Carbon pricing mechanisms in Australia: simulations with a dynamic stochastic general equilibrium model

Fariba Ramezani Khansari

University of Wollongong

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Carbon Pricing Mechanisms in Australia: Simulations with a Dynamic Stochastic General Equilibrium Model

By

Fariba Ramezani Khansari

Supervisors:

Associate Professor Charles Harvie

Doctor Amir Arjomandi

Doctor Michelle Dunbar

July 2016
Thesis Certification

I, Fariba Ramezani Khansari, state that this thesis submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Accounting, Economics and Finance, Faculty of Business, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.
Abstract

Purpose – This thesis investigates the environmental and economic effects of emissions pricing policies in Australia. By considering emissions as a by-product, that is, as a function of production, it can be seen that emissions follow output fluctuations. Ignoring the correlation between economic fluctuations and emissions may increase the risk of encountering undesired changes in emissions over a period of time. This issue has motivated the current research to investigate the impacts of emissions reduction policies on emissions fluctuations during business cycles. This thesis specifies four emissions reduction scenarios, in line with programs which have been designed and/or implemented in Australia: first, a business-as-usual or no policy scenario; second, a fixed emissions tax scenario resembling a carbon tax program; third, a variable emissions tax system as a proxy for an emissions trading scheme and fourth, an abatement subsidy scenario such as the Australian government’s current Emissions Reduction Fund.

Methodology – This thesis applies a dynamic stochastic general equilibrium (DSGE) model to investigate the impacts of real shocks, such as total factor productivity (TFP) shocks, on the Australian economy under the abovementioned emissions reduction scenarios. To this end the current research benefits from, and extends upon, a real business cycle (RBC) model developed by Heutel (2012). The model developed in this thesis, however, is different from his in three ways: the scenarios tested, parameterisation and analysis technique. After developing and solving the model, a calibration method is used for parameterisation to obtain and evaluate the empirical results. To this end, parameters from previous RBC studies for the Australian economy, and from the environmental literature, including literature on the Regional Integrated model of Climate and the Economy (RICE), are used. Only one parameter of the model, emissions from the rest of the world, which has not been estimated in
previous studies, is estimated in this thesis using Australian databases including the Australian National Accounts and Australia’s National Greenhouse Accounts.

**Findings** – The results show that a variable emissions tax or subsidy should be set to be pro-cyclical to business cycles so as to be able to provide motivation for firms to make abatement efforts. The results also show that when using a fixed emissions tax system, when the marginal cost of emissions does not change over time, the system loses its power to motivate firms to make abatement efforts. The results also indicate that under a variable tax or an abatement subsidy policy, emissions are less affected by business cycles and thus, they can enable the government to stabilise emissions. Additionally, the cumulative impact of various emissions reduction policies over the entire adjustment period reveals that a fixed tax program has the lowest cumulative effect on emissions and output. This implies that the policy choice depends on the regulator’s perspective and priorities. If the regulator’s priority is emissions reduction during a boom period, a subsidy or a variable emissions tax is the appropriate solution, while if the regulator’s main concern is to minimise the impact on output, a fixed emissions tax is preferable.

**Research Contributions** – This thesis provides the first analysis of Australian environmental policy in the presence of TFP shocks. It does so by applying a DSGE model. This thesis also contributes to the environmental DSGE literature by extending Heutel (2012) in three ways: the scenarios tested, parameterisation and analysis technique. This is the first study in the environmental DSGE literature to compare a fixed versus a variable emissions tax scenario. In addition, this thesis finds that the approach Heutel (2012) used to parameterise one of his exogenous variables, emissions from the rest of the world, would make it endogenous in such a way that any changes in domestic emissions would result in a change in emissions from the rest of the world. To avoid this distortion the current research applies another approach by
calculating emissions from the rest of the world under a business-as-usual scenario and using that value in emissions reduction scenarios. In addition, this thesis conducts a policy analysis in a dynamic context by calculating the cumulative effects of a TFP shock on variables under different emissions pricing programs. This technique can capture the effects of emissions reduction programs, not only on the steady state values of key variables, but also on the response paths of variables to shocks and thus, it can express the total effects of the shock under an emissions reduction program. Finally, this thesis contributes to policy analysis by providing unique insights into the costs and benefits of Australian emissions pricing programs by investigating the outcomes of such programs in boom and recession periods.
Acknowledgments

This thesis has relied on the assistance, advice and encouragement of many people. First and foremost I would like to offer my deepest gratitude to my principal supervisor Associate Professor Charles Harvie for his immense knowledge, constructive comments, continuous effort and kind support during the course of my PhD program. His enthusiasm, encouragement and patience were indeed inspiring and I owe my success in academia to his support. I would like to express my appreciation to my co-supervisor Dr Amir Arjomandi for his valuable assistance, friendly guidance and kind support during my PhD program. His advice and continual encouragement were extremely helpful. I am also thankful to my current and previous assistant supervisors, Dr Michelle Dunbar and Associate Professor Shuaian Wang, for their support and assistance.

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Professor Garth Heutel from the Department of Economics at Georgia State University who willingly provided me with his insights and expertise.

Last but not the least, I would like to thank my family who have sacrificed a lot for the sake of my future career: my husband Dr Behrad Shojaei for patiently standing by me with his heart-warming support, love and understanding; my parents Ebrahim Ramezani Khansari and Mansoor Zameni and my lovely sister Faezeh Ramezani Khansari for their unconditional love and never-ending support throughout my life.
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<td>ABARES</td>
<td>Australian Bureau of Agricultural Resource Economics and Sciences</td>
</tr>
<tr>
<td>BAU</td>
<td>Business-As-Usual</td>
</tr>
<tr>
<td>CPRS</td>
<td>Carbon Pollution Reduction Scheme</td>
</tr>
<tr>
<td>CER</td>
<td>Certified Emission Reduction</td>
</tr>
<tr>
<td>CES</td>
<td>Constant Elasticity of Substitution</td>
</tr>
<tr>
<td>CGE</td>
<td>Computable General Equilibrium</td>
</tr>
<tr>
<td>DCM</td>
<td>Clean Development Mechanism</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>CO₂e</td>
<td>Carbon Dioxide Equivalent</td>
</tr>
<tr>
<td>CPI</td>
<td>Consumer Price Index</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
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<tr>
<td>DTC</td>
<td>Directed Technological Change</td>
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<tr>
<td>DSGE</td>
<td>Dynamic Stochastic General Equilibrium</td>
</tr>
<tr>
<td>DICE</td>
<td>Dynamic Integrated Climate-Economy</td>
</tr>
<tr>
<td>ESAM</td>
<td>Extended Social Accounting Matrix</td>
</tr>
<tr>
<td>EU ETS</td>
<td>European Emissions Trading Scheme</td>
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<td>FOCs</td>
<td>First Order Conditions</td>
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<td>GHGs</td>
<td>Green House Gases</td>
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<tr>
<td>GNI</td>
<td>Gross National Income</td>
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<tr>
<td>GTAP</td>
<td>Global Trade Analysis Project</td>
</tr>
<tr>
<td>GTEM</td>
<td>Global Trade and Environment Model</td>
</tr>
<tr>
<td>GtC</td>
<td>Giga tons of carbon</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>--------------</td>
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<tr>
<td>IRF</td>
<td>Impulse Response Function</td>
</tr>
<tr>
<td>INDCs</td>
<td>Intended Nationally Determined Contributions</td>
</tr>
<tr>
<td>IPCC</td>
<td>International Panel on Climate Change</td>
</tr>
<tr>
<td>JI</td>
<td>Joint Implementation</td>
</tr>
<tr>
<td>LULUCF</td>
<td>Land Use, Land Use Change and Forestry</td>
</tr>
<tr>
<td>MMRF</td>
<td>Monash Multi-Regional Forecasting</td>
</tr>
<tr>
<td>OHI</td>
<td>Other High Income</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts Per Million</td>
</tr>
<tr>
<td>RBC</td>
<td>Real Business Cycle</td>
</tr>
<tr>
<td>RICE</td>
<td>Regional Integrated model of Climate and the Economy</td>
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<tr>
<td>TFP</td>
<td>Total Factor Productivity</td>
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List of Candidate’s Awards, Visiting Position and Research Papers

Awards

International Postgraduate Tuition Award 2012-2016

SMART Infrastructure Facility Scholarship 2012-2016

Visiting Position

Graduate student visitor, University of California Davis, USA 30/06/2014-17/08/2014

Conference Proceeding and Papers


Seminar Presentation

Chapter 1

Introduction

1.1. Introduction

Over the last three decades scientific evidence on global warming issues has attracted the interest of national governments, international institutions and researchers. A report, for example, was published by the International Panel on Climate Change (IPCC) in 1990 which showed that a doubling of greenhouse gas emissions (GHGs) in the atmosphere over pre-industrial levels would result in a rise in global temperatures of 1.5 to 5° C. The report also predicted that melting glaciers would increase sea levels by 50 to 100 cm by 2100 (IPCC, 1990). This IPCC report has since been updated and similar, and more alarming, estimations have been revealed in each update. The IPCC report in 2013, for instance, showed that during the last 30 years the Northern Hemisphere has experienced its warmest period since records began. A recent study published by the World Meteorological Organisation also indicated that the years 2011–2015 were the warmest years on record (World Meteorological Organization, 2015).

The main reason for global warming has been an increase in greenhouse gases (GHGs), especially carbon dioxide, in the atmosphere. It has been proven that carbon dioxide concentrations in the atmosphere have been amplified by 40 per cent since pre-industrial times (IPCC, 2013). Scientific evidence reveals that global carbon dioxide concentrations in the atmosphere have reached 400 parts per million (ppm) for the first time in recorded history (NASA, 2013). Highlighting the scientific evidence of global warming, the 2013 IPCC report emphasised the role of human activity in climate change. The IPCC investigated climate systems, global warming, atmospheric GHG concentrations and radioactive forcing and
found that it is extremely likely (i.e. there is a 95–100 per cent probability) that humans are responsible for more than half of global warming (IPCC, 2013, p. TS–25).

What problems can global warming cause? This question has become the main focus of interest of researchers since global warming issues were raised, and many studies have attempted to estimate the impacts of an increase in the global temperature in terms of its economic effects. A survey of these studies has been conducted by Tol (2009) and updated by Tol (2015). A summary of Tol (2015) findings is presented in Table 1.1. The estimated values are broad ranging in different studies since the methodology adopted is not the same, with different assumptions about future emissions, the pattern and extent of global warming, the extent of sea level rise, rainfall and extreme weather events (Tol, 2009). As the table shows, the estimated economic effects of global warming vary widely based on different temperature increases, but all estimates indicate that a welfare cost in terms of a decrease in global income can happen as a result of a 2.5°C or 3°C increase in the global temperature. One of the initial estimations, derived by Nordhaus (1994b), estimated that a 3°C global temperature increase would result in a 1.3 per cent decrease in global GDP. In one of his latest studies Nordhaus (2010) re-appraised this estimation and showed that a 3.4°C increase in global temperature would cause global damage equal to US$12 trillion, or a 2.8 per cent decrease in global output if GHG emissions are not controlled.

In Australia, the evidence of warming is significant. For instance, the autumn of 2016 was the warmest autumn on record in Australia (Vaughan, 2016). In their latest report the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Bureau of Meteorology (2012) indicated that Australia’s annual-average daily mean temperature has increased by 0.9°C since 1910, and will be 1°C to 5°C higher than the 1910 figure by 2050. Figure 1.1 shows average temperature changes in Australia over the period 1910 to 2010. The
orange line indicates the annual average, the grey boxes show decade averages, and the black line shows an 11-year average which is the standard period for the IPCC. This figure has not been updated as more recent data is not yet available.

Table 1.1: Estimated effects of global warming on global welfare in terms of annual income change (per cent)

<table>
<thead>
<tr>
<th>Study</th>
<th>Warming (°C)</th>
<th>Impact (% of global GDP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nordhaus (1994b)</td>
<td>3.0</td>
<td>-1.3</td>
</tr>
<tr>
<td>Nordhaus (1994a)</td>
<td>3.0</td>
<td>-3.6</td>
</tr>
<tr>
<td>Fankhauser (1995)</td>
<td>2.5</td>
<td>-1.4</td>
</tr>
<tr>
<td>Tol (1995)</td>
<td>2.5</td>
<td>-1.9</td>
</tr>
<tr>
<td>Nordhaus and Yang (1996)</td>
<td>2.5</td>
<td>-1.7</td>
</tr>
<tr>
<td>Plambeck and Hope (1996)</td>
<td>2.5</td>
<td>-2.5</td>
</tr>
<tr>
<td>Nordhaus and Boyer (2000)</td>
<td>2.5</td>
<td>-1.5</td>
</tr>
<tr>
<td>Maddison (2003)</td>
<td>2.5</td>
<td>-0.1</td>
</tr>
<tr>
<td>Rehdanz and Maddison (2005)</td>
<td>1.0</td>
<td>-0.4</td>
</tr>
<tr>
<td>Hope (2006)</td>
<td>2.5</td>
<td>-0.9</td>
</tr>
<tr>
<td>Nordhaus (2008)</td>
<td>3.0</td>
<td>-2.6</td>
</tr>
<tr>
<td>Maddison and Rehdanz (2011)</td>
<td>3.2</td>
<td>-12.4</td>
</tr>
<tr>
<td>Bosello et al. (2012)</td>
<td>1.9</td>
<td>-0.5</td>
</tr>
<tr>
<td>Roson and van der Mensbrugghe (2012)</td>
<td>2.9</td>
<td>-2.1</td>
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<td></td>
<td>5.4</td>
<td>-6.1</td>
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Based on the latest available data, Australia was the 16\textsuperscript{th}-largest producer of greenhouse gas emissions in the world in 2013, and produced about 1.2 per cent of global GHG emissions. In per capita terms Australia ranked 12\textsuperscript{th} in the world in 2013 (CDIAC, 2013). The relatively small contribution of Australia to GHG emissions in global terms may raise the question of why Australia needs to address the issue of emissions reduction.

