting gross domestic product exogenously in a reference case, then solving the model for the implied level of technical efficiency required to achieve it. This is interpreted as the general level of energy efficiency in the economy, which is then imposed exogenously in policy runs. G-Cubed uses a similar approach to that of MMRF–Green and MM600+, by imposing exogenous levels of technical change directly on reference and policy simulations. However, G-Cubed applies productivity growth rates to both energy and non-energy sectors in each zone, together with an autonomous energy efficiency index (AEEI) which is applied across all zones as a global constant. The productivity growth rates are based on US historical patterns of technical change at the sector level, and scaled up or down for the other zones. While total factor productivity in G-Cubed is exogenous, endogenous technical change is captured to some extent in its flexible treatment of production technology and in the larger set of input substitutions it implies.

Another way in which to reduce GHG emissions over time is to increase the efficiency of specific technologies used to abate noncombustion emissions (methane, nitrous oxide and noncombustion carbon dioxide, from sources listed in appendix C). Here, the challenge is to allow substitution to respond to the policy-induced higher price of GHG emissions. MMRF–Green models the abatement response of industries producing noncombustion emissions as being directly related to the size of any carbon penalty imposed. The relationship between the amount of abatement and the penalty relies on constants of proportionality obtained from point estimates. Given that the abatement undertaken by firms means that more inputs are required to produce the same level of output, and therefore abatement is costly for the economy as a whole, the abatement of non-fuel emissions is treated as negative technical progress. At the margin, the value of negative technical progress is equal to the price of carbon multiplied by the amount of non-fuel emissions abated.

GTEM also uses fixed relationships between the level of abatement by industries producing noncombustion emissions and the carbon penalty, but it treats abatement as a lagged process that can take up to seven years. This is captured using an emission response function, which represents a firm’s attempt to change production technology to reduce emissions in response to both changes in the carbon penalty and changes in energy (electricity) prices. A higher carbon penalty and higher energy prices both induce adoptions of technologies that reduce noncombustion emissions.

GTEM’s treatment of noncombustion abatement differs from that of MMRF–Green in another significant way. Thresholds are placed on the emission penalty before industries can undertake energy efficiency improvements. Both models assume that the emission-reducing technologies and practices are available at no cost to the firm. MMRF–Green assumes that the installation of these technologies and practices is instantaneous and therefore also costless. GTEM assumes industries can face costs arising from lagged installation processes. The extent of these costs depends on the value of the adjustment parameter used.

4.4 Treatment of government taxes and transfers

The way in which government taxes and transfers are treated in each of the models depends on how the models account for government revenue and expenditure. MMRF–Green uses a set of summary-of-financial-transactions (SOFT) accounts to describe movements in Commonwealth and regional government income and expenditure, and calculate governments deficits. Direct and indirect taxes are identified in these accounts, along with transfer payments to households. GTEM determines changes to government deficits (and other macroeconomic aggregates) from the microeconomic behaviour it models, rather than through detailed relationships as in MMRF–Green. The value of the macroeconomic aggregates is obtained from national accounting identities which are defined for national income and expenditure on the factor cost side and the expenditure side respectively, for each zone. Government revenue and expenditure comprise taxes, transfer payments to households and government consumption. Although government transfer payments are not explicitly identified, their value, together with the value of the government deficit, is implied by an equality imposed between the national income and expenditure flows.

MM600+ models policies as being budget neutral, so the impact of GHG policy on the government's budget is offset by a reduction in labour income tax. (An alternative method is to change the rate of the goods and services tax.) The movement in the tax on labour income to ensure the impact on the budget is neutral is called a 'fiscal swing mechanism'. Changes brought about by the new tax system are accounted for in the baseline. This means that analysis of GHG policy includes the impact of the goods and services tax. The model has a detailed representation of diesel tax rebates across different industry sectors. It also distinguishes the low rate of excise applied to aviation gasoline from the high rate applied to petrol. Thus the model can capture the different percentage changes in different petroleum products costs arising from a GHG policy such as a carbon tax.

MMRF–Green, GTEM and MM600+ simulate policies relating to government expenditure and taxes (fiscal policies) by exogenously changing the relevant variables. A carbon tax on goods, for example, is applied by increasing the tax on either the production or consumption of relevant goods by the amount required. Governments are assumed to intervene in markets by introducing *ad valorem* taxes (which can be negative if the intervention is a subsidy), thereby introducing a wedge between consumer and producer prices. GTEM follows the GTAP convention whereby taxes and subsidies create a wedge between the market price and the buyers' or sellers' price (Brockmeier 1996; Hertel and Tsigas 1997). Alternatively, MMRF–Green treats indirect product taxes as applying to the price received by the producer.

While G-Cubed also uses *ad valorem* taxes, the model is able to set fiscal policies that are consistent with optimising a macroeconomic variable over time. An important constraint on fiscal policy is the government's intertemporal budget constraint — if government debt rises in a year, then there must be a corresponding increase in taxes to cover the increased interest cost.

The categories into which the models divide taxes are shown in table 4.7. The number of tax categories in each model differs, but the extent to which this difference is important for GHG analysis depends on the policy question of interest. All the models can capture the effects of both carbon (or carbon dioxide) taxes or emission permits and the associated transfer of revenues. The impacts of these policies are determined by two important and related factors that vary over all four models. The first factor is the level to which economies (regions or zones) are disaggregated into sectors, which determines the types of equity impacts that are identifiable. The second factor is the capture of links between economies, which determines to what extent the equity impacts have included the effects of trade and movements of labour and capital.

4.5 Model closure and dynamics

To obtain a solution from a CGE model, the number of endogenous variables must equal the number of equations to be solved. To achieve this balance, some naturally endogenous variables need to be made exogenous via the imposition of further assumptions about their values. This set of decisions is referred to as model closure. The type of closure rule applied depends on whether the model is capable of generating comparative static and/or dynamic solutions, and on the type of analysis being performed. The four models use comparative static, forecasting and dynamic policy closures. Each model has different closure rules.

While MMRF–Green can be operated in comparative static mode, MM600+ is a comparative static model designed for mainly long run analyses. Short run closure rules have been designed to replicate the Australian Consumer and Competition Commission's price exploitation guidelines. These guidelines prevent businesses from using changes arising from the New Tax system to increase their net dollar margins on goods and services. Under the more widely used long run closure, the supply of labour is exogenous and rates of return on capital are fixed. The differences between the 'shocked' and 'unshocked' solutions are used for policy analysis. MMRF–Green allows for short run (one to two years after a shock) and long run (five years or more after the shock) comparative static closures. These closures are implemented by the setting of rules for how labour markets and capital goods markets adjust. In short run closures, real wages are fixed and the labour supply is assumed to be perfectly elastic, and industry capital stocks are fixed and rates of return on capital are endogenous. In long run closures, real wages are endogenous (adjusting in response to changes in demand) and the supply of labour is fixed (although mobile between industries), while capital is assumed to be perfectly elastic (with the capital market being open to international investors) and rates of return on capital are fixed.

Table 4.7 **Taxes incorporated into the models**

Model	*Direct taxes*	*Indirect — production taxes*	*Indirect — product taxes*
MMRF–Green	• PAYE — 8 occupations • Non-wage • 'Other' direct	• Payroll tax • Fringe benefits tax • Property tax • Land tax • 'Other' indirect tax	• Tariffs • Separate federal and State/Territory sales tax rates on all flows of goods and services
MM600+	• Income tax	• Land tax • Local Government Authority rates • Liquor and gambling taxes • Payroll tax • Insurance tax • Motor vehicle taxes • Stamp duties • Use of goods taxes • Fringe benefits tax • Departure tax • Other indirect tax	• Goods and Services Tax • Sales tax • Stamp duty • Gambling taxes • Primary production taxes • Regulatory service fees • Excise taxes • Motor vehicle taxes • Financial institutions duties • Customs duty on exports • Other commodity taxes • Customs duty on imports
GTEM	• Income taxes (net subsidies)	• Production taxes (net subsidies)	• Consumption taxes: – government – private households – intermediate inputs tax (net subsidies)
G-Cubed	• Personal income tax • Corporate income tax	• Investment tax credits • Other production taxes	• Sales taxes • Tariffs

Because MMRF–Green and MM600+ are national models, their closure requires assumptions about the behaviour in the rest of the world. Both models fulfil the criterion by specifying foreign export supply elasticities and import demand elasticities, and by imposing an external-sector trade balance condition. They assume that the economy faces fixed world prices for imports, while also facing a foreign demand function for exports that has constant own-price elasticities. Price-taking behaviour with respect to imported goods is modelled using the Armington assumption.

MMRF–Green, GTEM and G-Cubed can perform forecasting and dynamic policy closures (see below for the difference). These closures produce dynamic solutions, so some variables that are exogenous in comparative static closures are made endogenous. For example, investment in comparative static closures is treated as being exogenous (endogenous) and rates of return on physical capital are treated as being endogenous (exogenous); in a dynamic closure, both investment and rates of return are defined as being endogenous, and an investment equation is added to specify their relationship and to link them to future periods.

Forecasting closures produce a ‘baseline’ (also called ‘reference’ or ‘business as usual’) series of yearly results (projections). If necessary, model users can introduce any information on naturally endogenous variables that is obtained from external sources by making the variables exogenous. Closure is then completed by endogenising other variables to ensure the model can be solved. Policy closure is similar to forecasting closure except that it requires one or more of the exogenous policy variables to be set at a different value, or ‘shocked’. Policy analysis is performed on the computed deviations between the baseline and policy simulations.

The dynamic models use intertemporal relationships to connect each time period. All the models have dynamic equations for physical capital accumulation. In both MMRF–Green and GTEM, the behaviour of economic agents is assumed to account for only information in the current and next periods. MMRF–Green contains dynamic equations for physical capital accumulation and the adjustment in the real wage rate to policy shocks. Many of the dynamic relationships in GTEM relate to the demographic module, which in turn influences other variables. While GTEM also specifies a dynamic equation for capital stock, it includes a lagged adjustment process for the take up of emission-reducing technologies and practices in industries that are not involved in fossil fuel combustion.

G-Cubed adopts a different approach from that of MMRF–Green and GTEM. It assumes that economic agents use a combination of rational expectations and myopic behaviour. They make their decisions in the current period, knowing to some extent how those decisions will affect outcomes in all future periods. Under this assumption, the model fully accounts for the stocks and flows in each zone’s real and financial assets, and uses intertemporal budget constraints on household expenditure and each zone's trade deficit. A Ramsey neoclassical growth model provides dynamic investment and savings equations, which produce a transition path for each zone between the short run and long run macroeconomic closures. Adjustment costs play an important role in determining this transition path. In contrast to the other two dynamic models, G-Cubed explicitly accounts for the costs of adjusting household and industry physical capital stocks. This means that firms' capital stocks are quasi-fixed in the short run, so firms' supply curves slope upward. An implication is that firms can produce rents (super-normal profits) in the short run. As in MMRF–Green, G-cubed allows for employment to differ from its 'full employment' level.