There are two considerations which highlight the importance of emissions reduction in Australia. The first is the need to avoid the risks that climate change imposes on the economy and environment, including damage to ecosystems, changes in rainfall, and increases in extreme events such as heatwaves, droughts and floods. Such extreme events can impose not only moral costs but also economic costs to Australia.

One of the most vulnerable economic sectors, which will face severe economic costs if climate change is not addressed, is the agriculture sector. Employing more than 307,000 people, this sector is the largest employer in rural areas in Australia. Taking into account all
those employed in food manufacturing, input and output sectors, retail and distribution, the agriculture sector employs more than 1.6 million people in Australia (Batt, 2015). Additionally, about 52% of the Australian landmass is occupied by agriculture (Australian Bureau of Statistics, 2015). Australia produces more food than its population consumes (Department of Agriculture Fisheries and Forestry, 2011) and Australia’s exports of food are enough to feed 60 million people (Australian Bureau of Agriculture and Resource Economics and Science, 2011). In fact, Australian farmers contribute to 93 per cent of the domestic food supply and more than 13 per cent of the nation’s export revenue (Australian Bureau of Agriculture and Resource Economics and Science, 2014).

The capacity and price of agricultural production can be directly influenced by climate change and Australia has already experienced this (Climate Council of Australia Limited, 2015). For instance, during the 2005–2007 droughts, the growth rate of food prices was more than twice that of the Consumer Price Index (CPI), with the price of fresh fruit and vegetables increasing by 43% and 33% respectively. Similarly, Cyclone Larry in 2006 destroyed 90% of the North Queensland banana crop which resulted in a 500% increase in the price of bananas. A drop in rainfall in parts of Western Australia and Queensland also caused a decrease in total national crop production by 12% and a reduction in the value of beef and veal exports of 4% in 2014–15 (Climate Council of Australia Limited, 2015). This shows how vulnerable this sector is to climate change.

Australia has very specific rainfall features which can present a serious threat to the country: Australia is the driest inhabited continent on Earth. The variability of rainfall over Australia is four times greater than it is in Russia, three times greater than in the US, and more than double that of New Zealand, the UK and India (Hanna et al., 2011). Changes in rainfall patterns as a result of increased temperatures are estimated to be the most significant factor
affecting the future of agricultural productivity in Australia (Crimp et al., 2014). The impacts of extreme climate events on Australia’s agriculture sector will directly affect food exports and imports as well as the food security of Australia and its trading partners. Currently, Australia is the sixth-largest food exporter in the world (Australian Academy of Technological Sciences and Engineering, 2014) and more than 50% of its food exports are traded in Asia, with China and Japan together purchasing 30% of the total (Climate Council of Australia Limited, 2015). A reduction in Australian food production as a result of climate change could also adversely affect these countries. Additionally, it is estimated that global food demand will increase by 70–100% by 2050 (Alexandratos and Bruinsma, 2012). This will impose a notable opportunity cost on the Australian agriculture sector if it experiences a productivity reduction due to climate change (Climate Council of Australia, 2014).

Rising sea levels due to climate change can also impose a significant cost to Australia since most of its cities, towns and infrastructure are located in coastal areas which makes this nation very vulnerable to coastal flooding and a rise in sea levels. Without any programs to control global warming, more than $226 billion worth of assets located in Australia’s coastal regions are potentially at high risk from a 1.1 metre increase in sea levels by 2100. Such an increase is at the high end of expectations, but it is very plausible (Climate Council of Australia, 2014).

The extent of the abovementioned costs will depend on the size of temperature increases and there is significant evidence that Australia is already encountering climate change problems. For example, based on existing records, the frequency of high temperatures has increased while that of low temperatures has reduced; snowfall has decreased; the frequency and duration of heatwaves have increased and the coral population of the Great Barrier Reef has
been halved (Department of the Environment, 2014a). Such evidence suggests the need for quick action to slow global warming and avoid further environmental issues.¹

The first consideration, highlighting the importance of emissions reduction programs in Australia, is explained above as the need to avoid the risks that climate change imposes on the Australian economy and environment. The second consideration, highlighting the importance of emission reduction policies in Australia, is the country’s commitments made under international emissions reductions agreements. Before clarifying these commitments, a brief review of international climate change meetings is now presented. Evidence on global warming and its predicted negative effects have raised the concerns of national governments and international institutions and spurred action to avoid these predicted problems. To this end, several global conventions and programs have been initiated which are aimed at addressing global warming by reducing human-induced GHG emissions. The main aim of all national and international climate programs is to persuade countries to reduce emissions. Table 1.2 provides a summary of the most significant meetings and commitments.

In 1992 representatives from the world’s most developed countries, known as Annex I Parties, gathered in New York to discuss rising global temperatures and to agree on a way to limit their GHGs emissions. The outcome was an international treaty, named the United Nations Framework Convention on Climate Change, and it was signed in Rio de Janerio. This gathering is known as the “Rio Earth Summit” and it resulted in the “Rio conventions”. The conventions came into effect on 21 March 1994 and currently, 197 countries and/or regions, known as Parties, are signed up to the Convention (UNFCCC, 2014b).

¹ Despite these developments there are still climate change deniers both in Australia and globally which are explained in Chapter 2 Section 2.2.
<table>
<thead>
<tr>
<th>International Meeting</th>
<th>Outcomes</th>
<th>Australia’s Contribution</th>
</tr>
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<tbody>
<tr>
<td>Kyoto (1997)</td>
<td>Achieved the world’s first greenhouse gas emissions reduction treaty which committed participating Parties including industrial countries and the European Community to reduce emissions by an average of 5% below the 1990 levels during a five-year period from 2008 to 2012.</td>
<td>Attending the protocol, Australia eventually committed to decreasing its emissions by 5% relative to 1990 by 2012.</td>
</tr>
<tr>
<td>Copenhagen (2009)</td>
<td>Quantified emissions reduction targets for 2020 for each of the 114 Parties which signed it.</td>
<td>Attending the meeting, Australia committed to decreasing its emissions by 5% below 2000 levels unconditionally by 2020.</td>
</tr>
<tr>
<td>Doha (2012)</td>
<td>Continued the Kyoto Protocol to the second phase from 2013 to 2020 in which Parties are committed to reducing their emissions by at least 18% below the 1990 level. In this meeting the number of Parties increased to 192.</td>
<td>After attending this meeting, Australia follows the same target.</td>
</tr>
<tr>
<td>Warsaw (2013)</td>
<td>Committed Parties to initiate their intended nationally determined contribution (INDCs) before the Paris agreement.</td>
<td>Australia set and submitted its INDC to reduce emissions economy-wide by 26 to 28% below the 2005 level by 2030.</td>
</tr>
<tr>
<td>Paris (2015)</td>
<td>Reached a global consensus, of keeping global warming below 2°C above the pre-industrial temperature, agreed by 177 countries. To this end, all Parties set their NDCs and must commit themselves to them.</td>
<td>Attending this meeting, Australia signed the agreement in April 2016.</td>
</tr>
</tbody>
</table>

Source: Compiled by the author from the UNFCCC website: [http://unfccc.int/meetings/paris_nov_2015/meeting/8926.php](http://unfccc.int/meetings/paris_nov_2015/meeting/8926.php)
decreasing their greenhouse gas emissions by an average of five per cent below the 1990 levels during a five-year period from 2008 to 2012 (UNFCCC, 1992). Many developing countries also joined the protocol in the early 2000s and were categorised as non-Annex I Parties at the Montreal Conference in 2005 (UNFCCC, 2014a). Australia was one of the Annex I Parties that joined the Kyoto Protocol on 24 April 1998 and ratified its commitment on 12 December 2007 (Parliament of Australia, 2010). The Kyoto Protocol commitment period was subsequently extended from 2013 by eight years (The United Nations, 2013). Currently, there are 192 Parties to the Kyoto Protocol.

The Kyoto Protocol introduced three mechanisms to assist Parties to achieve their climate goals and all these mechanisms remain in operation. The first mechanism is emissions trading in which countries which produce less than the permitted emissions can sell this excess to countries which cannot meet their emissions targets. This method has been successfully used by the European Union (EU) countries and is clarified in more detail below and in Chapter 2 Section 2.4.2.

The second type of mechanism is the Clean Development Mechanism (CDM) where the Parties can earn Certified Emission Reduction (CER) credits if they implement environmental projects in developing countries. Each CER is equal to one tonne of CO₂ and can be traded in a carbon market (The United Nations, 2013). This mechanism has been operating since 2006 and more than 7708 projects have been registered and more than 1600 million CERs have been issued for project activities (UNFCCC, 2016a).

The Joint Implementation (JI) program is the third mechanism introduced by the Kyoto Protocol. Under this program Parties can earn another type of credit, called Earned Emission Reduction Units (ERUs) if they support an emission removal project conducted in the territories of other Parties. Like CER, each ERU is equal to one tonne of CO₂ and can be
traded in a carbon market. The top 10 JI projects implemented so far have been conducted between the Czech Republic, Denmark, Poland, Romania, Bulgaria, Netherlands, Austria, Russian Federation, Germany, Ukraine, Lithuania and France. They have resulted in more than 5.9 million tonnes CO₂ equivalent (CO₂e) of ERUs (The United Nations, 2013).

How successful was the first phase of the Kyoto Protocol? Clark (2012) attempted to answer this question by calculating the gap between the emissions reduction target and the actual change in emissions for each party to the Kyoto Protocol and plotted those gaps in terms of percentage. Figure 1.2 shows the gaps based on emissions data in 2010. The Parties which reduced their emissions to the level required by their protocol target or more are shown in blue and those which failed are displayed in red. As the figure shows, 21 nations successfully reduced their emissions while 16 countries failed to meet their targets. Among the latter Australia is the third-largest failure, producing 22 per cent more emissions than its target.

The Kyoto Protocol has been followed by other international meetings including Copenhagen in 2009, Cancun in 2010, Durban in 2011, Doha in 2012, Warsaw in 2013, Lima in 2014, Geneva in February 2015, Bonn in October 2015 and the most recent and important one, Paris from 30 November to 12 December 2015. These meetings were generally aimed at convincing nations that global warming is a serious threat and that it is critical to control global warming.

At one of the later meetings in Warsaw in 2013, countries including Australia agreed to set their emissions targets, or their intended nationally determined contributions (INDCs), and submit them to the UNFCCC before the Paris meeting. The Paris meeting is a historical one in which 196 countries attended and they agreed to keep the global temperature increase below 2°C of the overall global pre-industrial level. The agreement was designed to enter into force when at least 55 countries, which together are responsible for 55 per cent of global
greenhouse gas emissions, sign off on its ratification between April 2016 and April 2017 (Taylor, 2016). The agreement was signed by 170 countries including Australia on 22 April 2016 and now countries must ratify the agreement through their domestic procedures including votes in parliament.

Australia, also set and submitted its INDC and committed to reducing its emissions by 26 to 28% below their 2005 levels by 2030 (Center for Climate and Energy Solution, 2015). Australia also made a commitment to decreasing its per capita emissions by 50–52 per cent between 2005 and 2030 and to decreasing its emissions intensity by 54-56 per cent in the same period (Department of the Environment, 2015a). These targets, plus those of other countries including the two largest emissions producers China and US, are displayed in Figure 1.3. As the figure shows, Australia’s emissions intensity target is in line with those of other countries. For example, China has decided to decrease the emissions intensity of its economy by 65%, the US by 62%, New Zealand by 61%, and the EU, Canada and South Korea by 57%. The different populations and population policies of each country, however, make it difficult to compare the emissions reduction targets in per capita terms. For example, although Australia and China have similar emissions reduction targets in terms of intensity, their targets differ significantly in per capita terms as Australia is predicted to achieve a 50–52 per cent decrease while China will face a 127 per cent increase in emissions per capita (Department of the Environment, 2015a).
Figure 1.2: Kyoto successes and failures (the gap between the nations’ percentage reduction targets from 1990 and the real percentage change between 1990 and 2010)

Source: Clark (2012), the Guardian website:
http://www.theguardian.com/environment/blog/2012/nov/26/kyoto-protocol-carbon-emissions
In addition to the abovementioned INDC, which shows longer-term commitments, Australia has made pledges under the Copenhagen Accord to reduce emissions by the year 2020 as follows (Borrello, 2016):

- a 5% reduction relative to the 2000 level unconditionally
- a reduction of up to 15% if a global agreement secures the stabilisation of greenhouse gases at 450 parts per million (ppm) carbon dioxide equivalents, and if, under this agreement, major developing economies commit to substantially restraining their emissions and other advanced economies also take on commitments of around 15%
• a 25% reduction if the world agrees to an ambitious global deal capable of stabilising levels of greenhouse gases in the atmosphere at 450 ppm.

From these pledges, Australia is currently committed to an unconditional 5% emissions reduction relative to its 2000 emissions levels by 2020. Australia’s current and future pledges require it to implement an emissions reduction program.

In order to decrease emissions and meet international commitments, countries have applied several types of practical programs, including an emissions price arrangement under which polluters have to pay for each tonne of pollution they produce. This price can be determined by the government at a fixed rate, or by the market and at a flexible rate. The former is known as a price-based instrument, a so-called carbon tax, while the latter is a quantity-based instrument, called a cap-and-trade, or emissions trading scheme. A carbon tax was first introduced by Finland in 1990. Afterwards, the Netherlands (1990), Sweden (1991), Norway (1991), Denmark (1992), Great Britain (2001), New Zealand (2005), Switzerland (2008), Ireland (2010), France (2010), Japan (2012), Australia (2012, temporarily), and Chile (2014) implemented their own carbon tax systems (Carbon Tax Centre, 2011). These carbon tax programs, however, have been diverse, ranging from levying a tax directly on emissions, to having an ‘incentive tax’ on fossil fuels. These programs are explained in more detail in Chapter 2 Section 2.4.1.

In the flexible rate approach, the government specifies a limit, or cap, on pollution that each sector is permitted to produce. It does so by issuing a limited number of emission permits, each of which represents one tonne of carbon emissions. The government sells these permits, or allowances, to sectors or allocates them freely to some industries to support them. Generally, there are two reasons for free allocations. The first reason is political and the second is to avoid carbon leakage (Jegou and Rubini, 2011) that is, an environmental policy
provides an opportunity for countries with no emissions reduction policies to improve their international competitiveness at the expense of those countries that do have emissions policies (Parker and Blodgett, 2008).

Free allowances, however, may not be able to provide enough of an incentive for polluters to decrease emissions. Thus, governments usually try to reduce the number of free allowances over time. For example, in the European Emissions Trading Scheme (EU ETS), explained further below, the manufacturing sector received 80 per cent of its allowances for free in 2013 but it is planned to decrease this to 30 per cent by 2020 (World Bank, 2016). Permits can be traded: if a sector emits more than the permits that it has been allocated, it needs to buy permits from other sectors to offset the extra volume of pollution they produce. On the other hand, a sector which pollutes less than its permits allow can sell its excess permits. This trade, known as emissions trading, leads to the emergence of a market, called a carbon market, and this market determines the price of permits based on the demand and supply of permits.

A carbon market is supposed to be a competitive market where emissions producers compete to buy the permits they require to fulfil their commitments as determined by the government. Businesses with high emission reduction costs prefer to buy carbon permits even at high prices, while for others it is more economical to cut their emissions instead of buying permits. A good example of a cap-and-trade mechanism is the European Emissions Trading Scheme (EU ETS) which is the largest carbon trading system in the world (Ellerman and Buchner, 2007b) and was launched in 2005. The EU ETS is the only international carbon market. It has 31 participating countries, including the 28 members of the EU, plus Iceland, Liechtenstein and Norway and it covers more than 11000 manufacturing plants and power stations.
responsible for approximately 45 per cent of total EU emissions (European Commission, 2013a).

In Australia, an emissions pricing program was implemented but it experienced significant volatility as a result of the lack of a political consensus on the issue. Despite the scientific evidence highlighted earlier in this section, there is still debate on the existence and impact of climate change, which has led to different attitudes among policy makers about the importance of emissions reduction policies and the costs and benefits of such policies.

The political concern of emissions reduction policies in Australia was first raised when Stern (2007) published his review in which he highlighted the importance of quick actions to avoid economic and social problems that climate change would impose globally. The initial steps towards emission reduction programs were taken by the Australian government under the prime ministership of John Howard. The Howard government decided to implement an ETS in July 2007 (Crimp et al., 2010). This program, however, was not carried out due to a lack of political support. The first implemented program in Australia was the Clean Energy Program under the prime ministership of Julia Gillard in 2011. The program included two phases of emissions pricing: first, a fixed price, or a carbon tax, for a period which commenced on 1 July 2012. This phase was originally intended to continue until 30 July 2015 when the second phase, with a variable price system under an emissions trading scheme, would begin.

Under the prime ministership of Kevin Rudd, however, it was announced that this fixed price period would finish one year earlier, on 30 July 2014 (Australian Government, 2013). This program was further changed under the prime ministership of Tony Abbott who abolished the carbon pricing system with effect from 1 July 2014 (Australian Government, 2014a). As an

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2 The history of Australian emission reduction policies is presented in detail in Chapter 2, Section 2.7.
alternative, the government introduced the Emissions Reduction Fund program which came into effect on 13 December 2014. Under this programme the government funds emissions reduction activities (Department of the Environment, 2014a). This really shows the division over the emissions reduction issue in Australia and how the Abbott government’s policy conflicted with Stern’s (2006) recommendations.

In April 2016, the Australian Labor Party proposed two emissions trading schemes, one for the electricity sector and one for industrial polluters with a total cost of $355.6 million over four years. The program is similar to the model first proposed by the current prime minister Malcolm Turnbull in 2009 (Taylor, 2016). The proposed industrial ETS included two phases: phase one specifies a cap, or a certain level of emissions that the industries can produce without any penalty while they have to buy permits for the extra units of emissions. Phase two is yet to be designed (Borrello, 2016). The program confirms that the Labor Party is pledged to reducing emissions by 45% by 2030 and is committed to shifting electricity generation toward renewable resources (Grattan, 2016).

Despite the volatility in the implementation of environmental policies in Australia, the significance of environmental problems remains a great motivation for researchers to find an efficient climate change program in conjunction with studies of the environmental and economic impacts of alternative policies at both the national and global levels. This is the primary aim of this study. It evaluates the economic effects of competing emissions pricing policies in Australia. The policies examined include a carbon tax and a subsidy system. While the focus of this study will be on Australia, the framework developed could in principle be applied more generally to other countries if suitably adapted to local circumstances.

The chapter continues as follows: the significance of the current study is clarified in Section 1.2 and the questions addressed in this thesis are presented in Section 1.3. Section 1.4
specifies the hypotheses that are tested. Section 1.5 provides the background to the research by reviewing the literature and Section 1.6 presents the contributions of this thesis. Section 1.7 clarifies the major concepts of the methodology and Section 1.8 explains the parameterisation method used, and software used in this research. Section 1.9 outlines the structure of this thesis and Section 1.10 summarises and concludes this chapter.

1.2. Significance of the Research

As discussed in Section 1.1 emissions pricing policies in Australia have undergone several changes. This volatility in the attitudes of policy makers, or “the lack of cross-party political support”, is one of the fundamental sources of uncertainty about Australia’s carbon pricing mechanism (Jotzo et al., 2012). In addition to the effects of this political uncertainty, Australian emissions pricing policy is greatly influenced by other types of uncertainty which are common to all environmental policies. The source and size of uncertainty can affect optimal choices of environmental policies (Angelopoulos et al., 2013).

This research categorises these uncertainties into two groups: first, environmental uncertainty arising from unknown geological and environmental factors. As yet, no precise estimation of the life of carbon in the atmosphere and the contribution of GHGs to climate change and global warming is available. Additionally, the sensitivity of the earth to global warming also remains unknown, and consequently, an accurate estimation of the size and timing of damage due to pollution has not yet been suggested. In Australia it is predicted that the annual average temperature will increase by 2.8 to 5.1°C relative to the 1986–2005 period by the end of this century (CSIRO and the Australian Bureau of Meteorology, 2015). If the upper

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3 Angelopoulos et al. (2013) specify optimal choices of environmental policies in terms of maximising social welfare.

4 Tol (2009) and Tol (2015) provided a survey on estimations of the global economic effect of climate change which was presented in Section 1.1.
estimate proves to be accurate the temperature increase in Australia will be higher than the average global increase as it is predicted that the global temperature will increase by between 2.6 and 4.8°C (Lloyd, 2013). This would result in severe problems since Australia is already the driest inhabited continent on earth (Preston, 2009). These estimations call for effective interventions which take into account the possibility of such events while addressing economic considerations.

The second category of uncertainty is economic uncertainty. This type of uncertainty is related to the social and economic costs of emissions abatement, the social and economic costs of climate change damage, and the trade-off between these two expenses. Economic uncertainty comprises factors which can affect the future of this trade-off such as the development of alternative renewable sources of fuel, the progress of backstop technology and the arrival of new, cleaner technology. In Australia, the progress of renewable energy technology can significantly affect the approaches that policy makers adopt to achieve emissions targets, since production relies heavily on fossil fuels. Over eighty-six per cent of Australia’s electricity was generated by fossil fuels in 2012–13 (Bureau of Resources and Energy Economics, 2014).

Both types of uncertainty highlight the need for a model which can facilitate taking uncertainty into account in environmental policy analysis. To this end, dynamic stochastic general equilibrium (DSGE) models can be applied. Such analysis, however, has not yet been applied for Australia and is the main motivation of the current research. This is the major contribution of this research and it is expected that this thesis can provide a new modelling approach for Australian emissions pricing analysis which recognises the responses of economic and environmental variables to uncertainties and can have the potential to assist policy makers to learn about the effectiveness of different emissions reduction programs.
The emphasis of this thesis is on the effects of economic uncertainty on Australian emissions pricing policies. In particular, this research focuses on sudden changes in production technology in terms of total factor productivity (TFP) shocks. The role of TFP shocks in unexpected changes in macroeconomic fluctuations was first investigated by Kydland and Prescott (1982). A TFP shock leads to a change in the level of output obtained from the same level of inputs. The change in output subsequently results in changes in other economic variables and can trigger new business cycles or affect the amplitude of existing business cycles. Considering production as the main source of pollution, it can be expected that pollution flows, or emissions, follow the same fluctuations of production so that an expansion (recession) in production will bring about an increase (decrease) in emissions. In fact, the focus of this thesis is on neoclassical economics\(^5\) in which it is assumed that the market is self-stabilising and there are only real effects where a real shock, such as a TFP shock, occurs.

Why does the government need to consider TFP shocks? If the government ignores fluctuations that inevitably occur in emissions as a consequence of economic fluctuations, and sets emissions reduction policies based only on the currently observable economic and environmental situation, it may face undesired levels of emissions and increase the risk that emissions targets will not be met. To avoid this, the government should take emissions variations into consideration when formulating policies and attempting to control and stabilise emissions. This requires recognising the integration of climate policies with business cycle and macroeconomic fluctuations will help policy makers to understand how an Australian emissions pricing system can affect or be affected by business cycles, and how

\(^5\) As explained in Chapter 4, Section 4.2 this thesis does not adopt a New Keynesian approach since the focus of this research is not the effects of nominal shocks, and neither is it the relationship between monetary policy and emissions reduction policies.
best to adjust the system to shocks in order to stabilise emissions and obtain lower emissions. The aim of this thesis is to address these questions.

Since the focus of the current research is Australia, it specifies the emissions reduction systems in ways that resemble policies already implemented or planned to be implemented in Australia. The systems include a fixed emissions tax which resembles the Australian Carbon Tax, an abatement subsidy like the Australian Emissions Reduction Fund program, and a variable emissions tax. Based on theory and under conditions of perfect certainty, where both the regulator and firms have access to the same information, a tax will be set at the market price of a cap and trade system. Thus, the variable emissions tax specified in this thesis can be identified as a proxy for the emissions trading system which was planned to be applied in Australia. The next section clarifies the main research questions of this thesis.

1.3. Research Questions

The following research questions are addressed in this study:

1. What would be the effect of emissions reduction programs, including a fixed emissions tax, a variable emissions tax and an abatement subsidy, on Australian emissions and welfare\(^6\)?

2. Which one of these emissions reduction programs is likely to be the most efficient in terms of having less negative impacts on Australian GDP and welfare?