4.6 Transparency

Comparison of the models depends on being able to determine their key assumptions, which in turn depends on their 'transparency', or the amount and quality of information that is available about them. Information about a model may be obtained from both written documentation and access to the model. The MMRF–Green and G-Cubed models are thoroughly documented in terms of written description, mathematical equations and source code. Information on MMRF (the model on which MMRF–Green is based) and G-Cubed is readily available from the Centre of Policy Studies and McKibbin Software Group web sites respectively. These two models have a history of publications detailing both the structure and applications of earlier models from which they have been developed. Values of the elasticities for G-Cubed are available in McKibbin and Wilcoxen (1999) and from the McKibbin Software Group web site. While some elasticity values for MMRF–Green are provided in Adams, Horridge and Parmenter (2000a), it would be useful if all the elasticities for MMRF–Green were available in a single document. GTEM is also well documented in the areas of written description, mathematical equations and source code, but much of the information is spread over ABARE research reports and GTAP literature. Understanding of the model more completely would be helped if the original interim documentation for MEGABARE (ABARE 1996) was updated for GTEM, and if key elasticity values were publicly available. A description of the structure of the MM600+ model, along with the values of all its elasticities, can be downloaded from Econtech's web site (Murphy 2000). The written documentation does not include a listing of the mathematical equations, but the computer implementation of the model was made available for inspection and use in this review. MM600+ does not have the same level of publicly available documentation as that of the other models, which makes a complete understanding of the model more time consuming. However, the available information allows scrutiny of the reasonableness of the model's key assumptions and elasticities.

5 Implications for GHG control policy

The technical differences and similarities among the four chosen CGE models are highlighted in section 4. This section is an assessment of what these differences and similarities mean for how well the models can inform the development of efficient and equitable policies for GHG control in Australia. Rather than a full appraisal of both the inputs and outputs of each model, the main focus here is on the inputs. The first step in this appraisal is to consider key questions that policy makers may ask:

1. Can a model include types of control policy that are under debate? Can it model policies to promote renewable energy, for example, or policies that refund carbon tax revenues as a reduction in payroll tax?

2. Can a model estimate distributional effects that are under debate? Can it indicate, for example, how equitable a policy will be across various income classes, regions or industries?

3. Can a model indicate the best overall reduction of GHG emissions for a country, particularly in the context of what other countries may do? Does it adequately assess, for example, the benefits as well as the costs of controlling GHG emissions?

These questions can often be quite interdependent. Interest in a particular policy instrument under (1) — say, using the revenue from a carbon tax both to raise income tax thresholds and lower tax rates — may be aimed at reducing impacts on lower income households under (2), while still achieving a ‘double dividend’ reduction in the distortionary costs of taxation (Bovenberg 1999). Such an improvement in both efficiency and equity effects is then likely to make a higher degree of control desirable under (3), at least when agreed at the global level. Nevertheless, the questions provide a useful structure to the following appraisal of the models.

An obvious, but important and pervasive conclusion is that the choice of computable general equilibrium (CGE) models is often a matter of contextual preference. Models are generally best used for the purposes for which they were built. This suggests that national models (MMRF–Green or MM600+) provide better analyses of domestic policies than do global models (GTEM or G-Cubed). But, the choice is not necessarily that simple. For analysing the fate of the

Australian cement and aluminium industries under the Kyoto Protocol, for example, which is more important: the greater sectoral and geographic detail available in a national model? Or, the better modelling of competition from non-Annex B countries available in a global model? Further, policy makers' interests are not confined to domestic issues. Discussions at the Sixth Conference of Parties (COP6) confirmed the importance of negotiations on international issues, such as where and how much trade in carbon permits will be allowed. This section contains a brief comment on these issues.

5.1 What types of GHG control policies can be included?

The following discussion begins with policies that cannot be fully included in CGE models, before moving on to those that can be included.

5.1.1 'Non-price' policies that cannot be fully included in CGE models

CGE models cannot include a wide variety of 'non-price' policies that some commentators consider to be important ways of reducing GHG emissions (for a general analysis, see Hourcade and Robinson 1996; for comments focused on Australia, see Hamilton and Quiggin 1997 and Diesendorf 1998). Non-price policies include appropriate exhortation, information campaigns, building and product standards, building and product labelling, land-use planning, government purchasing, direct action such as mass insulation campaigns, and legal or other institutional changes to allow fair competition from 'energy service' companies, or low-GHG energy supplies. None of these policies directly affects the prices of factor inputs or commodities — thus the name 'non-price'.

It is often claimed, particularly by advocates of the 'bottom–up' modelling approach, that many non-price policies have 'no regrets', because they stimulate actions that have zero or negative net costs. If the costs and benefits of such actions fall on the same agents, then why are agents irrationally failing to take up the costless opportunities that are available? The answer may be that the net cost calculations overlook hard-to-measure, opportunity costs of agents' time and trouble. These opportunity costs should be included in the assessment of the non-price policy itself — for example, where a government pays for an information campaign, and private agents then benefit from better informed choices — so governments can make sensible choices about how much money to spend, and how best to spend it, on alternative types of non-price policy.

The authors’ view is that in the aggregate, non-price policies are significant but not free. They deserve careful, continuing assessment, and CGE modelling can do little to help with such assessment. All CGE models typically assume that households and firms are fully informed and rational in their constrained maximisation of utility or profits; in that sense, there are assumed to be no inefficiencies in economies, so CGE models give no useful results about whether or how non-price policies can remove such inefficiencies. They can often incorporate the total effects of these policies by means of assumed changes in exogenous technical and taste parameters, as long as the models have the necessary disaggregation. (Most models do not have the sectoral detail to assess an increased uptake of ceiling insulation in housing as a result of better information, or for that matter as a result of subsidies, a specialised price policy.) But, incorporation of the effects of ‘guesstimated’ parameter changes is not full inclusion. The model provides no extra information to suggest what those assumed parameter changes should be, and thus to help assess the effectiveness of the policies — at least no more than an exogenous assumption about population growth rates gives useful information for assessing immigration policies.

5.1.2 Policies that can be included in CGE models

CGE models provide insights into many types of policy that could be used to achieve targets for controlling GHG emissions. Such policies directly or indirectly increase the relative price of GHG-intensive products and processes. Table 5.1 provides details on some recent analyses of GHG policies/scenarios — undertaken using each of the four models — that have focused on mainly carbon taxes and tradeable carbon permits. MMRF–Green has been used to consider some regulatory measures too, which include a restriction on land clearing and a petrol tax. MM600+ has modelled a transport emissions tax. Both MMRF–Green and GTEM have been used to account for carbon sequestration, and GTEM has been run to analyse the potential impacts of the clean development mechanism proposed under the Kyoto Protocol. These examples of policy analysed in the models are no indication of what other policies could be included in future analyses.

The range of GHG policy options that can be represented in a model depends on the level of detail of the products, sectors and emissions that it covers. The additional policy choices that each model could analyse are suggested by the breakdown of energy and taxes in tables 4.5 and 4.7 respectively. Regarding technological choices, for example, if modelling policies for renewables, alternative fuel sources for electricity or the control of noncombustion GHGs is a priority, then the appropriate model to use is clearly one that separates out these technologies. If it is necessary to consider different policies for different industrial sectors, then sectoral detail is important.

The model must also have an appropriate representation of the policy instrument being used. CGE models commonly represent policies as '*ad valorem* equivalents', which is not always appropriate and which may produce inaccurate or misleading conclusions (Hertel 1999). Further, even if policies can be represented by a simple tax, there is not always universal agreement on how they should be treated in the model (Shoven and Whalley 1992).

With respect to GHG policy, national CGE models often treat carbon taxes and tradeable carbon permits as identical and, therefore, represent them by a single (tax) instrument. Because Australia is likely to be a net importer of permits under an international trading scheme, modelling of tradeable permits needs to allow for a transfer to the overseas sector arising from any net import of permits.

Global models distinguish taxes and tradeable permits as a matter of course. In GTEM, the marginal cost of abatement is assumed to vary across zones under independent abatement (because there are no transfers of tax 'offsets' between countries), but not under a full emission trading scheme. In G-Cubed, the distinction is that permit trading, but not taxation, gives rise to wealth effects.

Understanding how modellers have represented a particular policy is therefore important for determining how realistically the model can estimate its effects. Being aware of any assumptions concerning the policy environment is also important. When modelling international emission trading, for example, it is usual to assume that each zone implements fully cost-effective domestic policies, that no costs are involved in the operation of emission markets, and that there are no regulatory constraints (Ghersi and Toman 2000).

Both MMRF–Green and GTEM account for carbon sequestration and thus can model GHG policies that may encourage this form of carbon emission control. However, the basic scientific and economic parameters of carbon sequestration are still highly uncertain and difficult to measure, so the representation of carbon sequestration in these models can be only simplistic and speculative (N. Byron, Productivity Commission, Melbourne, pers. comm., 18 December). So, while the results from these models may provide insight into the direction of effects, much caution is needed in interpreting the numbers produced.

Table 5.1 Recent applications of Australian CGE models to GHG policy scenarios

Model/reference	*Policies/scenarios*	*Key assumptions*
MMRF–Green: Allen Consulting (2000a), *Greenhouse Emission Trading*	• Economy-wide cap and trade GHG emission permit system, with permits auctioned	• Modelled as a uniform tax on all GHG emissions covered by the model • Revenue recycled as a reduction in consumption taxes
	• Economy-wide cap and trade system, with permits grandfathered	• Modelled as a tax with revenue returned instantly to emitting industries • Some of the value of permits remitted overseas due to foreign ownership
	• Cap and trade system applying to stationary energy only, with permits grandfathered	• Modelled as a tax on emissions of stationary energy industries with revenue returned instantly
	• Combination of regulatory measures and economic instruments (petrol tax and cap and trade system applying to stationary energy only, with permits grandfathered)	• Grandfathered permits modelled as a tax with revenue returned. But, revenue from petrol tax not returned to community to reduce consumption taxes. Offset subsidies provided • Restrictions on land clearing; annual inspections on vehicles; an increase in fuel tax which subsidises tree planting; a vaccine for ruminant livestock; installation of ceiling insulation in existing dwellings; increased energy efficiency in industry through an enhanced Greenhouse Challenge program • Permit price set to ensure Kyoto target is satisfied, given the regulatory measures *General*: No international permit trading
MMRF–Green: Allen Consulting (2000b), *Meeting the Kyoto Target: Impact on Regional Australia*	• Economy-wide cap and trade GHG emission permit system, with permits grandfathered to domestic industries	• International permit trading with Australia as a price taker in the permit market.
	• Economy-wide cap and trade GHG emission permit system, with permits sold by the government at the internationally established permit price	• International permit trading, with Australia as a price taker in the permit market • Auction (sales) revenue recycled as a broad cut in consumption taxes

(continued on next page)

Table 5.1 (continued)