3. What would be the effect of TFP shocks on the Australian economy under each of these emissions reduction programs?

4. What would be the effect of these programs on Australia’s business cycles?

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\(^6\) This research considers welfare in terms of total discounted expected utility.
1.4. Research Hypotheses

The main hypothesis of this research is that any type of emissions pricing mechanism imposes extra costs on producers and may affect the level of output. As a result, the economy will be affected by emissions pricing systems and this can negatively affect major macroeconomic variables including output. On the other hand, the imposed costs of such a policy on polluters can provide motivation for polluters to decrease emissions. Thus, the main hypotheses of this research are:

1. Australian GDP and welfare will be lower under emissions reduction programs than under a business as usual scenario.
2. Australian emissions would be lower under emissions reduction programs than under a business as usual scenario.
3. A TFP shock would increase output and, consequently, emissions.
4. An emissions tax program will produce lower emissions than an abatement subsidy.
5. An abatement subsidy program will result in a lower economic cost of abatement than an emissions tax program.

In order to test these hypotheses the background to this research is reviewed first to identify how previous studies have addressed similar questions.

1.5. Research Background

In order to investigate the effects of policies on different sectors of an economy, and their relationships, general equilibrium models have been broadly applied to analyse the effects of
monetary and fiscal policies (Odior, 2014; Chen, 2015; Vella et al., 2015). In the case of environmental analysis, computable general equilibrium (CGE) models have been broadly used as an appropriate approach for analysis of the income distribution and resource allocation implications of emission control policies (Brendemoen and Vennemo, 1994; Muller-Furstenberger and Stephan, 2002; Bohringer et al., 2015; Karplus et al., 2015; Springmann et al., 2015).

The contribution of CGE models to Australian environmental policy analysis has also been dominant (Asafu-Adjaye and Mahadevan, 2013; Adams et al., 2014; Meng, 2014) and several sophisticated models such as ORANI (Dixon et al., 1977), MEGABARE (ABARE, 1996), Monash Multi-Regional Forecasting (MMRF) (Adams et al., 2000), the Global Trade and Environment Model (GTEM) (Ahammad et al., 2004) and G-Cubed (McKibbin, 1998) have been developed and each of them has been updated several times to illustrate widespread interactions between economic agents. These models are all deterministic in nature, and ignore any environmental or economic uncertainty related to environmental policies. However, as discussed in Section 1.2, the choice of environmental policy depends not only on factors such as the country’s circumstances, the particular sector(s) to which the program will be applied, and interactions with other policies (Sterne, 2007), but also on the size and sources of uncertainty (Angelopoulos et al., 2010).

The role of uncertainty in environmental policy analysis was first discussed by Weitzman (1974) in the form of asymmetric information about abatement costs (i.e. the regulator cannot observe the real firm’s abatement costs). He shows that under such asymmetric information conditions a price-based (quantity-based) control, such as a carbon tax (cap), will be the most

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7 Here, uncertainty refers to the lack of information about the current or future value of a variable(s). See Section 1.2 for a detailed explanation of uncertainty.
effective type of measure if the marginal cost curve is steeper (flatter) and the marginal benefit curve is flatter (steeper). Following him, many contributions have focused on asymmetric information as the main source of uncertainty in environmental policy analysis (Pizer, 2002; Newell and Pizer, 2003; Fell et al., 2012). These studies used different reduced quadratic forms for the cost function and for the benefit function. In order to add other types of uncertainty into environmental policy analysis, a dynamic stochastic general equilibrium (DSGE) model can also be used which involves all sectors of the economy and is more compatible with economic theories. A great advantage of DSGE models is that they are micro-founded models based on the optimisation behaviour of agents with different constraints, technologies and equilibriums. In contrast to CGE models, in DSGE models the modeller can include uncertainty and solve the model for exogenous shocks.

The literature on DSGE environmental analysis is still at a preliminary stage and mostly focuses on real business cycle (RBC)\(^8\) models. They show how environmental policies respond to economic fluctuations. These models were first introduced by Fischer and Springborn (2011) who applied an RBC model with technology shocks in terms of TFP shocks to provide a comparison between three climate policies: an emissions tax, an emissions cap, and an intensity target.\(^9\) Another primary study in the environmental DSGE literature was conducted by Heutel (2012) who developed an RBC model with TFP shocks to show how emissions tax policies should be adjusted to business cycles.

Following these two contributions other studies have applied DSGE models for environmental policy analysis. For instance, Hassler and Krusell (2012) developed a DSGE model by applying a Regional Integrated model of Climate and the Economy (RICE)

\(^8\) RBC models are briefly explained in Section 1.7.

\(^9\) An intensity target limits emissions relative to some measurement, mostly output, being constant.
combined with stochastic\textsuperscript{10} TFP shocks to provide an integrated investigation of climate policies on oil-producing and oil-importing countries. These contributions have focused on real shocks in terms of TFP and have recently been extended to other shocks such as environmental shocks by Angelopoulos \textit{et al.} (2013) and nominal shocks by Annicchiarico and Di Dio (2015). This thesis follows the literature by analysing emissions reduction policies in an RBC framework, however the approach of the current research differs in several ways as explained in the next section.

1.6. Research Contribution

This research makes four contributions to the literature. First, it makes a practical contribution by applying a DSGE model in an Australian environmental policy analysis context. As discussed in the research background provided in Section 1.5 the literature analysing Australian emissions reduction policies is wide ranging, and many researchers have attempted to investigate the effects of these policies on different economic and environmental variables. However, they have ignored the significant role of uncertainty in environmental policies and applied different types of deterministic models. This thesis provides the first environmental analysis under the condition of uncertainty by applying a DSGE model to Australian emissions pricing policy analysis. To this end it applies an RBC model to investigate how technology shocks in terms of TFP can affect the economy under different emissions pricing policies.

The second contribution of this thesis is related to the specification of the policies. The policies which are analysed in this thesis are similar to policies recently implemented in Australia, including a fixed tax policy similar to the carbon tax program, and an abatement

\textsuperscript{10} A stochastic event is an unpredicted event caused by a random variable.
subsidy policy like the Emissions Reduction Fund program. A variable emissions tax scenario is also tested in this thesis. Specifying and testing these policies is the second contribution of the current study to the environmental DSGE analysis literature, since other studies have mostly focused on emissions taxes. For instance, Heutel (2012) and Angelopoulos et al. (2013) examined a variable emissions tax, Dissou and Karnizova (2012) compared the outcomes of taxes and permits, Hassler and Krusell (2012) specified climate policy in terms of taxation on oil, and Fischer and Springborn (2011) and Annicchiarico and Di Dio (2015) examined three policies: an emissions tax, an emissions cap, and an intensity target specified in terms of the shadow price of emissions.

The third contribution of this research is related to the parameterisation method applied in this research. As discussed in Section 1.7 this research applies and adapts a model presented by Heutel (2012). He specifies an exogenous variable, emissions, produced by the rest of the world in his model. However, this thesis finds that the approach he used to parameterise this variable would make it endogenous in such a way that changes in domestic emissions would result in changes in emissions from the rest of the world. To avoid this problem the current research applies another approach to keep emissions from the rest of the world exogenous under all emissions reduction scenarios.

Finally, the fourth contribution is in regard to the techniques used for the analysis. The studies reviewed in Section 1.5 mostly conducted policy analysis by comparing the response paths of variables to a TFP shock and/or the steady state of variables under different emissions pricing programs. In addition to these two techniques, this thesis conducts a policy analysis in a dynamic context by calculating the cumulative effects that a TFP shock can have on the variables under different emissions pricing programs. This technique can capture not only the effects of emissions reduction programs on the steady state values of key variables,
but also the effects on the response paths of variables to shocks and, thus, it can express the total effects of the shock under an emissions reduction program.

Having reviewed the background of the research and the contribution of the current study to the literature, the methodology applied in this thesis is explained in the next section.

1.7. Methodology

A DSGE model was first introduced by Kydland and Prescott (1982) and Long and Plosser (1983) for the purposes of analysing real business cycles. DSGE models are macroeconomic models derived from microeconomic foundations, including market clearing, rational expectations and optimising agents. These types of models were developed to address the Lucas critique. Lucas (1976) argues that applying macroeconomic models based on historical data and not on economic theory can only indicate estimated relationships and are not appropriate for providing any predictions. To have a suitable framework for predictions, he argues, a model should indicate the real structural relationships in which current and lagged values of observable variables form expectations.

As can be understood from their name, DSGE models are:

- dynamic, that is they can be used to investigate an economy over time
- stochastic, so they can show the effects of uncertainties or shocks on the economy
- general equilibrium; that is, they describe the behaviour of a whole economy through analysing the optimising behaviour of micro agents where all agents are in equilibrium.

Generally, there are two schools of DSGE modelling. One uses RBC models, which were the first type of DSGE models introduced by Kydland and Prescott (1982) and Long and Plosser
(1983). These researchers developed a dynamic general equilibrium model to investigate if real shocks, in terms of TFP shocks, are the main source of business cycle fluctuations. RBC models are based on neoclassical growth theories under the assumption of flexible prices. This assumption was later changed to allow for price stickiness. Other modifications included adding a monetary side and monopolistic competition in order to make DSGE models more appropriate for monetary policy analysis. These changes in RBC models resulted in a second type of DSGE model known as New-Keynesian. The New-Keynesian models were introduced by Rotemberg and Woodford (1997) who employ monopolistically competitive market assumptions in which price adjustments involve time and costs.

This thesis applies an RBC model since the aim of this research is to investigate how an optimal emissions pricing system should be adjusted to business cycles. Applying a DSGE model involves six steps: First, the main structure of the model is set by specifying different sectors of the model. Second, each sector is optimised and the first order conditions are found. Additionally, market clearance conditions and shocks are specified. Third, the system is usually nonlinear and without a closed analytical solution. To obtain a numerical solution the model needs to be approximated in the neighbourhood of a non-stochastic steady state point. Fourth, the model is parameterised. Fifth, the size and direction of the shock is specified. Sixth, the model is solved numerically and the results are analysed. All these steps are covered in different chapters of this thesis. The model is parameterised to the Australian economy. The parameterisation method and software used to solve the model are explained in the next section.

1.8. Data and Software

After developing and solving the model, a calibration method is used for parameterisation to obtain and evaluate the empirical results. Calibration is a popular approach for
parameterisation introduced by Kydland and Prescott (1982) in which the parameters of the model are taken from the literature in order to study the behaviour of variables. In this thesis an RBC model is developed and then calibrated using parameter values estimated in previous RBC studies for the Australian economy. The environmental parameters are calibrated to the environmental literature including the Regional Integrated model of Climate and the Economy (RICE). In the latest version, RICE–2010, Nordhaus (2010) divided the global economy into 12 regions: the United States, the European Union, Japan, Russia, Eurasia, China, India, Middle East, Africa, Latin America, Other High Income (OHI) countries and Other Asia. Australia is included in the OHI group. Therefore, this research uses the parameters of the OHI group to calibrate the environmental coefficients for Australia. The economic parameters, which were taken from Australian RBC literature, and the environmental parameters, will be used directly, except for three environmental parameters relating to the damage function. These parameters are taken from the RICE model and amended.

This research also uses estimations for one of the environmental parameters which has not previously been estimated in the literature. To this end Australian databases including the Australian National Accounts (Australian Bureau of Statistics, 2014) and Australia’s National Greenhouse Accounts (Department of the Environment, 2014b) are used. A sensitivity analysis will then be conducted to investigate how sensitive the results are to this estimated parameter. Finally, the model is coded and run on MATLAB to solve the model and simulate the responses of economic and environmental variables to shocks under different emissions reduction scenarios.
1.9. Thesis Structure

This thesis contains eight chapters. The chapters are organised as follows. Chapter 1 provides an introduction to the thesis by highlighting the significance of the study, the questions that this study attempts to address and the method it applies. Chapter 2 provides the background of the study including the importance of emissions reduction policies in the world and in Australia, the instruments and programs which can be applied to obtain emissions reduction targets, and the history of emissions reduction policies. Focusing on Australia, the chapter reviews the main features of Australian emissions, Australia’s international emissions reduction commitments and the history of emissions reduction policies in this country.

Chapter 3 provides the literature review. The focus of this chapter is on reviewing emissions reduction policy analysis which aims to show the effects of such policies on the whole economy. To this end general equilibrium models have been broadly used. Thus, this chapter reviews the application of general equilibrium models including CGE and DSGE models in environmental policy analysis. The chapter reviews the major CGE models which have been developed and applied to analysing Australia’s environmental policy. Then the literature on environmental DSGE models, which have been mostly applied to the US economy and not for Australia until this research, is reviewed.

The model used in this study is presented in Chapter 4. The chapter starts by clarifying the main features of DSGE models and then specifies the model applied in this thesis. The model comprises a production sector, a consumption sector and environment sector which can affect each other. The model is extended to four emissions reduction scenarios. These scenarios are specified to be similar to the programs designed and/or applied in Australia. They comprise: a business-as-usual or no policy scenario, a fixed emissions tax, a variable emissions tax and an abatement subsidy scenario.
The model is then calibrated in Chapter 5. In order to obtain the impulse response functions, (i.e. the response paths of economic and environmental variables to a shock), the model needs to be log-linearised which is also done in Chapter 5. The simulation results are presented in Chapter 6, including the numerical results for the steady state (i.e. with no shock), the impulse response functions and the numerical results for the cumulative effects. Chapter 7 investigates the sensitivity of the results to a change in a parameter and also discusses key policy implications from the findings of this study. Chapter 8 summarises the major results from this thesis and identifies answers to the research questions posed in Chapter 1. It also identifies areas for future research.