Model/reference	*Policies/scenarios*	*Key assumptions*
MM600+: Econtech (2000), *The Potential Impact of Taxing Transport to Reduce Greenhouse Emissions*	• Transport tax – A$27/t CO_2 • Transport tax – A$206/t CO_2 • Transport tax – A$346/t CO_2 • Transport tax – A$594/t CO_2	• All transport tax scenarios – Tax on only emissions from transport –Tax on only CO_2 emissions from fuel combustion – Tax applied to domestic transport – Tax applied only in Australia
	• Broad emission tax on all forms of energy – A$7/t CO_2	
	• Broad emission tax on all forms of energy – A$35/t CO_2	• 11 per cent cut in the world coal price
		General: Revenue from taxes recycled as a reduction in the labour tax, with a neutral impact on budget deficit
GTEM: Brown et al. (1999), *Economic Impacts of the Kyoto Protocol*	• Annex B countries using independent abatement to meet Kyoto commitments	• A tax imposed on GHG emissions (point taxation), which could represent a domestic emission trading scheme or a uniform carbon equivalent penalty applied in a particular zone • Revenue recycled to the economy in a lump sum fashion, which has a neutral impact
	• Annex B countries using an international tradeable emission quota scheme to meet Kyoto commitments	• A uniform carbon equivalent penalty applied across Annex B countries to meet the aggregate emission target • Entire quota for a zone allocated to households
GTEM: Tulpulé et al. (1999), *The Kyoto Protocol: An Economic Analysis using GTEM*	• No trading	• Annex 1 zones acting independently to meet Kyoto commitments (emissions of CO_2 from fossil fuel combustion)
	• Annex 1 trading	• Annex 1 zones engaged in emission trading
	• 'Double bubble'	• Umbrella group, and European Union and eastern Europe — trading within each group but not between
		General: Revenue from carbon penalty returned to economy in lump sum, with a neutral effect

(continued on next page)

Table 5.1 (continued)

Model/reference	Policies/scenarios	Key assumptions
GTEM: Polidano et al. (2000), *The Kyoto Protocol and Developing Countries*	• Annex B countries using an international tradeable emission quota scheme to meet Kyoto commitments	• Certified emission reductions (CERs) available under the clean development mechanism, with uniform improvements in the thermal efficiency of 2.5 per cent and in thermal electricity production of 7.5 per cent applied across all non-Annex B zones • Certified emission reductions as perfect substitutes with tradeable Annex B emissions quotas
	• Annex B countries using independent abatement to meet Kyoto commitments	*General*: Sequestration from afforestation and reforestation associated with timber supply accounted for, including reference case and policy induced sequestration
G-Cubed: McKibbin, Shackleton and Wilcoxen (1999a), *What to Expect from an International System of Tradeable Permits for Carbon Emissions*	• Unilateral stabilisation by the United States using auctioned carbon emission permits	• Acquittal for use of primary fossil fuels • Policy announced 10 years before implementation
	• Emission trading system in each OECD zone	• No international trading
	• Emission trading system in each OECD zone	• International trading among OECD zones *General:* Permits auctioned, with revenue recycled as a deficit-neutral lump sum payment to households
G-Cubed: McKibbin et al. (1999b), *Emissions Trading, Capital Flows and the Kyoto Protocol*	• Unilateral stabilisation by the United States using auctioned carbon emission permits	• No international permit trading
	• Emissions trading in each Annex 1 zone	• No international permit trading
	• Emission trading in each Annex 1 zone	• International permit trading
	• ‘Double bubble’ — emission trading within each of two Annex 1 zones	• Permit trading between zones divided into two groups — OECD zones and the rest of the Annex 1 zones
	• Global trading — Annex 1 and non-Annex 1 developing zones	*General*: Permits auctioned, with revenue recycled as a deficit-neutral lump sum payment to households

Other key issues with CGE modelling of GHG control policies include the treatment of the revenue raised from a GHG policy and how far in advance the policy is announced. Many models assume that the revenue raised from GHG policy initiatives is returned to the economy as a lump sum payment to the taxpayer. However, assumptions about the way in which revenue raised is used (for instance, on increased government spending, reducing the budget deficit or cutting specific taxes) have an important impact on projected costs of control (Industry Commission 1991; Repetto and Austin 1997). Policies that raise revenue that can be used to adjust the overall tax system have considerably different impacts from revenue-neutral policies (Kopp and Toman 1997). The overall welfare costs of GHG control will usually be reduced if revenue raised is used to reduce specific taxes such as capital taxes (McKibbin 1998) and payroll taxes or investment taxes (Hamilton and Quiggin 1997), rather than returned as lump sums; however, the distribution of welfare is not necessarily improved. Table 4.7 shows the range of direct and indirect taxes specified in the models. MM600+ distinguishes between a wide range of indirect taxes, which allows it to capture many distorting effects.

To improve assessments of the different policy options for recycling revenue, model documentation needs to provide more detail on which thresholds can be incorporated into various person- or business-based taxes such as personal or corporate income tax. None of the models clarifies whether they can and do specify thresholds above which the tax per marginal unit is paid, and below which either no tax is paid or a subsidy is paid for reductions.

MMRF–Green specifies a firm-specific wage-bill threshold for payroll taxes. Payroll tax is paid only at the marginal rate if the wage bill is over the threshold; otherwise, no tax is paid. This approach can be (but currently is not) applied to any of the tax rates in the model. MM600+ also models the payroll tax threshold, which affects the choice of business size in each industry. The model applies an average rate of income tax to the representative household. However, welfare effects are calculated for different income levels based on changes in the price of essential and non-essential consumption. GTEM distinguishes between total emissions and taxable emissions. In calculating the latter, GTEM has a provision to exempt some emissions from being taxed. In a standard simulation, emissions from some use of own product (that is, oil being transformed to make petroleum products) are exempt from being taxed. A small modification to the formula, which accounts for emissions over and above the threshold, would allow GTEM to capture the implementation of emission thresholds.

The expectations of economic agents, along with when the policy is announced, also affect the calculation of control costs in dynamic models. Other factors being equal, if agents adjust to the new policy environment instantaneously and fully, then control costs will be higher than if they adjust slowly over time. In dynamic models the expectations of agents are assumed to be full rational expectations, myopic expectations or a combination. Rational expectations are considered to be better suited for long run analysis of well-anticipated policies, while myopic expectations provide some insights into the short run adjustments arising from policy surprises (Kopp and Toman 1997). G-Cubed is the only model that assumes that households and firms have rational expectations to some extent (rational expectations apply to 30 per cent of agents). People that have rational expectations 'see' the future clearly and respond in the current period to satisfy objectives such as emission targets optimally over time. Capital adjustment is therefore more gradual and thus less costly in this case than if economic agents are assumed to be completely myopic (as is the case in MMRF–Green and GTEM).

The extent to which expectations are important depends on the period of interest for the particular analysis. MMRF–Green, GTEM and G-Cubed are suited to analysing the short to medium run and thus the period in which transitional effects are likely to arise. However, G-Cubed can also analyse long run effects because it models long run optimising behaviour. MM600+, being a long run comparative static model, is suited to analysing long run effects.

5.2 What are the distributional effects?

The impacts of GHG control policy will not be distributed equally across all sectors in the economy. Consumers and producers of fossil fuels are specific groups that may bear a greater proportion of the costs. These costs will also have an effect on regions where such groups are located. GHG control, therefore, gives rise to consumer, producer and geographically related distributional issues.

CGE modelling not only can help to assess such impacts quantitatively, but also can analyse the effects of policies that attempt to overcome them. To offset impacts on consumers and producers, for example, some of the following policies may be implemented (some of which are included as 'revenue recycling'): reductions in income or payroll tax rates for low income earners; reductions in the consumption tax (goods and services tax) rate; increases in income tax rebates; finance assistance for energy conservation measures; company tax exemptions; partial offsets of profit losses by grandfathering a proportion of permits allocated; and changes in tax rates. Given the large range of policies that could be used, it is important to identify which are likely to relieve unacceptable distribution burdens at least cost. This is an example of how the policy choices and distributional detail available in a model cannot be considered in isolation.

How well each model undertakes this type of analysis depends on its level of sectoral and regional detail, among other factors. Although the two national models (MMRF–Green and MM600+) provide more detail for the Australian economy and, therefore, can shed more light on domestic distributional issues, international impacts must be imposed exogenously via the setting of export and import prices taken from other models. The two global models (GTEM and G-Cubed) avoid this problem by linking zones through flows of investment and commodities and, in the case of G-Cubed, financial assets. In providing a wider set of interactions they forgo much of the individual economy detail, but capturing international links is important. The use of global models to analyse distributional issues at the more aggregated level can improve understanding of the effects of transaction costs, the effects of carbon leakage, and the impact of international commodity trade and financial flows on international permit trading (Ghersi and Toman 2000).

Understanding the international dimensions of GHG policy is also important for Australian policy analysis for additional reasons. Australian GHG policy is being driven by international negotiations, so international effects arising from them do matter. Further, because Australia is a small open economy, it is affected by what happens in the global economy in terms of international capital flows and trade related impacts. The model needs to capture any changes in real exchange rates that may occur as a result of a global redistribution of investment needs. There appear to be substantial benefits from using a global model to simulate external conditions, and then linking these to a national model for more detailed analysis of domestic distributional issues.

5.3 What overall reduction of GHG emissions is desirable?

Some discussion of how well the models assess the overall costs and benefits of GHG control is appropriate here, because it raises questions of more general interest. Sections 5.3.1–5.3.3 consider the costs of GHG control, while section 5.3.4 considers the benefits. Three related assumptions have major influences on the marginal cost of abatement: the reference case (‘business-as-usual’) emissions projected by the model; the size of the substitution and demand elasticities; and the representation of technical change (Weyant and Hill 1999). Each are discussed in turn.

5.3.1 Reference case emissions

Other factors remaining constant, the higher the reference case emissions, the higher are the costs of implementing some absolute GHG policy target (Weyant and Hill 1999). Factors important in determining reference case emissions are population and economic activity, the availability of energy resources and their prices, and the availability and cost of technology (Weyant 2000). The emission database used in the model also has an important influence on reference case emissions. The more current the database, the more likely it is to capture any energy policy changes that have occurred and thus have affected the emission intensity of the economy. Of the four CGE models reviewed, GTEM is the only one that endogenously determines population; the other models rely on external population growth projections. The four CGE models also assume that production uses constant-returns-to-scale (CRS) technology. This assumption has implications for the availability and cost of future energy resources and technologies, which may (as has been the case with solar and wind power) be subject to increasing returns to scale (Diesendorf 1998).

5.3.2 Input and demand substitution

All input and demand substitution elasticities in a CGE model are important for results, but some are relatively more important than others, depending on the policies being analysed. Fossil fuel combustion significantly contributes to GHG emissions, so the models' assumptions about the substitution possibilities among both capital and energy inputs are important. (They will also affect the distributional results.) To avoid complexity and maintain a focus on key issues, the following discussion does not refer to the values of other substitution elasticities.

Capital enters all the models as an aggregate for each industry sector. Substitution between different capital inputs is therefore not captured. However, assumptions relating to changes within the capital aggregate over time vary between the models (see section 5.1.2 for comments on expectations effects). MMRF–Green and MM600+ treat capital similarly in long run comparative static simulations. GTEM assumes that each industry sector's capital stock instantaneously adjusts to any policy change. MMRF–Green and G-Cubed constrain year-by-year changes in each industry's capital stock by assuming slow capital adjustment due to investors' perceptions of risk and the presence of adjustment costs, respectively. The speed at which capital stocks are allowed to adjust to GHG policy initiatives directly affects the overall cost to the economy.

Substitution between energy inputs is permitted in all four models. The overall input substitution possibilities in the models are discussed in section 4.3.2, and the substitution possibilities for the production nodes relating to energy bundles (including elasticities) are shown in table 4.6. While all the models use CES functions to represent the substitution between different forms of energy, the types of energy included in the bundle (electricity supply in the case of MMRF–Green) and the position of the bundle in the production structure vary. The CES function assumes that substitution between energy inputs is a smooth and continuous process, unconstrained by the current or expected range of possible technologies. Further, the models assume that substitutions between energy inputs is costless.