1.10. Summary

This chapter has provided an explanation of the importance of a study of Australian emissions pricing policies utilising a DSGE model. It has briefly described the importance of environmental policies in Australia and reviewed relevant policies implemented in Australia. It has also pointed to the importance of considering uncertainty in environmental policy analysis which requires a stochastic analysis approach such as that of a DSGE model. This is the first attempt at applying an environmental DSGE model for the case of Australia. Then the general concepts and characteristics of a DSGE model were clarified. The parameterisation approach and software to be applied in current research were also specified. Finally, the structure of the thesis was presented. The next chapter provides a more detailed discussion of the background to this study.
Chapter 2

An Overview of Global and Australian Emission Reduction Policies

2.1. Introduction

The aim of this chapter is to present background information to this research. This includes highlighting the importance of emissions control policies, a review of global environmental actions including targets and agreements, a review of market policies to achieve the targets, a review of Australian emissions control policies, and an examination of the role of uncertainty in policy analysis. An examination of these issues related to environmental policy helps us to understand the significance and difficulties of emissions pricing policies in Australia.

This chapter refers to two distinguished studies which discuss different aspects of emission control programs: the Stern Report (Stern, 2007) and the Garnaut Report. The report, the Review of the Economics of Climate Change was conducted by Sir Nicholas Stern from the London School of Economics and it was released on 30 October 2006. Stern believes that climate change is a very serious economic challenge as “it is the greatest and widest-ranging market failure ever seen”. To overcome this high-risk problem he suggests taking “strong, early action on climate change” by stimulating good market signals, overcoming market failures and reducing the risk of severe consequences from emissions. Stern (2007) applied different economic models such as integrated assessment models to calculate the economic impacts of climate change on an economy. He also used macroeconomic models to estimate the costs and benefits of transition to low emission systems. The findings of the models suggested that the benefits of such strong, early action would outweigh its costs.

The second study used in this chapter is the Garnaut Report written in 2007 and updated in 2011, which focuses on Australia. Garnaut (2011) divides his report into three sections. In the
first section, “the Global Review”, he provides information about the necessity of a climate system for Australia. In the second part “Australia’s Path” he suggests a carbon tax as an efficient instrument for achieving Australia’s abatement targets, and in the third part “Australian Transformation” he concentrates on the transformation that Australia would experience after the introduction of a carbon tax. Several points from each of these reports are presented in this chapter.

The debate on the implementation of emissions control policies worldwide, as well as in Australia, has been divisive. For many centuries, and before the industrial revolution in the 1800s, the inflows of GHGs produced by animals and sediment, and outflows of carbon absorbed by ocean and plants, was naturally balanced. The major human activity which changed this balance is the burning of fossil fuels, which caused carbon dioxide emissions from fossil fuel to increase by more than three per cent per year on average in the 2000s (Garnaut, 2011). This role of humans in climate change is emphasised in other studies including the report published by the Intergovernmental Panel on Climate Change (IPCC), which indicates that there is a 95 per cent probability that humans are responsible for global warming (IPCC, 2013).

The accumulated GHGs impose externalities (i.e. costs on the environment and all people around the world) not only in the present but also in the future. The externalities and their negative effects on social welfare result in the world having become increasingly concerned about environmental issues over recent decades and attempts to control pollution caused by human activity. One of the earliest and most significant steps towards this end was the Kyoto Protocol, signed in 1997, in which 37 industrialised countries and the European community committed themselves to decreasing their greenhouse gas emissions. To achieve this aim,
governments needed to intervene by implementing emissions control policies which would motivate economic agents to decrease the amounts of pollution they produced.

This issue was previously raised by Pigou (1920) who introduced the concept of externalities in welfare economics and highlighted the role of government intervention to correct these externalities. He argues that setting a price, or a tax, equal to the social costs of the activity which imposes the externality is necessary to correct the inefficiency of the market and to provide an incentive for the producer to internalise the social cost. This type of price is known as a Pigovian tax. For human activities which generate pollution of the atmosphere, the damage is borne by a range of sufferers worldwide over long time periods. This requires an effective global response to correct such market inefficiency. This idea has been applied in environmental economics to address the externality of pollution and led to the advocacy of an emissions tax, also known as a carbon tax.

However, estimating in monetary terms the costs of the pollution and the benefits from controlling its level, especially in detail and based on economic theory, is very difficult and perhaps even impossible (Spash, 2002). Despite associated difficulties, environmental taxation is identified as a useful public policy measure. For instance, Ekins and Barker (2001) believe that emissions taxation is simple and cheap to administer, with insignificant regressive side effects that minimise the economic problems associated with a pollution externality, while at the same time generating revenue and stimulating innovation and investment in renewable technology.

In a carbon tax system, the polluting agents must pay for each tonne of pollution they produce. Paying a price on emissions is an effective instrument to make polluters address the social costs of their actions by internalising the cost of the pollution in their private costs and stimulating them to move away from high-carbon technologies and goods and services to
low-carbon ones. A carbon tax was first introduced by Finland in 1990. Afterwards, the Netherlands, Sweden, Norway, Denmark, Great Britain, New Zealand, France, Switzerland, Ireland, Japan and temporarily Australia, implemented their own emissions tax systems (Carbon Tax Centre, 2011).

During the 1990s, and with the introduction of new climate policies, many economists attempted to investigate the short-run and long-run economic impacts of the policies that had been introduced. The literature on the environmental and economic effects of emissions control policies such as carbon taxes is wide-ranging with different results obtained from a large variety of countries, assumptions and methods. The results of such analyses, however, are highly influenced by a broad range of uncertainties about emissions control policies, including the size of pollution externalities and the future of low-carbon technologies. Such uncertainties can influence the choice of environmental policies (Angelopoulos et al., 2010).

The implementation of emissions control policies in Australia has experienced significant volatility over the last decade and remains in doubt due to different attitudes towards such policies by policy makers. The Australian emissions pricing system was introduced under the Clean Energy Program introduced during the prime ministership of Julia Gillard in 2011. The program included two planned phases: first, a fixed price, or a carbon tax, commenced in 1 July 2012 and was originally planned to continue until 30 July 2015 when the second phase, with a flexible price system under an emissions trading scheme, would begin. However, under the prime ministership of Kevin Rudd in 2013, it was announced that this fixed price period would finish one year earlier, on 30 July 2014 (Australian Government, 2013).

This program was further changed under the prime ministership of Tony Abbott who abolished the carbon pricing system with effect from 1 July 2014 (Australian Government, 2014a). As an alternative, the government introduced the Emissions Reduction Fund program
which came into effect on 13 December 2014. Under this program the government funds emissions reduction activities including the improvement of energy efficiency standards (Department of the Environment, 2014a). The history of Australia’s emissions reduction programs is explained in more detail in Section 2.7 and summarised in Table 2.1.

Table 2.1: Summary of Australian emissions reduction programs

<table>
<thead>
<tr>
<th>Time</th>
<th>Performer</th>
<th>Emissions Reduction Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 2007</td>
<td>Howard</td>
<td>Proposing an Emissions Trading Scheme</td>
</tr>
<tr>
<td>July 2008</td>
<td>Rudd</td>
<td>Introducing the Carbon Pollution Reduction Scheme (CPRS) intending to become effective in 2010</td>
</tr>
<tr>
<td>2009</td>
<td>Parliament</td>
<td>Rejecting CPRS</td>
</tr>
<tr>
<td>July 2011</td>
<td>Gillard</td>
<td>Introducing Securing a Clean Energy Future, the Australian Government’s Climate Change Plan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• a carbon tax program from 2012-2015</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• an emissions trading scheme from 2015 onwards</td>
</tr>
<tr>
<td>November 2011</td>
<td>Parliament</td>
<td>Passing the Securing a Clean Energy Future, the Australian Government’s climate change plan</td>
</tr>
<tr>
<td>July 2012</td>
<td>Gillard</td>
<td>Beginning of a carbon tax</td>
</tr>
<tr>
<td>July 2013</td>
<td>Rudd</td>
<td>Announcing that the tax period would finish in July 2014</td>
</tr>
<tr>
<td>November 2013</td>
<td>Abbott</td>
<td>Introducing legislation to abolish the carbon tax</td>
</tr>
<tr>
<td>July 2014</td>
<td>Parliament</td>
<td>Passing the repeal of the carbon tax</td>
</tr>
<tr>
<td>December 2014</td>
<td>Abbott</td>
<td>Introducing the Emissions Reduction Fund program</td>
</tr>
</tbody>
</table>

Source: Compiled by the author.

Such volatility in policy implementation stands in contrast to actions advocated by Stern (2007), who emphasises that a successful scheme requires that society, especially consumers and investors, are made to believe in the continuity and stability of policies, such as the implementation of a carbon tax, and particularly those measures addressing high-carbon goods and services. The government also has to support the development of technology and extend its collaboration with the private sector, since the private sector is the major player in
research and development and in technology transmission (Stern, 2007). Currently, low-carbon technologies are more expensive than fossil-fuel ones; however this is anticipated to change in the future as the result of progress in research and development (Nordhaus, 2010).

The remainder of this chapter is structured as follows: Section 2.2 presents an overview of estimated global environmental problems due to GHG pollution and the call for emission control programs. Global emissions reduction agreements and targets are presented in Section 2.3. Section 2.4 reviews emissions tax and permit policies as the two most popular emissions control instruments, and Section 2.5 discusses the role of uncertainty in such policies and the importance of conducting an emissions reduction policy analysis which includes uncertainty. Section 2.6 discusses some issues regarding the importance and targets of Australia’s emissions control programs. Then the history of emissions reduction policies and the implemented programs, including former emissions pricing policies and the current Emissions Reduction Fund, are reviewed in Section 2.7. Finally, Section 2.8 summarises the main points from this chapter.

2.2. The Importance of Emissions Control Policies

In previous centuries all economies focused on development through increasing industrial production and extending their share of markets. Over the last three decades the effects of human activities on the environment have become a growing concern worldwide. These effects include the impacts of pollution on public health problems (Janke, 2014; Malina and Scheffler, 2015; Wang et al., 2015), and human health quality and life expectancy (Varvarigos, 2008; Pautrel, 2009 and 2012; Mariani et al., 2009; Jouvet et al., 2010). According to a World Health Organisation report published in 2011, air pollution is the main health risk to the extent that about two million deaths a year are caused by indoor smoke from
biomass fuels and coal used for cooking and heating, and 1.3 million deaths are caused by outdoor air pollution, mostly in developing countries (World Health Organization, 2011).

The effects of human activities and pollution are not limited to human health issues. Over the last decades the evidence of climate change and the role of human activities in global warming have increasingly attracted the attention of many in the scientific community. Recent observed global changes, such as rising temperatures, climate volatility, increases in sea levels and the melting of land ice have encouraged many scientists to find ways to reduce GHG emissions and control their causes. World Meteorological Organisation statistics show that global temperature from January to June 2016 breaks a new record which implies that 2016 is expected to be recorded as the world’s hottest year (World Meteorological Organization, 2016). So far, the years 2011–2015 were the warmest years on record (World Meteorological Organization, 2015) followed by 2010, 2005 and 1998 (The World Meteorological Organization, 2010).

The evidence of global warming has motivated many researchers to investigate the effects of climate change. Among others, Stern (2007) conducted a comprehensive study to investigate the economic and environmental impacts of a 2–3°C increase in temperature by 2050. The results and implications of his study were considerable. He found that the consequences of the increase in temperature would be broad and would include: the melting of glaciers which would increase in the risks of floods and water supply shortages thereby threatening one-sixth of the global population; a reduction in crop yields; an increase in diseases and deaths related to heat stress; and negative changes in ecosystems as 15–40 per cent of species would become extinct with further warming of 2°C. These negative impacts will accelerate as the planet gets warmer.
Climate change and global warming may impact positively on some cold, developed countries such as Canada and Russia for a while, but the impacts will be more severe for the poorest countries, which are mostly in hot, dry places, and for coastal countries. In other words, the distribution of the negative impacts of climate change is not equal worldwide in that it will hurt the most vulnerable and poor people and countries earliest and most severely.

A good example is Bangladesh. This country generates about 0.3% of global emissions but will be severely and disproportionately impacted by the consequences of climate change since about 70% of the country’s total area is less than one metre above sea level (Gardiner, 2014). Once climate change occurs, reversing the process is almost impossible (Stern, 2007). Similar results have been found by other researchers. For instance, Mendelsohn et al. (2000), Nordhaus and Boyer (2000), Tol (2002) and Rehdanz and Maddison (2005) found that some of the countries which would be most adversely affected by climate change would be African countries.