The extent to which the models capture changing patterns of energy use in response to relative price changes arising from GHG policy depends on how the models specify these substitution possibilities. The use of nested CES functions means that substitution possibilities are a complex function of the pattern of the nesting, the nodal substitution elasticities and the input cost structure of a particular industry. It is therefore difficult to identify, from the information presented in section 4, (a) the exact energy substitution possibilities for each model and (b) their implications for results. Depending on how models specify the substitution possibilities, different energy types may act as either substitutes or complements for an industry. The only way to identify substitution possibilities is to present the full range of elasticity values for each pair of inputs for all industries. Perhaps this task should be undertaken in the future.

If models do not accurately represent the complete range of substitutions achievable in the economy, then cost and benefit estimates may be misleading. A recent study identifies the three most important substitutions influencing how an economy will respond to climate change policy: flexibility in production, flexibility in consumption, and flexibility between labour and leisure (Jorgenson et al. 2000). The flexibility by which an economy can move production away from emission-intensive sectors to less emission-intensive sectors will affect GHG control costs. How well each model captures this flexibility depends on the behavioural and technical assumptions about production and consumption, and on the extent of emission coverage.

G-Cubed’s composition of production and consumption allows a high degree of flexibility in agents’ response to GHG policies; however, it covers only carbon emitted from fossil fuel combustion. MM600+ also captures only emissions from fossil fuel combustion (carbon dioxide), but it provides a more comprehensive set of substitution possibilities by allowing the household to substitute both between and within broad consumption groups, and by identifying freight transport separately in its production structure. Apart from MM600+ having more substitution possibilities, the consumption structure of that model is similar to that of MMRF–Green and GTEM. For production, both MMRF–Green and GTEM distinguish between sectors requiring energy-intensive inputs, either by using different production structures (electricity supply in MMRF–Green, and the electricity and iron and steel industries in GTEM) or, as in MMRF–Green, by using different substitution elasticities. MMRF–Green and GTEM also extend their range of emission coverage beyond fossil fuel combustion. For the labour–leisure trade-off, G-Cubed is the only model that allows the labour market to vary from its full employment level.

GTEM's technology bundle approach is a significant departure from how the other models treat both energy production and use. Rather than allowing for the substitution between inputs, it allows for substitution between technologies. While this approach means that energy and capital cannot be substitutes for one another within a technology, the technology bundle allows for substitution between less energy-intensive and more capital-intensive technologies (Truong 1999, pp. 14–15). Although MMRF–Green also uses a separate production structure for electricity supply, it adopts a more conventional CES formulation.

This raises the issue of how well either the technology bundle approach or a CES formulation captures the effects of relative price changes. The CES formulation may, for example, provide a less suitable representation of the substitution possibilities in industries with a limited number of technologies. In this situation, by assuming production is CES, the model may produce results based on unrealistic production techniques. This may not be an issue for small relative price changes, but it could be for large ones. Further, the technology bundle approach may not provide as much flexibility in response to small relative price changes as does the CES formulation. Insights into how such issues affect results would be useful.

Given limited information, the only possible assessment is that the models' treatment of substitution possibilities in production and consumption are very different, and that this difference is due to structural differences between the models and the different methods by which the models obtain elasticity values. Deciding which model provides a better representation of the underlying behaviour being modelled is an empirical question, highlighting the importance of model validation in any evaluation of these models.

5.3.3 Technical change

Technical change here means change in the efficiency of input use enabled by technical innovation (movement of the production possibility frontier) that lies beyond existing substitution possibilities (movements along the possibility frontier). It lowers the costs of GHG control by reducing the amount of GHG per unit of output emitted by industry. The assumed rate of technical change has a large effect on the substitution possibilities among fossil fuel energy inputs and other inputs.

The difference between assuming a 1 per cent and 2 per cent rate of technical change over 10 years, is an improvement in energy efficiency of about 11 per cent (and about 27 per cent over 20 years).

In practice, the rate of technical change in each industry sector should not be an exogenous constant but endogenous — that is, it should respond to movements in relative prices. As the prices of fossil fuels become higher, more effort will be directed into research and development of alternative energy forms. The modelled cost of GHG abatement has been shown to be very sensitive to whether technical change is imposed exogenously or endogenously (Dowlatabadi 1998).

Of the four models, MMRF–Green and GTEM model endogenous technical change for industries emitting noncombustion GHGs, but they do not model it as an endogenous variable related to current and expected prices (see section 4.3.3). These two approaches attempt to account for the technological response to penalties that may arise from GHG policy. Technical change in other industries (and in the other two models) are imposed using one or more exogenous rates of change. MM600+ and G-Cubed capture the effects of technical change on only carbon dioxide emissions.

G-Cubed, by using a very flexible representation of production technology, can capture a larger set of input substitution possibilities than can the other models. This flexibility allows it to capture more technical change that may occur with substitution between inputs (capital for energy, for example), but this is still not endogenous technical change.

5.3.4 Identifying the benefits of GHG control

A study by Repetto and Austin (1997), found that two of the seven important assumptions that accounted for 80 per cent of the variation in the projected economic impacts produced by models analysing GHG policy related to whether the models accounted for the benefits of pollution and environmental damages avoided. None of the four models reviewed here accounts for the benefits of reducing GHGs, because this requires modelling of the global climate system and its effects on output and welfare.

5.4 Sample results on marginal abatement costs: the importance of assumptions

Section 5.3 highlighted the important role of key assumptions in determining the projected costs and benefits of GHG policies. A recent worldwide comparison of global economic models of climate change policies found that the marginal cost of abating carbon emissions varied widely across models (Weyant and Hill 1999). The researchers' view is that of the many factors that could account for such differences, the key ones were the reference case projections of output and population growth, the energy substitution possibilities and the treatment of technical change.

No comparative policy runs from the four models were commissioned for this report. A comparison of results from CGE models without subjecting them all to the same policy run is thus difficult and liable to be misleading. Factors such as when the analysis was performed, the type of currency exchange rate used, the specific policy issue that was analysed, and changes in a model's structure and/or database affect results. Nevertheless, table 5.2 contains a rough comparison of recent projections of marginal abatement cost — the marginal cost of a percentage reduction in emissions varies by up to a factor of about 2. Reference case emissions are not included because they are difficult to obtain for the various studies. The technical change details are from section 4.3.3. Values for the marginal cost of abatement and the change in carbon dioxide emissions are from the modellers directly in the case of MMRF–Green and MM600+, and from published studies for GTEM (Polidano et al. 2000) and G-Cubed (McKibbin et al. 1999b). Where the marginal abatement cost was not given in 1995A$, an A$/US$ exchange rate of 0.738 was used (compared with rates often around 0.55 during the period of this study). Global GHG policies could cause significant changes in real exchange rates, and the inability of national models to endogenise these changes reinforces the case for linking a national model and a global model. Where a number is missing, a question mark (?) indicates that comparable details could not be obtained. All numbers relate to Australia and assume that the Kyoto Protocol targets for 2010 are met with permit trading among all Annex I countries but not worldwide.

GTEM calculated a carbon equivalent penalty per tonne under international emission trading of US$114 (Tulpulé et al. 1999), approximately US$85 (Brown et al. 1999) and US$58 (Polidano et al. 2000) in successive analyses. The differences in these projections are due to more extensive accounting of GHGs in addition to carbon dioxide from fossil fuel combustion, and the effect of carbon sequestration. The differences highlight the importance of assumptions and data in generating projections.

Table 5.2 **Rough comparison of some model results on marginal abatement costs**

	Reference case assumptions			*Results in 2010*		
Model	*Output growth (GDP)*	*Population growth*	*Technical change*	*Marginal cost per tonne of CO_2 abatement*	*Change in CO_2 emissions*	*Cost per % cut in CO_2 emissions*
	%	*%*		*1995A$*	*%*	*1995A$*
MMRF–Green	2.9	1.2	Varies across sectors in line with recent history	26	–20	1.3
MM600+	?	?	Varies across sectors	34	–14	2.5
GTEM[a]	3.5	1.15	Implied level of technical efficiency	21	–10	2.1
G-Cubed[b]	?	0.8	AEEI; energy sector productivity growth; non-energy productivity growth	23	–13	1.7

[a] Polidano et al. (2000); Annex B-wide emissions trading.

[b] McKibbin et al. (1999b); Annex 1 international emission trading.

Table 5.2 also gives the estimated change in the marginal cost of a 1 per cent change in emissions. Although the percentage variation between the highest and lowest estimate is large, from the information obtained it is impossible to determine the significance of any of the key factors noted by Weyant and Hill (1999). Again this reveals the importance of revealing the likely effect of modelling assumptions and structures on results — a task that may include using sensitivity analyses, which are the topic of the next section.

5.5 Model validation and sensitivity analysis

As discussed in section 4.6, the models should be transparent to those using the results. In addition, analyses of GHG policy should include information on validation — that is, information on how well the model represents the economy or economies being modelled. If possible, modellers should show how well their models represent an actual past event that involved roughly similar policy instruments (or equivalent exogenous shocks) to those being proposed for GHG control. Such an exercise would need to be designed to prevent results being driven by re-calibration, and thus to ensure each model's structure was being truly validated. Possible validation techniques include backcasting and *ex post* analysis (Hertel 1999). The first technique requires stepping the model back in time to examine how well it replicates what happened. An alternative, *ex post* analysis, can be used on data series; it involves not using the complete series in setting parameters, and examining how well the model tracks the remaining data as it projects into the future.

For this report, the modellers did not volunteer any documentation of validation exercises they may have undertaken, and none of the documentation provided or publicly available mentioned any validation that is both recent and relevant to long run scenarios of greenhouse gas control. In future model development, it would be desirable if modellers could carry out and report on validation exercises as standard practice, since potential users or providers of development funding will always be interested to know the results. MM600+ is the only model for which there is recent evidence on how well it performed in representing actual behavior. Results comparing the predicted effect of the new tax system and the actual consumer price index show, for most consumption categories, that the model performed very well. Given that changes to all the models are ongoing, potential users or providers of development funding should expect evidence from validation experiments.

In addition to validation evidence, sensitivity analysis of key assumptions is also important. In the studies identified in table 5.1, sensitivity analyses were provided for both the GTEM and G-Cubed applications. For GTEM, Brown et al. (1999) and Tulpulé et al. (1999) analysed the sensitivity of the carbon emission penalty to assumptions about both the restrictions on electricity technologies (the availability of nuclear and hydro electricity generation) and the growth in reference case emissions in the former Soviet Union. They found that relaxing both assumptions reduced the required carbon penalty. The study by Polidano et al. (2000) includes sensitivity analysis of the Armington elasticities, fossil fuel supply elasticities and reference case emissions. While it showed that changing the reference case values of these parameters changed real impacts on gross national product in non-Annex B zones, the directions of these impacts were not affected.

The sensitivity analysis reported for G-Cubed in McKibbin, Shackleton and Wilcoxen (1999a) relates to the Armington elasticities. This study found that these elasticities, although important in determining the size of capital flow and exchange rate responses to permit trading, did not alter the key insights obtained from the model. The other G-Cubed study, McKibbin et al. (1999b), conducted sensitivity analysis of the Armington elasticities too, but also analysed the impact of changing the capital adjustment cost parameter. A lower adjustment cost parameter was found to significantly affect investment in developing countries and, consequently, their exchange rate, gross domestic product and gross national product.