Stern (2007) extended his study to estimate the economic effects of a 5–6°C warming in the next century. As he explains, the time lags between actions and their effects are very long. He applied integrated models and found that an increase of 5–6°C in the global temperature would lead to 5–10 per cent cuts in world GDP and reductions in GDP would be more than 10% for poor countries. Using a particular model, PAGE2002, Stern (2007) studied possible changes of the estimations derived from the integrated assessment models in response to possible increase in the degrees of temperature. This model enabled Stern to estimate the total costs of climate change related to a business-as-usual (BAU) path of emissions (i.e. no emission reduction policy, over the next two centuries). The results indicated the impacts would be severe, equivalent to at least a 5% reduction in global per-capita consumption. The costs would increase to a 20% reduction in consumption per capita if we consider non-market effects including the effects on human health and on the environment. Moreover, weighting
the inequitable distribution of costs on poor countries could increase the cost of a 5–6°C warming by 25% compared to the estimates when we exclude the weighting for inequality.

However, Stern (2007) points out that because he considers a wide range of environmental factors and a time frame of 100 to 200 years, the costs may appear very large. He believes that a deliberate mitigation policy would be able to decrease some of these risks and could be implemented at a lower cost than the costs he has calculated. On the other hand, any attempt to decrease GHG emissions may be interpreted as slowing economic growth since emissions are driven by production. A strong policy, however, can benefit the world by stabilising the level of GHG emissions. That is, by reducing GHG concentrations to a level that can be absorbed by the earth. Obviously, this stabilisation level will be higher if emissions remain above this natural level for a longer period of time. Mitigation measures can be applied in four ways and costs will be depending on the combination of these methods:

- decreasing the demand for emissions-intensive goods and services
- improving production efficiency which leads to savings in terms of both emissions and money
- implementing non-energy emissions actions (e.g. avoiding deforestation)
- shifting to technologies which use less carbon to produce heat, power and transport.

In order to estimate the costs of stabilisation, macroeconomic models can be used to study the wider effects of a transition to a cleaner energy economy. Although this is complex and involves a wide range of assumptions, it can provide an opportunity to track the dynamic interactions of several factors. Using a macroeconomic model, Stern (2007) found that stabilisation at the level of 500-550 parts per million (ppm) of CO₂ would cost approximately 1% of annual global GDP by the year 2050. This cost seems very large, but compared with the costs associated with doing nothing about climate change, these costs may be acceptable.
Moreover, measures to reduce GHG emissions would also have the benefit of reducing inefficiency in some sectors of the economy. Generally, the more flexible and adaptable an economy is the more successful it will be in achieving positive environmental outcomes.

Finally, Stern (2007) suggests that stabilisation should occur at 450-550 ppm CO₂. This range varies in other studies. For instance, Hassol (2007) reviewed several studies on stabilisation and concluded that CO₂ concentrations must be stabilised at 400-450 ppm to avoid crossing the threshold into dangerous climate change. Achieving such levels would require the introduction of fundamental programs and policies. Stern (2007) suggested that when designing such policies governments should consider three strategies, which should be applied together: a carbon price, a technology policy, and the removal of barriers to behavioural change. In order to achieve the last non-economic policy outcome, the government must provide certainty for consumers and businesses by developing a clear information system. He explains that ignoring climate change will destroy economic growth eventually, and emphasises that the earlier effective action is taken, the less costly it will be; and that the longer mitigation action is delayed, the more difficult its adoption in the future will be.

Like Stern (2007) a large number of scientific studies emphasise that increased concentrations of GHGs due to human activities have caused global temperatures to increase, leading to several environmental problems which are predicted to worsen if they are not controlled (IPCC, 2013; 2014; Center for Climate and Energy Solution, 2015). However, several studies have been sceptical or in denial about global warming issues including the existence of global warming and its threat (UNFCCC, 2014b; Environmental Defence Fund et al., 2015; Business Council of Australia, 2016; Fueki et al., 2016). These studies argue that there is not enough accurate evidence of global warming and that the models applied to
predict current and future global temperatures are not precise, suffering from several assumptions and limitations.

Although the global warming issue still remains controversial for many economists and politicians, the estimated costs that it can impose, such as the Stern (2007) estimation discussed above, are considerable, so that even a small possibility of its occurrence requires serious actions to avoid. This issue has been of global concern since the 1990s, when several programs and conventions were developed to control emissions. These programs are reviewed in the next section.

2.3. Global Emissions Control Policies

As explained in the previous section, global warming, and excessive increases in greenhouse gas emissions, attracted worldwide attention in the last few decades of the twentieth century, resulting in the modification of economic targets. To control greenhouse gas emissions many policies have been applied and several agreements have been reached and implemented. In 1992, countries were encouraged to combat global temperature increases and limit their greenhouse gas emissions through an international treaty, the United Nations Framework Convention on Climate Change (UNFCCC). Article 3, p.4, of the UNFCCC states that (UNFCCC, 1992):

“The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effect thereof.”
In 1997, countries reinforced the convention by introducing the Kyoto Protocol in which 37 industrialised countries and the European Community, known as Annex I Parties, committed to decreasing their greenhouse gas emissions by an average of five per cent against 1990 levels in the five-year period from 2008 to 2012. Afterwards, the governments of the Parties to the Kyoto Protocol added a second commitment period following the end of the first one, from 2013 onwards, for eight years (The United Nations, 2013).

Following the UNFCCC targets and the Kyoto Protocol several meetings were held to investigate the efficiency of performed actions and to set new targets and commitments. Subsequent annual conferences have included Copenhagen in 2009, Cancun in 2010, Durban in 2011, Doha in 2012, Warsaw in 2013, Lima in 2014, Geneva in February 2015, Bonn in October 2015 and the most recent one in Paris from 30 November to 12 December 2015. A summary of the most significant meetings and their outcomes was presented in Table 1.2. While the Kyoto Protocol involved only developed countries, subsequent conferences brought both developed and developing countries to the table to set targets and sign commitments after prolonged negotiations.

The Copenhagen meeting is regarded as one of the most significant global meetings, as binding commitments were set for participating Parties. After the United Nations 2009 Copenhagen Climate Change Conference, and the 2010 conference in Cancun, more than 100 countries agreed to keep their emissions to a level that would limit the average global temperature growth to less than two degrees Celsius above pre-industrial levels. This target has been the clearest commitment ever made and has been repeated in subsequent conferences. China and the United States, the world’s two biggest emissions producers, also joined these global climate plans (URS Australia Pty Ltd, 2011) and set their emissions targets in subsequent meetings. In Warsaw in 2013, for example, all countries agreed to set
their emissions targets, or their intended nationally determined contributions (INDCs), and submit them to UNFCCC before the Paris meeting.

In the Paris meeting a historic agreement was reached. The 196 countries who attended agreed to keep the global temperatures to less than 2°C higher than pre-industrial levels. The agreement is to come into force between April 2016 and 2017 after at least 55 countries, which together are responsible for 55 per cent of global greenhouse gas emissions, ratify it (Taylor, 2016). The agreement was signed by 170 countries including Australia on 22 April 2016 and now countries must ratify it through their domestic procedures including their parliaments.

Although the abovementioned conferences achieved different outcomes, all negotiations to control climate change have focused on two types of aims:

- Mitigation: to reduce not only GHG emissions by producers, but also to avoid any actions, such as deforestation, that will lead to a rise in GHG intensities.

- Adaptation: Parry et al. (2007), p.6 defines adaptation as:

  “Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.”

As a Party to the agreement, Australia is also involved in these negotiations. The next subsection reviews Australia’s emissions obligations to date.

2.3.1. Australia’s International Pledges

Australia signed the Kyoto Protocol on 24 April 1998 and ratified it on 12 December 2007 (Parliament of Australia, 2010). The most significant commitment of Australia has been
specified in the Copenhagen Accord in which Australia pledged to decrease emissions by the year 2020 as below (Borrello, 2016):

- a 5% unconditional reduction relative to 2000 levels
- a reduction of up to 15% if there is a global agreement that falls short of securing stabilisation of greenhouse gases at 450 ppm carbon dioxide equivalent and under which major developing economies commit to substantially restraining emissions and advanced economies take on commitments comparable to Australia’s
- a 25% reduction if the world agrees to an ambitious global deal capable of stabilising levels of greenhouse gases in the atmosphere at 450 ppm.

The research conducted for this thesis investigated whether it would be possible to reach these targets. To this end data from the National Greenhouse Gas Inventory (including the land sector) was collected from 2004 to 2014, as shown in Table 8 pages 45-47, of the Inventory (Department of the Environment, 2015b) and the percentage changes of emissions compared to the 2000 level are calculated and displayed in Table 2.2. As the table shows Australia’s emissions significantly increased compared to the 2000 level during the 2000s. From 2010, however, emissions started to decrease in absolute terms. A possible reason for this decrease could be the introduction and implementation of environmental policies in Australia which were seriously followed by the government during those years, as explained below in Section 2.7. The highest emissions reduction occurred in 2013 and 2014, when there were 1.485 and 1.986 per cent reductions below the 2000 level respectively. During these years the carbon tax system was in force. This implies that Australia’s carbon tax system could have achieved the desired environmental outcomes and could be considered as an effective instrument for Australia to meet its Copenhagen commitment of reducing emissions by 5 per cent below the 2000 level to 2020.
2.4. Emissions Control Instruments

To achieve emissions reduction targets governments have applied several instruments which can be classified into three groups (Perman et al., 2003): first, market-based instruments which affect market variables such as prices in order to provide incentives for emissions control and/or abatement. The market-based instruments include emissions taxes and subsidies, resource taxes and marketable emissions permits. The second approach is to use command and control instruments in which the regulator sets restrictions or standards on inputs, outputs, production methods or even the location of activities. The third group of instruments are institutional methods which facilitate emissions abatement targets by means of socialisation and education programs which promote social responsibility. Among all of these, market-based instruments are the most popular. In this section, two market-based instruments are explained in detail: an emissions tax, known as a price-based instrument, and marketable emissions permits which are usually called a quantity-based instrument.

2.4.1. Emissions Tax (a Price-Based Instrument)

An emissions tax, also known as a carbon tax, is a mechanism in which each tonne of GHG emissions produced by an industrial sector is monitored and greenhouse gas emitters have to pay the cost. The price generates a cost as an incentive for profit maximising firms to take into account in their behaviour (Perman et al., 2003). The government can use the revenues from the emissions tax in several ways, such as reducing budget deficits, cutting existing marginal tax rates such as that of income or payroll taxes, or returning revenues to selected groups of households or firms in order to reduce the adverse effects of the tax (Congressional Budget Office, 2013). These taxes have been used worldwide for more than two decades. Below, the experiences of countries applying the emissions tax are reviewed:
Table 2.2: Australian emissions over 2004-2014 and changes from 2000 level

<table>
<thead>
<tr>
<th>Inventory Year</th>
<th>Emissions (Mt CO₂-e)</th>
<th>% difference from 2000 level</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>558.8</td>
<td>0</td>
</tr>
<tr>
<td>2004</td>
<td>576.3</td>
<td>3.131711</td>
</tr>
<tr>
<td>2005</td>
<td>608.7</td>
<td>8.92985</td>
</tr>
<tr>
<td>2006</td>
<td>614.1</td>
<td>9.896206</td>
</tr>
<tr>
<td>2007</td>
<td>597.2</td>
<td>6.871868</td>
</tr>
<tr>
<td>2008</td>
<td>591.7</td>
<td>5.887616</td>
</tr>
<tr>
<td>2009</td>
<td>592.9</td>
<td>6.102362</td>
</tr>
<tr>
<td>2010</td>
<td>577.4</td>
<td>3.328561</td>
</tr>
<tr>
<td>2011</td>
<td>552.5</td>
<td>-1.12742</td>
</tr>
<tr>
<td>2012</td>
<td>559.4</td>
<td>0.107373</td>
</tr>
<tr>
<td>2013</td>
<td>550.5</td>
<td>-1.48533</td>
</tr>
<tr>
<td>2014</td>
<td>547.7</td>
<td>-1.9864</td>
</tr>
</tbody>
</table>

Source: Compiled by the author from Department of the Environment (2015b), Table 8, p. 45-47.

1. Finland was the first country to introduce an emissions tax in 1990. The structure of this tax was a combination of a carbon tax and an energy content tax. The rate of the tax was changed from €1.12/t CO₂ in 1990 to €20/t CO₂ in 2010 (Carbon Tax Centre, 2011).

2. The Netherlands also initiated an emissions mechanism in 1990. The tax is on electricity, natural gas, blast furnaces, refinery and coal gas, coke ovens, coal signification gas, diesel, gasoline and light fuel. The tax rate was US$20 per tonne of CO₂ in 1996. Revenue from the emissions tax is used to reduce the general tax burden for both businesses and individuals by decreasing other taxes, and for use in other climate programs. It was estimated that the tax would reduce CO₂ emissions by about 1.7 to 2.7 million tonnes annually in 2000, increasing to 3.6 to 3.8 million tonnes in
2010 and 4.6 to 5.1 million tonnes in 2020 (Sumner et al., 2011). In 2013 total GHG emissions reductions in the Netherlands resulting from the tax were estimated to be 25.3 million tonnes, equal to an 11.5% reduction in emissions compared to the base year of 1990 (Caldara et al., 2014).

3. Sweden introduced an emissions price in 1991. The tax was set at US$100 per tonne of CO₂. Currently, the tax is US$150. Electricity generation was exempted and industrial consumers paid just 50% of the tax while non-industrial sectors had to pay not only the whole amount but also a separate tax on electricity. To encourage all sectors to use renewable energy the government excluded ethanol, methane, biofuels, peat and fuel from waste materials from the tax. These exceptions resulted in an increase in the use of biomass for heating and industry (Carbon Tax Centre, 2011).

4. Norway also introduced an emissions tax mechanism in 1991. It was imposed on light and heavy fuel oil, gasoline, oil and gas at the rate of US$65 per tonne of CO₂ emissions. Fishing in Norway or in distant waters, foreign shipping and external aviation were exempted (Sumner et al., 2011). The program covered 50% of GHG emissions which includes 68% of CO₂ emissions in 2005 (Environmental Defence Fund et al., 2015).

5. Denmark initiated an emissions tax in 1992. The tax was imposed on light and heavy fuel oil, natural gas and pit coal at the rate of US$16.91 per tonne of CO₂ at the beginning. In 2005 this was reduced to, and has remained at, US $16.41. Beside the carbon tax, fossil fuels are subject to an energy tax as well. Sixty per cent of the revenue from the carbon tax was returned to industries through different supporting packages, while the remaining 40 per cent was used for environmental subsidies. Total revenue from the carbon tax in 2008 was about US$905 million. Denmark
successfully reduced per capita emissions by 15 per cent from 1990 to 2005 including a decrease in industrial emissions by 23 per cent in the 1990s (Sumner et al., 2011).

6. Great Britain made plans in 2001 to collect an emissions tax on the use of energy in the industry, commerce and public sectors. The plan included rates of 0.15p/kWh for gas (US$0.003), 0.07p/kWh for liquid petroleum gas (US$0.0014), 0.44p/kWh ($0.0087) for electricity and 0.12p (US$0.0024) for any other taxable commodity. The government used revenue from the tax to support employment and energy efficiency and renewable energy, and also exempted electricity generation from new renewable resources (Carbon Tax Centre, 2011).

7. New Zealand implemented a tax on carbon emissions in 2005 at the rate of US$10.67 per tonne of carbon. The government cut other taxes to offset its negative effects. However, the emissions tax system was not efficient enough to decrease CO₂ emissions to the level permitted under the Kyoto Protocol, and a cap-and-trade scheme was then applied to help the economy achieve its climate goals (Carbon Tax Centre, 2011).

8. Boulder (Colorado) is the only city in the US with a tax on carbon emissions from electricity. It was introduced in 2007 at a rate of US$7 per ton of carbon. The tax costs households about US$1.33 per month but they receive a discount if they use renewable energy. The state government uses the revenue to fund more climate projects in order to comply with the Kyoto Protocol (Carbon Tax Centre, 2011).

9. Quebec was the first province in Canada to introduce an emissions tax system in 2007. This included a petroleum tax equal to just 3.1 US cents per gallon of gasoline and 3.6 US cents for diesel. The effect of the tax on the price of power has been negligible since almost all electricity in Quebec is generated by hydropower (Carbon Tax Centre, 2011).
10. The Canadian province of British Columbia has been collecting an emissions tax since 2008. The tax started at a rate of CA$10 per tonne of carbon dioxide, rising by CA$5/tonne annually to reach CA$30 per tonne in 2012. The tax is offset by personal income and business income tax cuts. The British Columbia government believes that the tax has not weakened the economy which has been growing well especially in comparison to other provinces in Canada (Carbon Tax Centre, 2011). The tax reached its expected value of CA$30 per tonne in 2012 and has remained at this rate (Fagiolo and Roventini, 2012).

11. France also implemented an emissions tax policy in 2010 and levied it on households’ and businesses’ consumption of oil, coal and gas. It did not include electricity since this is mostly generated by nuclear reactors. CO\textsubscript{2} emissions from households and businesses are taxed at a rate of €17 per tonne of CO\textsubscript{2}. It was estimated that the government’s income from the tax was between €3 to 4.5 billion per annum, 55 per cent coming from households and 45 per cent from businesses (Saltmarsh, 2010).

12. Ireland also introduced an emissions tax in 2010. The tax is applied to almost all types of fossil fuels including marked gas oil (MGO), kerosene, liquid petroleum gas, natural gas and fuel oil and it is not applied to solid fuels like coal or peat. The initial carbon tax rate was €15 per tonne of carbon dioxide emissions from fossil fuels, but in the 2012 budget it was increased to €20 (Citizens Information Board, 2012). It is estimated that the tax yield was approximately €250 million in 2010. The government uses the revenue to increase energy efficiency, reduce fuel poverty and improve rural transport (Burker, 2010).

Since emissions tax systems do not have the same structures across all countries it is not realistic to expect the same results and effects. However, the pros and cons of all emissions tax systems can be discussed. An emissions tax encourages the emitters to apply the most
cost effective abatement strategies and also leads to CO₂ emissions reductions and energy conservation by promoting a shift to cleaner fuels such as from coal and oil to natural gas (Mongelli et al., 2009).

On the other hand, adopting an emissions tax system can negatively impact international competitiveness (Poterba, 1993). This negative effect is due to the fact that an emissions tax increases the cost of fuels and consequently domestic production costs, which leads to a reduction of competitiveness for firms that operate in international markets. This will cause firms to relocate to countries which have less stringent environmental policies. This concept is known as the “pollution haven hypothesis” (Jaffe et al., 1995; Ho et al., 2008). This issue is also known as “carbon leakage” in which the differentiated emissions policies in Annex I countries, who committed to decrease CO₂ emissions under the Kyoto Protocol, and non-Annex I countries will lead to a relative improvement in the international competitiveness of the latter (Parker and Blodgett, 2008).

Another type of emissions pricing system that governments can apply to internalise the costs of emissions and provide motivation for polluters to decrease emissions is an emissions permit system. The main difference between a tax and a permit system is that the former is directed at prices while the latter is focused on quantities – a so-called quantity-based instrument. The next section provides an overview of how permit systems work.

2.4.2. Emissions Permits (a Quantity-Based Instrument)

An emissions permit is a quantity-based emission control program in which the regulator limits the emissions firms can produce by issuing a certain number of permits to relevant firms. The authority usually auctions the permits or allocates them for free (Kerr and Cramton, 2005). The regulator can also allow permit banking; that is, it allows firms to transfer unused permits to the next period(s) (Li, 2014). A marketable emissions permit
system, where firms can buy and sell their emissions permits, is based on the principle that an increase in emissions will be offset by an equivalent decrease elsewhere.

A good example of an emissions permit system is the EU Emissions Trading Scheme (EU ETS), also known as the EU Emissions Trading System, which is the largest one in the world. It was launched in 2005 (Ellerman and Buchner, 2007a). Since then the scheme has gone through three phases. The first phase was from January 2005 to December 2007 with the target of controlling GHGs emissions, or setting a cap, at about 2.2 billion tonnes of CO₂-equivalent emission permits per annum. The cap included 12,000 enterprises that were responsible for about 40% of CO₂ emissions in the EU. These enterprises traded their credits at a total value of €7.2 billion for 362 million tonnes of CO₂ (Hasselknippe and Roine, 2006). The price fluctuated dramatically, with a peak level of approximately €30 per tonne of CO₂ in April 2006. However, verified emissions indicate an increase of 1.9% over the first period of the system. The second phase started in January 2008 and finished in December 2012. During this phase a lower cap, at the level of 2.08 billion per annum, was determined. As was the case in the first period the price fluctuated intensely with a peak of €22 per tonne in 2008 and a declining trend thereafter (Committee on Climate Change, 2009). The third phase started in January 2013 and will continue until December 2020. For this period the European Commission will apply several changes, including:

- It will set an overall EU cap at first and then allocate permits to EU members. In the first two phases the members’ caps were set first and then the overall EU cap was calculated as the aggregation of the members’ caps. This centralised allowance will be decreased at a rate of 1.74% per annum and this will continue beyond 2020.
- It will restrict the banking of allowances between Phases II and III. Banking enables businesses to save a current allocated allowance for the next period; borrowing
enables them use an upcoming allowance in advance. Both mechanisms are permitted in Phase III, but will be restricted since they were a major cause of carbon price volatility in previous periods.

- It will shift from allowances to auctioning. The free allocation of emissions allowances resulted in an efficiency loss during the first two phases. In Phase III only the power sector will not be given auction emission allowances. It was estimated that about 40% of all allowances would be auctioned in 2013 (Committee on Climate Change, 2008). This estimation proved accurate as more than 40% of all allowances were auctioned in 2013, providing total revenue of €3.6 billion for the EU. From this about €3 billion earmarked for climate- and energy-related areas including energy efficiency and research and sustainable transport (World Bank, 2016).

The EU ETS is operated by 28 EU members plus Iceland, Norway and Liechtenstein. The number of countries in the EU ETS has now risen to 31, covering more than 11000 manufacturing plants and power stations responsible for approximately 45% of total EU emissions in 2013 (European Commission, 2013b).

Although both price-based and quantity-based policies are considered to be effective instruments (Weitzman, 1974; Perman et al., 2003) to achieve emissions reduction targets and have been applied over the last two decades, the choice between a price-based and quantity-based policy is still controversial especially among policy makers. Ekins and Barker (2001) explained that the main advantage of an emissions permit over a tax system is its flexibility, since the regulator can choose between different methods of allocation. Lohmann (2008) also favours a cap policy since it is based on the assumption of a competitive market. However, there are several concerns about emissions cap programs due to their strong
uncertainty, asymmetric of information, national protectionism and corporate power (Grubb et al., 2005; Lohmann, 2006; Spash, 2010).

On the other hand, a tax system can be superior to a permit regime since the government receives all revenues in the tax system. Additionally, emissions taxation is considered to achieve a “double dividend”. The double dividend hypothesis refers to two types of benefits from levying a tax on pollution. The first is pursuing the major aim of improving the environment; the second is improving the efficiency of the taxation system via using the revenue from environmental taxes to reduce other taxes such as income taxes that impact labour supply and saving decisions (Goulder, 1995; Oates, 1995). The principle behind the first dividend is the stimulatory effects of emissions taxes in the development of cleaner technologies. According to neoclassical economics the most significant factor in driving new technology are the profits which the developers expect to receive. Businesses’ decisions are rational and they invest in research and development based on expected returns and the opportunity cost of capital (Spash and Lo, 2012). Emissions taxes tend to increase the incentives of budget-constrained households and profit-seeking firms to modify their consumption and production to be more energy efficient and cleaner.

The second dividend comes from recycling the revenue from emissions taxes. If the revenue returns to the economy via transfers to sectors or other types of taxes the government’s budget remains unchanged, and emissions taxes would be revenue-neutral (Spash and Lo, 2012). However, emissions taxes can be considered to provide an economic gain if the revenues are used to decrease the distortionary taxes on major economic inputs such as labour and capital (Goulder, 1995; Ekins and Barker, 2001). This second dividend is the strongest argument against quantity-based policies (e.g. cap-and-trade systems) in which the government restricts the firms to produce a limited amount of GHG emissions because these
policies generate less public revenue (Humphreys, 2007). Table 2.3 summarises the pros and cons of the two emissions pricing instruments.

Under perfect certainty, where both the regulator and firms have access to the same information, both price-based and quantity-based policies will result in the same economic and environmental outcomes. This is due to the fact that under perfect certainty taxes will be set at the market price of the permits and, thus, both systems will achieve the same environmental objectives and the costs of doing so will be approximately equal.