Sensitivity analysis, however, depends on how significant the parameters chosen for analysis are for the final results, and the choice of the parameters analysed is often in the hands of the modeller. This is why any evidence from previous analyses on a model's predictive abilities is useful for model validation, instead of complete reliance on sensitivity analysis.

6 Conclusions

This report is a review of the individual technical abilities of four computable general equilibrium models — MMRF–Green, MM600+, GTEM and G-Cubed — to simulate various policies, that an Australian government may pursue as part of its commitment to control greenhouse gas (GHG) emissions. Section 4 is an examination of the differences and similarities among the models, and section 5 is a discussion of how significant these may be for modelling GHG control policies. No conclusions are drawn about the overall abilities or output quality of any model; this is not part of the study objectives and, in any case, it is impossible to do without first knowing the questions that the model is intended to answer. The agenda of questions that policy makers may ask is long, and each model can contribute to the analysis of different sets of policy questions.

Moreover, no model is fixed. Given time and money, many developments are possible which would fill in acknowledged gaps in the current version of each model. Table 6.1 summarises recent development proposals by the modellers. The feasibility, timing and value for money of these proposals are not discussed here, although any comments about the specialities or shortcomings of current model versions must be considered in the context of these proposals.

6.1 What can be concluded about the models

The most obvious difference among the four current models is in their treatment of international flows of both goods and assets. Two models are national (MMRF–Green and MM600+) and two are global (GTEM and G-Cubed). The former give regional and more sectoral details on the Australian economy; the latter provide information about the effects on Australia of international phenomena, such as whether the final implementation of a global GHG control treaty allows full, restricted or no trading of GHG permits between countries. Thus, at face value, the former are more relevant to considering the detailed distributional effects of potential GHG control policies in Australia, and the latter are more relevant to determining Australia’s negotiating stance at international meetings such as the Sixth Conference of Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in The Hague, November 2000, and the next meeting in Bonn, July 2001.

However, policy concerns often cannot be so neatly separated. Domestic distributional concerns affect a country's international negotiations, and vice versa for a small open economy especially: GHG policy in Australia is strongly driven by international negotiations under the UNFCCC. And, the choice between a national and a global model is particularly difficult when considering trade-exposed industries such as cement and aluminium. Should one use a national model with good sectoral and regional detail to highlight localised employment changes, or a global model which better deals with trade interactions with Australia's competitors, especially those in non-Annex B countries? The ideal solution would be a combined model: a national Australian model that is comprehensively and consistently linked with a global model. Table 6.1 shows that modellers recognise this need and are either already working on or proposing the development of such combined models.

Apart from the obvious difference between national and global models, a few other differences among the current model versions (which would be removed only by significant development) are worth highlighting. MMRF–Green has the most regional detail, both in having eight independent but inter-linked State/Territory models and in the number of subregions for which it can disaggregate results. MMRF–Green and GTEM have the greatest technological detail, both of methods of electricity generation (including renewables) and of the different GHGs. MM600+ has the most product and sectoral detail, and partly as a result of this, also the most detailed set of taxes. This model, however, is less documented than the other three models, and its provision of access to the model software in spreadsheet form can only partly compensate for this. With the proposed development of AUSTEM as reported in section 3.3.10, GTEM is the closest to being part of a combined global–national model. Finally, G-Cubed has the most sophisticated treatment of time and money. Agents are assumed to have forward-looking expectations to some extent, asset markets and international flows of financial capital are explicitly modelled, and, partly as a result, the model allows for transitional, involuntary unemployment.

It is hard to judge which of these various features has the most influence on the 'headline' results of the model, such as the permit price per unit of carbon dioxide equivalent needed to achieve a given reduction in GHG emissions in 2010, or the loss in gross domestic product from meeting Australia's Kyoto target. Given the wide disparities reported in table 5.2, further work is needed here, probably involving the kind of scenario-based comparisons used in James (1996) and Weyant and Hill (1999).

Table 6.1 Summary of proposals for further development of the models

Type of development	*MMRF–Green*	*MM600+*	*GTEM*	*G-Cubed*
Development of a detailed Australian model	Already exists as independent State models; proposed disaggregation to statistical divisions	Results disaggregated by State already reported	AUSTEM under development, could be enhanced; possibility of linking to MMRF–Green	Under way
Link to global model	Proposed link with GTEM	Proposed	Already exists	Already exists
Inclusion of CH_4 and N_2O	Already exists	Proposed	Already exists	Proposed
Development of forestry sector, to allow for carbon sequestration	Proposed		Proposed	
Inclusion of land clearing and agricultural sinks			Proposed, as part of AUSTEM development	
Further detail of industry sectors	Proposed for transport and oil refining	Some already exists	Proposed for transport, renewable electricity and aluminium	
More detail on taxation, including the goods and services tax	Proposed	Already exists		
Explicit permit market with transactions costs	Proposed			
Technology subsidies			Proposed	
Energy efficiency measures by households			Proposed	
Statistical modelling of uncertainty	Proposed			Under way

Prior to such work, each model should be more explicitly validated; as discussed in section 5.6, modellers should, ideally, show how well their models represent an actual past event that involved roughly similar policy instruments (or equivalent exogenous shocks) to those being proposed for GHG control. An example of such a past event is the major fall in oil prices in the mid 1980s. Other recommendations for further work are given in the next section.

6.2 Recommendations for further work

The recommendations in section 6.2.1, in no particular order of cost or priority, are for work complementary to scenario-based comparisons which can readily be carried out within the framework of CGE modelling. Also mentioned in section 6.2.2 is work that cannot easily be conducted in this framework.

6.2.1 Developments inside CGE models

1. None of the models appears to allow for significant endogenous technical progress (increases in total factor productivity) — that is, none allows for faster development of new technologies that reduce GHG emissions (as opposed to substitution towards existing, low-emission technologies) — in response to the price of emissions created by control policies. This is worth exploring, particularly given its potential for reducing emissions over the very long run. A crude first idea may be to make the annual rate of technical progress in saving fossil fuels some positive function of increased fuel prices in the model. However, careful thought would be required on at least two points (see Goulder and Schneider 1999). First, a 'learning by doing' process may point in the other direction; progress could slow in precisely those sectors (such as coal) with the highest fuel price rises, because output in those sectors is stagnant or declining, so capital is not renewed. Second, an assumption of continual technical progress can imply thermodynamically impossible efficiencies in the distant future, particularly when individual technologies are specified (as MMRF–Green or GTEM).

2. None of the models reports rents (short run or long run profits in excess of normal) made by firms or sectors of firms. In the case of MMRF–Green, MM600+ and GTEM, there are none to be reported because the models assume away the possibility of super-normal profits. In G-Cubed, the explicit modelling of adjustment costs means firms make short run super-normal profits but they are not reported. Given the possible political effect of changes in profits on the acceptability of various initial distributions of emission permits, work in this area could be fruitful (for an example applied to the US economy, see Bovenberg and Goulder 2000). Treating super-normal profits as just being passed on to a representative shareholder, no different from the representative consumer, does not fully reflect their political or even economic impacts. Thus,

it would be interesting to see results reported for other than the polar cases of all permits being initially auctioned or all permits being initially grandfathered.

3. All four models currently use just one household type to represent consumers in each separate economy. Equity effects for different income levels can be calculated only by disaggregating the basic results for this single representative household. To better understand the equity effects of GHG policies, it would be desirable for households to be initially modelled by different income levels, as well as by sector and region. This approach would reduce the influence of any aggregation bias on results in cases where a policy instrument does not affect all households equally. However, this would probably be a major and difficult undertaking, in terms of increased data needs and computational complexity.

4. The developments proposed for GTEM on technology subsidies and energy efficiency measures by households, and for MMRF on transaction costs in the permit market, are welcome. The latter in particular is an interesting idea about including information costs that CGE modelling has previously ignored. However, there will be a limit to which such policies can be modelled, specifically when they involve non-price elements such as exhortation, information, standards and regulations. For completeness, non-price policies are considered in the next section.

6.2.2 Developments outside CGE models

Computable general equilibrium (CGE) modelling can say little about the economic potential of non-price policies, such as exhortation, information, public programs, land-use planning, government purchasing, labelling and standards for buildings and products (see section 5.1.1). It can explore the total effects of assuming how much extra technical efficiency may result from such policies. But, it cannot analyse the detailed working of the effects or the priorities among them. It cannot, for example, directly model the psychological or institutional workings of how much an advertising campaign can lead consumers to lower permanently the rate of return that they demand for investments in energy efficiency. For this question, a bottom–up model may provide useful information. Neither can CGE models indicate much about some short run, economy-wide impacts (such as those on inflation), for which a macroeconomic model would be more appropriate. Thus, the exclusive focus of this report on CGE modelling is not a conclusion that other modelling techniques or non-price policies should be overlooked. As well as setting sound price-based policies, governments can and should act to research, coordinate, inform and motivate the technical, institutional and cultural changes that also have a significant role in controlling GHG emissions.

A Mathematical production and utility functions used in CGE modelling

Notation:$Y =$ produced output, or utility, as a function of goods inputs
X_i, where $i = 1, \ldots, n$ are quantities of n goods that are inputs
A, a_i, b_i, p_i, ε are positive parameters.

CES (constant elasticity of substitution)

$Y = A(\sum_{i=1}^{n} a_i X_i^{-\varepsilon})^{-1/\varepsilon}$; usually $\Sigma a_i = 1$ is assumed, to give CRS (constant returns to scale)

Elasticity of substitution $\sigma = 1/(1+\varepsilon)$

Cobb-Douglas (unit elasticity of substitution)

$Y = A\prod_{i=1}^{n} X_i^{a_i}$, with $\Sigma a_i = 1$ usually assumed for CRS

Special case of CES with $\varepsilon = 0$; elasticity of substitution $\sigma = 1$.

Linear (infinite elasticity of substitution)

$Y = A\sum_{i=1}^{n} a_i X_i$; always CRS whatever the value of Σa_i

Special case of CES with $\varepsilon = -1$; elasticity of substitution $\sigma = \infty$

Leontief (zero elasticity of substitution)

$Y = A \min_{i = 1, \ldots, n} \{b_i X_i\}$; always CRS whatever the value of b_i

Special case of CES with $\varepsilon \to \infty$; elasticity of substitution $\sigma = 0$

CRESH (constant ratios of elasticities of substitution, homothetic)

Defined by $\sum_{i=1}^{n} a_i \left[\frac{X_i}{h(Y)}\right]^{-\varepsilon_i} = 1$ with $0 \le Y \le \bar{Y} < \infty$, $h(0) = 0$, $h(\bar{Y}) = \infty$, $h'(Y) > 0$.

CRESH is CRS if $h(Y) = Y$; CRESH becomes CES if all $\varepsilon_i = \varepsilon$

(General) linear expenditure system (LES)

$$Y = A\left[\sum_{i=1}^{n} a_i (X_i - b_i)^{-\varepsilon}\right]^{-1/\varepsilon}$$

This cannot be CRS unless all the $b_i = 0$ and $\Sigma a_i = 1$, in which case it becomes the CES form; elasticity of substitution $\sigma = 1 / (1+\varepsilon)$; demand function is $q_i = b_i +$ [(function of prices) x income]; linearity with respect to income gives the name

Stone-Geary (also called the LES by some authors)

$Y = A\prod_{i=1}^{n}(X_i - b_i)^{a_i}$ with $\Sigma a_i = 1$ usually assumed

Special case of general LES with $\varepsilon = 0$; elasticity of substitution $\sigma = 1$

CDE (constant difference of elasticities of substitution) (Hanoch 1975)

Y is defined by $\sum_{i=1}^{n} G^i(C/p_i, Y) = 1$, where p_i = price of good i, $C = \Sigma p_i X_i$ = total input cost, and $G^i(C/p_i,Y) = B_i(Y).(C/p_i)^{1-ai}$ for $\alpha_i \neq 1$, or $B_i(Y).log(C/p_i)$ for $\alpha_i = 1$.

Differences in elasticities of substitution, $\sigma_{ik} - \sigma_{jk}$, depend on only i and j, not k

B Summary table of CGE model features

Table B.1 **Summary table of model features**

Feature	*MMRF–Green*	*MM600+*	*GTEM*	*G-Cubed*
Model Type	*Dynamic CGE*	*Comparative static CGE*	*Dynamic CGE*	*Dynamic intertemporal GE*
Scale	*National, multi-regional, multi-sectoral*	*National, multi-regional, multi-sectoral*	*International (zones), multi-sectoral*	*International (zones), multi-sectoral*
Economic agents represented	• Producers • Investors • Consumers • Foreign purchasers and sellers • Government – State, Territory and Federal	• Producers • Consumers • Government • Foreign purchasers and sellers	For each zone: • producers • investors • consumers • government	For each zone: • producers • investors • financial markets • consumers • government
Level of disaggregation	• 1 zone · Federal Government • 8 regions (6 States and 2 Territories), each comprising: · 40 industry sectors (15 energy) · 40 capital creators · a household · a government · a foreign purchaser and seller · 45 products (15 energy) • 57 sub regions	• 1 zone · a government • 23 regions, each comprising: · 108 industries (12 energy) · a capital goods producer · a household · 672 products	• 45 zones, each comprising: · 50 industry sectors (11 energy), including 1 capital goods industry · a ‘super household’ · a government · 50 products (11 energy)	• 8 zones, each comprising: · 12 industry sectors (5 energy) · a capital goods producer · a household · a government · a financial sector · 12 products (5 energy)
Closure rules available (setting exogenous and endogenous variables)	• Comparative static closure · short run (1–2 years after shock) · long run (5+ years after shock) • Forecasting closures • Policy closures	• Comparative static closure · short run · long run (5 to 10 years)	• Short run and long run closure	• Full short run and long run macroeconomic closure with annual dynamics around a long-run Ramsey neoclassical growth model

continued

Table B.1 (continued)

Feature	*MMRF–Green*	*MM600+*	*GTEM*	*G-Cubed*
Production	Industries other than electricity supply: • 3 level nested CES production technology Electricity supply industry: • 1-level CES production technology	All industries: • total supply given by a 3-level nested production structure • Leontief for output from intermediate inputs and primary-factor, energy and freight bundles • CES for all other combinations forming these bundles	All industries except electricity and iron and steel: • Leontief for output from an intermediate-input bundle and an energy-factor bundle • CES for the energy-factor bundle, and the energy-input and primary-factor bundles • CES for the intermediate-input bundle and individual inputs formed from imported and domestic goods Electricity and iron and steel industries: • Leontief for output from a technology bundle and an intermediate-input bundle • CRESH for known technologies in the technology bundle • Leontief for specific technology inputs forming a known technology • Leontief for the intermediate input bundle (inputs not in the technology bundle) • CES for individual inputs formed from imported and domestic goods	All industries: • 3-level nested CES KLEM production technology
Household consumption	• Stone-Geary utility function (LES)	• A generalised LES (allowing substitution between and within broad consumption groups)	• A CDE demand system	• 2-tier nested CES utility function

continued

Table B.1 (continued)

Feature	*MMRF–Green*	*MM600+*	*GTEM*	*G-Cubed*
Government consumption demands	• State and Federal government demands can be set either: · Endogenously by specifying a rule · Endogenously as an instrument that achieves an exogenously determined target · Exogenously	• Assumption that the long run budget is in balance, because it must be sustainable • Use of the rate of tax on labour income as a swing fiscal policy instrument	• Assumption that the ratio of private consumption to government consumption is constant • Allocation of government consumption modelled as a Cobb-Douglas demand system • Value of each commodity purchased as a constant share of total government consumption	• Assumption that Government spending is exogenous and allocated among goods and services in fixed proportions based on historical values • Specification of budget constraint in terms of the accumulation of public debt • Different closure rules possible
Labour supply	• Labour supply at national level determined by demographic factors or by labour demand • Labour demand derived from solution to producer's problem of choosing the least cost combination of occupation-specific labour inputs • Labour mobility across regions to take advantage of regional employment opportunities	• Assumption that the labour market is assumed to be in equilibrium in the long run · Level of total employment exogenous	• Labour supply determined endogenously · Growing at same rate as working age population · Determined by population module • Full employment assumption · Downward shifts in demand offset by lower real wages growth (keeping unemployment at its natural rate)	• Labour that is perfectly mobile among sectors and within regions but immobile between regions • Long run labour supply that is perfectly inelastic · Determined by exogenous rate of population growth • Long run wages that adjust so each region is at full employment • Short run nominal wages that adjust slowly according to an overlapping contracts model · Wages based on current and expected inflation and on labour demand relative to supply

continued

Table B.1 (continued)

Feature	*MMRF–Green*	*MM600+*	*GTEM*	*G-Cubed*
Financial markets, capital flows and balance of payments	• Assumption that government adjusts macroeconomic policies to achieve a balance of trade target	• Net liabilities to foreign sector follow a sustainable path · Trade balance set equal to the cost of servicing payments on foreign owned capital · The real exchange rate determined by the model	• Current account imbalances offset by changes to the capital account to ensure a balance of payments • Changes to the capital account brought about through a flexible exchange rate	• Balance of payments achieved through any trade imbalance being offset by financial capital flows • Assumption of perfectly mobile financial capital
Capital investment	Dynamic: • Capital accumulation with the assumption of a one year lag between investment and productive capital • Use of the relationship between annual capital growth and rate of return expectations • Capital growth limited by investors' perception of risk	• Rates of return on capital fixed in the long-run, with the capital stock adjusting	• Capital accumulation determined by investment and depreciation each period	• Capital stock that changes according to the fixed rate of capital formation and the rate of geometric depreciation • Assumption of existence of adjustment costs, so investment is subject to rising marginal installation costs • Investment as a function of an after-tax marginal version of Tobin's *q* and current cash flows
Population growth	Exogenous	Exogenous	Endogenous	Exogenous
Technical change	• Imposed exogenously for intermediate-input and primary-factor use • Endogenous for the abatement of noncombustion GHG emissions	Imposed exogenously	• Imposed exogenously for all industry sectors • Endogenous for the abatement of noncombustion GHG emissions	Imposed exogenously
Imports	CES for domestic substitution (Armington preference structure)	CES for domestic substitution (Armington preference structure)	CES for domestic substitution (Armington preference structure)	CES for domestic substitution (Armington preference structure)

continued

Table B.1 (continued)

Feature	*MMRF–Green*	*MM600+*	*GTEM*	*G-Cubed*
GHG policy analysis	Emission from: • fuel combustion • fugitives • non-fuel combustion agricultural • other services • rubbish dumps • forestry • cement production • aluminium production Fuel combustion emissions: • Assumed to be directly proportional to fuel usage • Indirect forms of substitution (price induced) as the main scope for emission reduction; strength of input substitution depends on industry: – strong for electricity supply – weak for other energy-intensive commodities – inter-fuel substitution in electricity generation by region Activity (non-combustion) emissions: • Assumed to be directly proportional to output of related industries • Abatement of emissions directly related to price of emission permits (or level of CO_2 tax) • Constants of proportionality derived from point estimates of the amount of abatement likely given a particular tax level	Allows for large range of production and consumption substitution possibilities: • Distinguishes 24 different indirect taxes on industry production and products • Accounts for differences in diesel fuel tax across • qualifying road use • non-qualifying road use • rail and marine transport • agriculture and fishing use • mining use • other non-transport use • Distinguishes between road and rail freight transport	Models emissions of CO_2, methane and nitrous oxide: Carbon dioxide • Combustion sources: • coal • oil (consumption of petroleum) • natural gas • Non-combustion sources: • fugitive emissions from oil and natural gas systems • emissions from aluminium production • emissions from cement manufacture • Modelling begun on accounting for emissions from changes in land use and sequestration by sinks Methane • Includes emissions from: • the livestock sector • paddy rice cultivation • fugitive emissions from • coal mining • oil extraction • natural gas systems • Excludes emissions from: • burning agricultural residues or savannas • the disposal of solid waste • wastewater handling Waste incineration (An explicit waste industry is not currently included.)	Explicitly models carbon emission permits: • Each input used in fixed proportions to the use of an input-specific permit

continued

Table B.1 (continued)

Feature	*MMRF–Green*	*MM600+*	*GTEM*	*G-Cubed*
GHG policy analysis (continued)	• Abatement response assumed to raise the requirements for other inputs at the margin by a value equal to the tax saved • Carbon sequestered by forestry related to forestry activity as a whole, including logging		• Uses emission coefficients for the livestock sector (carbon dioxide equivalent emissions per dollar of output) Nitrous oxide • Includes emissions from – the transport sector – chemical industries – livestock waste – nitrogenous fertilisers used in agricultural industries Emission response function used to simulate the introduction of technologies and practices that reduce emissions in industries that emit methane, nitrous oxide and non-combustion carbon dioxide • Function reflecting the ability of an industry to reduce emissions per unit of output in response to emission costs • Adjustment assumed to take time, so a lagged adjustment equation is used Inter-fuel substitution and substitution between fuel and primary factors captured by an energy-factor bundle	

C Commodities and greenhouse gases covered by the models

Table C.1 **Commodity and greenhouse gas emission coverage in MMRF–Green**

Commodity	*CO_2-e from black coal combustion*	*CO_2-e from brown coal combustion*	*CO_2-e from natural gas combustion*	*CO_2-e from petrol combustion*	*CO_2-e from non-combustion*
Energy					
Black coal	✓		✓	✓	✓
Brown coal	✓	✓		✓	✓
Natural gas	✓		✓	✓	✓
Crude oil	✓		✓	✓	✓
Petroleum – auto				✓	
Aviation gasoline				✓	
Aviation – turbine				✓	
Diesel				✓	
LPG				✓	
Petroleum products – other	✓			✓	
Electricity – black coal	✓				
Electricity – brown coal		✓			
Electricity – gas			✓		
Electricity – oil products				✓	
Electricity – other					
Mineral and metals					
Iron ore	✓		✓	✓	
Non-iron ore	✓		✓	✓	
Cement	✓		✓	✓	✓
Iron and steel	✓		✓	✓	
Alumina and aluminium	✓		✓	✓	✓
Manufacturing					
Chemical products excluding petrol	✓		✓	✓	✓
Other metal products	✓		✓	✓	
Other manufacturing	✓		✓	✓	
Textiles, clothing, footwear	✓		✓	✓	
Wood and paper products	✓		✓	✓	
Building products	✓		✓	✓	
Motor vehicle parts	✓		✓	✓	

(continued)

Table C.1 (continued)

Commodity	*CO_2-e from black coal combustion*	*CO_2-e from brown coal combustion*	*CO_2-e from natural gas combustion*	*CO_2-e from petrol combustion*	*CO_2-e from non-combustion*
Services					
Trade services	✓		✓	✓	
Road transport services			✓	✓	
Rail transport				✓	
Water transport				✓	
Air transport				✓	
Other transport services	✓		✓	✓	
Electricity supply					
Urban gas distribution	✓		✓	✓	
Water and sewerage services	✓			✓	
Construction services	✓		✓	✓	
Communication services			✓	✓	
Financial/business services			✓	✓	
Dwelling ownership				✓	
Public services	✓		✓	✓	
Other services	✓		✓	✓	✓
Agriculture					
Agriculture			✓	✓	✓
Forestry			✓	✓	✓
Processed food					
Food, beverages and tobacco	✓		✓	✓	
Residential	✓		✓	✓	

Note: CO_2-e = carbon dioxide equivalent.

Source: Adapted from M. Horridge, B. Parmenter and P. Adams, Monash University, pers comm., 22 November 2000.

Table C.2 **Commodity and greenhouse gas emission coverage in MM600+**

Industry	*Products releasing CO_2 on combustion*
Sheep	
Grains	
Beef cattle	
Dairy cattle	
Pigs	
Poultry	
Other agriculture	
Services to agriculture, hunting	
Forestry and logging	
Commercial fishing	
Coal, oil and gas	Black coal (all types incl. briquettes); brown coal-lignite (incl. briquettes); crude oil (incl. Condensate); natural gas; liquefied natural gas; liquefied natural petroleum gases; oil and gas nec
Iron ores	
Nonferrous metal ores	
Other mining	
Services to mining	
Meat and meat products	
Dairy products	
Fruit and vegetable products	
Oils and fats	
Flour and cereal foods	
Bakery products	
Confectionery	
Other food products	
Soft drinks, cordials, syrups	
Beer and malt	
Wine and spirits	
Tobacco products	
Textile fibres, yarns etc.	
Textile products	
Misc. textile product manufacturing	
Knitting mill products	
Clothing	
Footwear	
Leather and leather products	
Sawmill products	
Other wood products	
Pulp, paper and paperboard	
Paper bags and products	
Printing, services to printing	
Publishing, recorded media etc.	

continued)

Table C.2 (continued)

Industry	*Products releasing CO_2 on combustion*
Petroleum and coal products	Automotive petrol; gasoline refining or blending; motor spirit (incl. aviation spirit); gas oil or fuel oil (excl. motor spirit and kerosene); kerosene (incl. kerosene type jet fuel); liquefied petroleum gas produced at refineries; refinery products nec, miscellaneous other petroleum and coal products
Basic chemicals	
Paints	
Pharmaceuticals etc.	
Soap and detergents	
Cosmetics and toiletries	
Other chemical products	
Rubber products	
Plastic products	
Glass and glass products	
Ceramic products	
Cement, lime and concrete slurry	
Plaster; other concrete products	
Nonmetallic mineral product	
Iron and steel	
Basic nonferrous metals etc. material	
Structural metal products	
Sheet metal products	
Fabricated metal products	
Motor vehicles and parts etc.	
Ships and boats	
Railway equipment	
Aircraft	
Scientific etc. equipment	
Electronic equipment	
Household appliances	
Other electrical equipment	
Agricultural, mining etc. machinery	
Other machinery and equipment	
Prefabricated buildings	
Furniture	
Other manufacturing	
Electricity generation and distribution	
Gas production and distribution	
Water, sewerage and drainage	
Residential building	
Other construction	
Wholesale trade	
Retail trade	

continued)

Table C.2 (continued)

Industry	*Products releasing CO_2 on combustion*
Mechanical repairs	
Other repairs	
Accommodation, cafes and restaurants	
Road transport	
Rail, pipeline, other transport	
Water transport	
Air and space transport	
Services to transport	
Communication services	
Banking	
Non-bank finance	
Financial asset investors	
Life insurance and superannuation	
Other insurance	
Services to finance etc.	
Ownership of dwellings	
Other property services	
Scientific research etc.	
Legal, accounting etc. services	
Other business services	
Government administration	
Defence	
Education	
Health services	
Community services	
Motion picture, radio etc.	
Libraries, museums, arts	
Sport, gambling etc.	
Personal services	
Other services	
Travel imports	

nec Not elsewhere classified.

Source: Econtech (2000).

Table C.3 **Commodity and greenhouse gas emission coverage in GTEM**

Commodity (produced by a single industry)	*CO_2 from fossil fuel combustion*	*CO_2 from other sources*	*Methane*	*Nitrous oxide*
Energy				
Coal	✓		✓	
Oil	✓	✓	✓	
Natural gas	✓	✓	✓	
Petroleum products	✓			
Electricity	✓			
Mineral and metals				
Nonmetallic minerals	✓	✓		
Other minerals	✓			
Iron and steel	✓			
Nonferrous metals	✓	✓		
Manufacturing				
Chemicals, rubber and plastics	✓			
Fabricated metal products	✓			✓
Other manufacturing	✓			
Capital goods	✓			
Services				
Trade and transport	✓			✓
Other services	✓			
Agriculture				
Paddy rice	✓		✓	✓
Grains	✓			✓
Non-grain crops	✓			✓
Livestock	✓		✓	✓
Forestry and fisheries	✓			
Processed food				
Processed rice	✓			
Meat and milk	✓			
Other processed food	✓			

Source: Brown et al (1999).

Table C.4 **Commodity and greenhouse gas emission coverage in G-Cubed**

Commodity (produced by a single industry)	*Carbon from fossil fuel combustion*	*Carbon from other sources*	*Other GHG emissions*
Energy			
Coal	✓		
Oil and gas extracted	✓		
Gas	✓		
Petroleum products	✓		
Electricity	✓		
Mineral and metals			
Other mining	✓		
Manufacturing			
Durable goods	✓		
Non-durables	✓		
Services			
Transportation	✓		
Services	✓		
Agriculture			
Forestry and wood products	✓		
Agriculture	✓		

Source: McKibbin et al (1999b).

Glossary

AEEI	Autonomous Energy Efficiency Index — a scaling factor to reduce aggregate energy use per unit of output over time. It reduces intermediate energy use in production functions
ad valorem tax	Tax levied as a given percentage of the price
Annex I (of the UNFCCC) or Annex B (of the Kyoto Protocol)	Annex of countries committed to emission abatement under the UNFCCC — generally, developed countries, or countries in transition to a market economy
Armington preference structure	An assumption used in CGE modelling that domestic and imported goods in the same sector are not perfect substitutes, such that preferences can be represented by a CES utility function
AUSTEM	Australian Trade and Environment Model; ABARE's CGE model of the Australian economy, it is already linked to GTEM but is still undergoing development and documentation
CDE utility or production function	See appendix A
CES utility or production function	A moderately general utility or production function which includes the linear and Leontief functions as special cases. See appendix A

CH_4	The chemical formula for methane (natural gas) — a powerful but transient greenhouse gas, which is emitted by mainly animal digestion and rice paddies
CO_2	Carbon dioxide — the dominant greenhouse gas, which is produced by burning/decaying coal, oil, gas or wood
Cobb-Douglas production or utility function	See appendix A
combustion emissions	Carbon dioxide emissions resulting from burning fossil fuels
constant returns to scale (CRS) production function	A function such that if all inputs are increased by the same proportion, then output is increased by that proportion also. This property is independent of elasticity of substitution. See appendix A
CoPS	Centre of Policy Studies, Monash University
endogenous	To be determined by some equilibrium condition when the model calculations are done; these include the answers for which the model has been constructed
exogenous	Fixed with some known numerical value before the model calculations are performed
financial capital	Money or some other form of paper asset that functions like money
fossil fuel	Coal, oil and natural gas
fugitive emissions	Intentional or unintentional releases of greenhouse gases from human activities. These include emissions from the combustion of fossil-fuels only if they are from a nonproductive activity

full employment	An unemployment rate equal to the 'natural' rate of unemployment
G-Cubed	Global general equilibrium growth model which is a CGE model of the world economy produced by McKibbin Software Group
GEMPACK	Computer program used to calculate the model solution in both MMRF–Green and GTEM
GHG	Greenhouse gas. The six greenhouse gases listed in the Kyoto Protocol are carbon dioxide, methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons and sulphur hexafluoride
grandfathering	Distributing emissions permits free of charge. Studies vary on whether or not the free amount distributed is assumed to be based on past levels of emissions
GTAP	Global Trade Analysis Project
GTEM	Global Trade and Environment Model, which is the latest world CGE model developed by ABARE, using many techniques and data from GTAP
induced technological change	Technological change that occurs through price-induced behaviour
IPCC	Intergovernmental Panel on Climate Change (established in 1988 by the World Meteorological Organisation and the United Nations Environment Programme)
KLEM	A type of production function with capital (K), labour (L), energy (E) and materials (M) as inputs

Kyoto Protocol	An international agreement reached in 1997 in Kyoto, Japan (but not yet ratified), which extends the commitments of the UNFCCC, particularly by setting future emission targets for each Annex 1 country
Leontief utility or production function	A utility or production function that allows no substitution between inputs. See appendix A
LPG	liquid petroleum gas
LNG	liquefied natural gas
MEGABARE	The world CGE model developed by ABARE (precursor to GTEM)
model closure	The set of variables (mainly policy choices such as tax rates) that the model user has to choose to define a model run (rather than the exogenous variables set within the model or the endogenous variables calculated by the model)
MM600+	CGE model of the Australian economy (built and maintained by Econtech)
MMRF	Monash Multi-Regional Forecasting, which is a suite of CGE models of the world economy (built and maintained by CoPS)
N_2O	Nitrous oxide – a greenhouse gas which is produced mainly by livestock waste and fertilisers
natural rate of unemployment	The rate of unemployment that causes no inflation. In a rational expectations model, unemployment cannot be forever held below the natural rate. See also ‘full employment’

NIEIR	National Institute for Economic and Industry Research
noncombustion emissions	Greenhouse gas emissions (including carbon dioxide) that are released during productive activities but do not result from burning fossil fuels
ORANI	CGE model of the Australian economy (the precursor to MMRF–Green)
ORANI–E	A version of the ORANI CGE model incorporating a detailed representation of the Australian energy sector
PC	Productivity Commission
physical capital	Stocks of physical buildings and machines which are needed to make any material outputs
region	Geographic part (such as Tasmania or Texas) of a nation. Regions are used in a national model. See also ‘zone’
Stone-Geary utility function	A type of utility function that specifies minimum necessary consumption levels for at least some commodities. See appendix A
Tobin’s *q*	The ratio of the market value of capital to its replacement cost
UNCED	United Nations Conference on Environment and Development held in Rio de Janeiro, Brazil, in 1992
Walrus’s Law	Given *n* markets, if *n-1* markets are in equilibrium, the last one must also be in equilibrium because there cannot be a net excess of demand or supply for goods (including money)

zone	Geographic part (such as the OECD or Japan) of the world. Zones are used in a global model. See also ‘region’

References

ABARE (Australian Bureau of Agricultural and Resource Economics) 1996, *The MEGABARE Model: Interim Documentation,* Canberra.

—— 2000, *GTEM.tab: Tablo file for the Global Trade and Environment Model,* Canberra, http://www.abare.gov.au/research/climchang.htm (accessed 25 August 2000).

—— and DFAT (Department of Foreign Affairs and Trade) 1995, *Global Climate Change: Economic Dimensions of a Cooperative International Policy Response Beyond 2000,* Canberra.

Adams, P. D., Horridge, J. M. and Parmenter, B. R. 2000a, *MMRF–Green: A Dynamic, Multi-sectoral, Multi-regional Model of Australia,* Centre of Policy Studies, Monash University, Melbourne.

—— 2000b, *Report on Modelling for a Consultancy Examining the Microeconomic Impacts of an Efficiency Standards Measure,* Report for Allen Consulting and the Australian Greenhouse Office, Centre of Policy Studies, Monash University, Melbourne.

AGO (Australian Greenhouse Office) 1999, *National Emissions Trading: Establishing the Boundaries,* Discussion Paper 1, Commonwealth of Australia, Canberra.

Allen Consulting Group 2000a, *Greenhouse Emissions Trading*, Report to the Victorian Department of Premier and Cabinet, Melbourne.

—— 2000b, *Meeting the Kyoto Target: Impact on Regional Australia,* Report to the Minerals Council of Australia, Allen Consulting Group, Melbourne.

Armington, P. S. 1969, ‘The geographic pattern of trade and the effects of price changes’, *IMF Staff Papers,* vol. 16, July, pp. 176–99.

BIE (Bureau of Industry Economics) 1994, *Economic Impact of Reducing Greenhouse Gas Emissions in Australia: A Survey of Recent Studies,* Occasional Paper 24, AGPS, Canberra.

Bovenberg, A. L. 1999, ‘Green tax reforms and the double dividend: an updated reader's guide’, *International Tax and Public Finance,* vol. 6, no. 3, pp. 421–43.

—— and Goulder, L. 2000, ‘Neutralizing the adverse industry impacts of CO_2 abatement policies: what does it cost?’, in Carraro, C. and Metcalf, G. (eds), *Behaviour and Distribution Effects of Environmental Policy: Evidence and Controversies*, University of Chicago Press, Chicago, pp. 45–85.

Brockmeier, M. 1996, *A Graphical Exposition of the GTAP Model*, GTAP Technical Paper no. 8, Center for Global Trade Analysis, Purdue University, Indiana.

Brown, S., Kennedy, D., Polidano, C., Woffenden, K., Jakeman, G., Graham, B., Jotzo, F. and Fisher, B. S. 1999, *Economic Impacts of the Kyoto Protocol: Accounting for the Three Major Greenhouse Gases*, ABARE Research Report 99.6, Canberra.

Diesendorf, M. 1998, ‘Australian economic models of greenhouse abatement’, *Environmental Science & Policy*, vol. 1, no. 1, pp. 1–12.

Dixon, P. B., Parmenter, B. R., Sutton, J. and Vincent, D. P. 1982, *ORANI: A Multisectoral Model of the Australian Economy,* North-Holland, Amsterdam.

—— and Rimmer, M. T. 1999, *MONASH: A Disaggregated, Dynamic Model of the Australian Economy: Technical Documentation*, Centre for Policy Studies and IMPACT Project, Monash University, Melbourne.

Dowlatabadi, H. 1998, ‘Sensitivity of climate change mitigation estimates to assumptions about technical change’, *Energy Economics*, vol. 20, nos. 5–6, pp. 473–93.

Econtech 2000, *The Potential Impact of Taxing Transport to Reduce Greenhouse Emissions,* Final report to the Commonwealth Department of Transport and Regional Services, Canberra.

Ghersi, F. and Toman, M. 2000, *Modelling Challenges in Analyzing Greenhouse Gas Trading,* Report to Resources for the Future, Washington DC, http://www.weathervane.rff.org/research/monograph_toman/trading%20monograph_ghersi_toman_final1.pdf (accessed 27 February 2001).

Goulder, L. H. and Schneider, S. H. 1999, ‘Induced technological change and the attractiveness of CO_2 abatement policies’, *Resource and Energy Economics*, vol. 21, nos. 3–4, pp. 211–53.

Hamilton, C. and Quiggin, J. 1997, *Economic Analysis of Greenhouse Policy: A Layperson’s Guide to the Perils of Economic Modelling,* The Australia Institute, Discussion Paper no. 15, Canberra.

—— and Vellen, L. 1999, ‘Land-use change in Australia and the Kyoto Protocol’, *Environmental Science & Policy*, vol. 2, no. 2, pp. 145–52.

Hanoch, G. 1971, CRESH production functions, *Econometrica,* vol. 39, no. 5, pp. 95–12.

—— 1975, ‘Production and demand models with direct or indirect implicit additivity’, *Econometrica*, vol. 43, no. 3, pp. 395–420.

Hanslow, K. Hinchy, M. and Fisher, B. S. 1998, *Induced Innovations and Climate Change Policy,* Paper presented at the First Annual Conference on Global Economic Analysis, Centre for Global Trade Analysis, Purdue University, Indiana, 8–10 June.

Hargreaves, C. 1994, *A Comparison of Economy-wide Models of Australia: Responses to a Rise in Labour Productivity*, Economic Planning Advisory Council/Economic Modelling Bureau of Australia, AGPS, Canberra.

Hertel, T. W. (ed.) 1997, *Global Trade Analysis: Modeling and Applications*, Cambridge University Press, Massachusetts.

—— 1999, *Applied General Equilibrium Analysis of Agricultural and Resource Policies,* Staff Paper 99-2, Department of Agricultural Economics, Purdue University, Indiana.

—— and Tsigas, M. E. 1997, ‘Structure of GTAP’, in Hertel, T. W. (ed.), *Global Trade Analysis: Modeling and Applications*, Cambridge University Press, Massachusetts, pp. 13-73.

Hourcade, J. and Robinson, J. 1996, ‘Mitigating factors: assessing the costs of reducing GHG emissions’, *Energy Policy*, vol. 24, nos. 10–11, pp. 863–73.

Industry Commission 1991, *Costs and Benefits of Reducing Greenhouse Gas Emissions*, Report no. 15, AGPS, Canberra.

James, D. 1996, *Comparison of Economic–Environmental Models*, Commonwealth Department of Environment, Sport and Territories, Canberra.

Jorgenson, D. W., Goettle, R. J., Wilcoxen, P. J. and Ho, M. S. 2000, *The Role of Substitution in Understanding the Costs of Climate Change Policy*, Report to the Pew Center on Global Climate Change, Stanford University, July. http://www.pewclimate.org/projects/substitution.cfm (accessed 26 February 2001).

Kopp, R. J. and Toman, M. A. 1997, *Experts Meeting on the Choice of Modeling Platform for Carbon Policy Analysis*, Resources for the Future, Washington DC.

McDougal, R. A. 1993, *Energy Taxes and Greenhouse Gas Emissions in Australia*, General Paper no. G-104, Centre of Policy Studies, Monash University, Melbourne.

McKibbin, W. J. 1998, ‘Greenhouse abatement policy: insights from the G-Cubed multi-country model’, *Australian Journal of Agricultural and Resource Economics*, vol. 42, no. 1, pp. 99–113.

—— and Sachs, J. 1991, *Global Linkages: Macroeconomic Interdependence and Co-operation in the World Economy*, The Brookings Institute, Washington DC.

—— and Wilcoxen, P. J. 1999, 'The theoretical and empirical structure of the G-Cubed model', *Economic Modelling*, vol. 16, no. 1, pp.123–48.

——, Shackleton, R. and Wilcoxen, P. J. 1999a, 'What to expect from an international system of tradable permits for carbon emissions', *Resource and Energy Economics*, vol. 21, nos. 3–4, pp. 319–46.

——, Ross, M., Shackleton, R. and Wilcoxen, P. J. 1999b, 'Emissions trading, capital flows and the Kyoto Protocol', *Energy Journal*, Kyoto Special Issue, pp. 287–333.

McKibbin Software Group 2000, *The G-Cubed Multi-country Model: Specification, Parameters, Data and Variable Definitions,* http://www.msgpl.com.au/msgpl/msghome.htm (accessed 26 February 2001).

Murphy, C. 2000, *A Guide to Econtech's Industry Model — Murphy Model 600 Plus (MM600+)*, Econtech, Kingston, Australian Capital Territory.

Peter, M. W., Horridge, M., Meagher, G. A., Naqvi, F. and Parmenter, B. R. 1996, *The Theoretical Structure of MONASH-MRF*, Preliminary Working Paper no. OP-85, Centre of Policy Studies, Monash University, Melbourne.

Pezzey, J. 1992, 'The symmetry between controlling pollution by price and controlling it by quantity', *Canadian Journal of Economics*, vol. 25, no. 4, pp. 983–91.

Polidano, C., Jotzo, F., Heyhoe, E., Jakeman, G., Woffenden, K. and Fisher, B. S. 2000, *The Kyoto Protocol and Developing Countries: Impacts and Implications for Mechanism Design*, ABARE Research Report 2000.4, Canberra.

Powell, A. A. and Lawson, T. 1990, 'A decade of applied general equilibrium modelling for policy work', in Bergman, L., Jorgenson, D. W. and Zalai, E. (eds), *General Equilibrium Modeling and Economic Policy Analysis*, Basil Blackwell, Oxford, pp. 241–90.

Powell, A. A. and Snape, R. H. 1993, 'The contribution of applied general equilibrium analysis to policy reform in Australia', *Journal of Policy Modelling*, vol. 15, no. 4, pp. 393–414.

Repetto, R. and Austin, D. 1997, *The Costs of Climate Protection*, World Resources Institute, Washington DC.

Shoven, J. B. and Whalley, J. 1992, *Applying General Equilibrium*, Cambridge University Press, New York.

Tobin, J., 1969, 'A General Equilibrium Approach to Monetary Theory', *Journal of Money, Credit and Banking*, vol. 1, no. 1, pp. 15-29.

Truong, T. P. 1999, *GTAP-E: Incorporating Energy Substitution into the GTAP Model*, GTAP Technical Paper no. 16, Center for Global Trade Analysis, Purdue University, Indiana.

Tulpulé, V., Brown, S., Lim, J., Polidano, C., Pant, H. and Fisher, B. S. 1999, ‘The Kyoto Protocol: an economic analysis using GTEM’, *Energy Journal*, Kyoto Special Issue, pp. 257–85.

United Nations 1997, *Kyoto Protocol to the United Nations Framework Convention on Climate Change*, http://www.unfccc.de/resource/docs/convkp/kpeng.pdf (accessed 26 February 2001).

Vincent, D. P. 1990, ‘Applied general equilibrium modelling in the Australian Industries Assistance Commission: perspectives of a policy analyst’ in Bergman L., Jorgenson, D. W. and Zalai, E. (eds), *General Equilibrium Modelling and Economic Policy Analysis*, Basil Blackwell, Oxford, pp. 291–347.

Weyant, J. P. 2000, *An Introduction to the Economics of Climate Change Policy*, Report to the Pew Center on Global Climate Change, Stanford University, http://www.pewclimate.org/projects/econ_introduction.cfm (accessed 26 February 2001).

—— and Hill, J. 1999, ‘Introduction and overview’, *Energy Journal*, Kyoto Special Issue, pp. vii–xliv.