Under conditions of uncertainty, however, the outcomes of the two systems are different. This was first pointed out by Weitzman (1974) who shows that under asymmetric information conditions – that is, when the regulator cannot observe the firm’s real abatement costs, the policy choice depends on the marginal cost and benefit curves. A price-based (quantity-based) control will be an advantage if the marginal cost curve is steeper (flatter) and the marginal benefit curve is flatter (steeper). Asymmetric information is known as a type of macroeconomic uncertainty (Dissou and Karnizova, 2012). There are other types of uncertainty about environmental issues and policies which can affect emissions control policies. In the next section these uncertainties are clarified.
<table>
<thead>
<tr>
<th>Emissions Tax</th>
<th>Emissions Permit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both systems can encourage the emitters to apply the most cost effective abatement strategies and also lead to CO₂ emissions reductions and energy conservation by promoting a shift to cleaner fuels such as from coal and oil to natural gas.</td>
<td>Both systems can negatively impact international competitiveness and result in the “pollution haven hypothesis” or “carbon leakage” in which firms tend to relocate to countries which have less stringent environmental policies.</td>
</tr>
<tr>
<td>The price is set by the regulator.</td>
<td>The price is set by the market and the system works based on the assumption of a competitive market.</td>
</tr>
<tr>
<td>It is rigid as the regulator sets the price of emissions and collects the tax from polluters arising from the emissions they produce.</td>
<td>It is flexible since the regulator can choose between different methods of allocation: auction or free allocation.</td>
</tr>
<tr>
<td>It is straight forward: polluters pay for each unit of pollution they produce at a certain price.</td>
<td>There are several concerns about this program arising from: their strong uncertainty, asymmetry of information, national protectionism and corporate power.</td>
</tr>
<tr>
<td>It generates revenue for the government and the revenue can be used to reduce the distortionary taxes on major economic inputs such as labour and capital, known as the “double dividend”.</td>
<td>It does not generate revenue.</td>
</tr>
</tbody>
</table>
2.5. Uncertainty in Emissions Control Policies

As explained above, according to theory first put forward by Weitzman (1974), the main criterion for the choice between price-based and quantity-based policies is uncertainty about the costs of pollution abatement. This uncertainty has also been highlighted by other researchers. Stern (2007), for instance, points to the role of uncertainty in estimating the cost of mitigation policies. This type of uncertainty arises since forecasting the costs of technology changes and estimating any future fossil-fuel price changes, and also people’s responses to these changes, cannot be valued precisely. An improvement in efficiency can decrease the cost significantly. The author estimates that efficiency in energy supply grew 1000 per cent over the last century and that the energy sector will be the largest source of emissions reduction between now and the year 2050. Currently, there are several clean technologies which are too expensive to apply. Thus, the priority should be to find a way to decrease their costs and make them competitive under an emissions pricing mechanism.

In addition to emissions abatement costs, there are other types of uncertainty which can significantly influence estimation of the costs and benefits of emissions control policies. Such uncertainties can be generally divided into two groups: first, environmental uncertainties arising from unknown geological and environmental factors. As explained in Chapter 1 Section 1.2 no precise estimates of the life of carbon in the atmosphere and the contribution of GHGs to climate change and global warming are available. Additionally, the sensitivity of the earth to global warming also remains unknown, and consequently, an accurate estimate of the level and timing of the damage due to GHG emissions has not yet been calculated.\textsuperscript{11} For instance, Falk and Mendelsohn (1993) found that a half-life of atmospheric carbon dioxide is equal to 139 years while Reilly and Anderson (1992) estimated it to be 83 years.

\textsuperscript{11} See Tol (2009), Tol (2015) and Table 1.1 for a survey of estimates of the total global output effect from climate change.
The second type of uncertainty in emissions reduction policy is economic uncertainty: this type of uncertainty is related to the estimated social and economic costs of emissions abatement and the costs of climate change damage, and the trade-off between these two expenses. For instance, predictions about the welfare effect of a 2.5°C increase in average global temperatures vary widely, from a 1.9% loss of global GDP (Tol, 1995) to a 0.9% gain (Hope, 2006). Economic uncertainty also includes other factors which can affect the future of this trade-off such as substitution between fuels, the progress of backstop technology and the arrival of new and cleaner technology. Therefore, emissions control policies are highly subject to uncertainty to the point that the source and size of uncertainty can affect the optimal choice of environmental policies (Angelopoulos et al., 2013). This highlights the necessity of emissions control policy analyses which can display and track uncertainties.

Australian emissions control policies are greatly influenced by both types of uncertainty. For instance, it is predicted that annual average temperatures will increase by 2.8°C to 5.1°C by the end of this century (CSIRO and the Australian Bureau of Meteorology, 2015). If the upper estimate is accurate Australia would become the warmest country in the world, which would lead to severe problems since it is also the driest inhabited continent on earth (Preston, 2009). These estimates call for effective interventions which take into account environmental uncertainties. Additionally, the progress of renewable energy technology can significantly affect the approaches available to policy makers for achieving emissions targets since the production sector relies heavily on fossil fuels. For example, 86.9% of Australian electricity was generated by fossil fuels in 2012-13 (Bureau of Resources and Energy Economics, 2014).

Looking at Australia’s emissions control policies, it is easily seen that they have been highly influenced by political uncertainty, resulting in considerable volatility in policies over the last
decade, as discussed previously. This type of uncertainty is revealed as a “lack of cross-party political support” and is one of the fundamental sources of uncertainty about Australia’s emissions pricing mechanism (Jotzo et al., 2012). In fact, climate change has become a political as well as an economic issue. The next section presents a review of Australia’s emissions control policies over the last decade.

2.6. Australia’s Emission Control Policies

This section reviews Australia’s emissions control policies. To this end some environmental issues which call for emissions control policies in Australia are first presented in Section 2.6.1. Then the main features of Australia’s emissions profile are specified in Section 2.6.2. This section is followed by a historical review of policies developed and implemented in Australia in Section 2.7.

2.6.1. The Importance of Emissions Control Policies in Australia

As reviewed in Section 2.2, recent global changes such as rising temperatures have resulted in calls for emissions control policies (Tol, 2002; Stern, 2008; Lloyd, 2013; Crimp et al., 2014; Department of the Environment, 2015a). In Australia there is significant evidence from the scientific community (Bureau of Meteorology, 2014; CSIRO and the Australian Bureau of Meteorology, 2015) that the country is being impacted by the effects of climate change. For instance, the Australian Bureau of Meteorology (BOM) time series data shows that the average temperature has increased by 0.9°C per annum more than 1910 and the increase in GHG emissions has been a key contributor to this temperature increase. The BOM data also shows that several mean, maximum and minimum temperature records were broken in 2013 as Australia experienced the hottest summer and spring, the hottest January and September, the hottest summer day and the warmest winter day on record in that year (Perman, 2015). The year 2013 is the hottest year on record while 2015 is the fifth-hottest (Arimura and Iwata,
2015) and 2016 is shaping up to be the hottest of all (World Meteorological Organization, 2016).

These changes have resulted in an increase in the frequency of severe weather events including major droughts, floods, tropical cyclones, heatwaves and bushfires. These events have occurred at times of the year and in places where they have previously been considered rare. For example, Garnaut (2011) points to the 2009 Black Saturday bushfires in Victoria, or the Queensland cyclones in 2011, as being the result of global warming. He also points out that the pattern of rainfall intensity has changed as the risk of flooding has increased in areas close to the equator or poles, while the risk of drought in the mid-latitude regions such as southern Australia, is expected to increase. In other words, the extremes of both high rainfall and low rainfall in Australia have increased as greenhouse gas concentrations have increased.

The main burden of such changes is on urban water supplies and agriculture. For instance, increases in temperature and decreases in rainfall could lead to agriculture yield reductions of more than 30% by 2050 in Western Australia (Zagaglia, 2005). Climate change can also have significant ecological impacts in Australia, including reductions in the populations of some species and shifts in the ranges of others, and changes in the dynamics and structures of biological communities (NASA, 2013). It is estimated that under a no emissions reduction policy the Great Barrier Reef would be severely damaged by 2050 and the three-dimensional coral of the reef is even likely to completely disappear (Garnaut, 2011). These consequences of climate change highlight the importance of adopting appropriate environmental policies in Australia.

With increasing evidence of climate change and its negative effects, Australia has participated in global environmental conventions which oblige participating countries to implement emissions control policies, as explained in Section 2.3.1. To reach its Copenhagen
target, that is a five per cent reduction in emissions relative to 2000 levels, Australia needs to limit its net emissions to 537 million tonnes by 2020. This target is a 236 million tonne challenge in 2014–2015 (Tol, 2015). Garnaut (2011) showed that this target could have been achieved with an emissions pricing system starting at about AU$26 per tonne of carbon dioxide equivalents in 2012. He pointed out that this price would be comparable to international emissions prices. For example, the US government estimated that the price should be US$21 per tonne of carbon dioxide equivalents, rising to US$26 in 2020 and US$33 in 2030 based on 2007 exchange rates. In the United Kingdom the price is considered higher at £26 per tonne of carbon dioxide equivalents. However, the price would grow over time at a rate which was set at four per cent per year in Garnaut’s model.

Garnaut’s recommended emissions price was initially applied as the key instrument in Australia’s emissions reduction policies. However, the current policy, which was introduced 2015, does not include an emissions price. Instead, it consists of a subsidy on emissions reduction under the Emissions Reduction Fund program. These policies are explained in detail in Section 2.7 after a review of Australia’s emissions in Section 2.6.2.

2.6.2. The Features of Australia’s Emissions

Although Australia’s emissions have fluctuated over the last few decades, they contributed little more than 1.2 per cent of global GHG emissions from 2000 to 2010 (CDIAC, 2013). Based on the latest available data, Australia was the sixteenth-largest emissions producer in the world in 2013, producing about 1.2 per cent of global GHG emissions and it was also ranked twelfth in per capita terms in the world (CDIAC, 2013). In terms of the sources of emissions, however, Australia has the third-largest emissions from burning coal in per capita terms (BNP Paribas, 2014), which illustrates the reliance of the economy on fossil fuels, and especially coal.
Reviewing the sources of emissions in Australia also highlights the role of burning fossil fuels, especially coal. Australia’s Emissions Projections 2014–15 report published by Tol (2015) showed that the major emissions producer in Australia is the electricity sector, since it depends to a significant extent on the burning of brown coal. The next two largest sources of emissions are the direct use of gas and other fuels by households or businesses, through direct fuel combustion, and transportation. Each of these sources contributes about 17 per cent of total emissions. Fugitive emissions, that is the carbon dioxide and methane generated during gas production and coal mining processes, are responsible for eight per cent of Australia’s emissions. Industrial processes, deforestation and forestry and waste decomposition are other sources of emissions. Figure 2.1 shows the proportions of Australia’s total emissions produced by different sources in 2014.

Finally, this research investigates the relationship between Australian output and GHG emissions. To this end the seasonally adjusted data of emissions and GDP over the period September 2001 to September 2014 was collected from the Quarterly Update of Australia’s National Greenhouse Gas Inventory (Department of the Environment, 2015b) and Australian National Accounts (Australian Bureau of Statistics, 2016). Both series of data are normalised to their September 2001 levels and shown in Figure 2.2. As the figure reveals, both emissions and GDP grew during this period. The growth of GDP is steeper and to a higher level, from 1.0 per cent to 2.2 per cent, while emissions grew from 1.0 per cent to less than 1.1 per cent. This might be due to an increase in energy efficiency or technology advancements.

Additionally, business cycle fluctuations can be observed in both series, including the recession of 2009 arising from the Global Financial Crisis. Similar cyclical changes are also seen in emissions which motivate this thesis to study the relationship between fluctuations of emissions and GDP. This requires removing the trends of both series. To this end the log
values of both series are found and then the Hodrick-Prescott filter with a smoothness parameter\textsuperscript{12} of 1600 is applied. The results contain only the cyclical component of both series, as shown by Figure 2.3. As the figure shows, although the cyclical fluctuations of GDP are greater than the fluctuations in emissions, generally both series follow similar cycles. This correlation between GDP and emissions implies that fluctuations in business output can result in similar fluctuations in emissions. The government should recognise this and take into account the relationship between emissions and output business cycles. Otherwise, even with an efficient emissions reduction program, the government might encounter undesired fluctuations in emissions. This issue has not been investigated before for the case of Australia and will be addressed in the current research.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2_1.png}
\caption{A comparison of emissions sources in Australia in 2014}
\end{figure}

Note: LULUCF refers to land use, land use change and forestry.

The next section reviews the development of emissions reduction policies in Australia.

\textsuperscript{12} This parameter removes the cyclical component of a time series and determines the smoothness of the trend components.
Figure 2.2: Seasonally adjusted emissions and GDP of Australia from September 2001-September 2014 normalised to the September 2001 level

Source: Compiled by the author using Department of the Environment (2015b) and Australian Bureau of Statistics (2016)

Figure 2.3: Cyclical component of Australian emissions and GDP from September 2001 to September 2014

Source: Compiled by the author using Department of the Environment (2015b) and Australian Bureau of Statistics (2016)
2.7. Australian Emissions Reduction Policies

The first steps towards emissions reduction in Australia was taken when Stern (2007) published his review in which he highlighted market failure in controlling climate change and underlined the importance of serious and prompt actions to avoid economic and social problems that climate change would impose on the world. This report motivated the Australian government, under the prime ministership of John Howard, to develop and implement an emissions reduction policy. To this end ‘the Prime Ministerial Task Group on Emissions Trading’ was established in order to investigate the pros and cons of implementing an Emissions Trading System (ETS) in Australia (Adjemian et al., 2014). Based on the findings of the group the Howard government decided to implement an ETS in July 2007 (Crimp et al., 2010).

The first environmental actions, however, occurred after the Australian Labor Party won the 2007 federal election and the Rudd Labor government ratified the Kyoto Protocol in December 2007. This ratification committed Australia to limiting increases to its GHG emissions to no more than 8% of its 1990 level by 2012 (Parliament of Australia, 2010). In September 2008 the Garnaut Climate Change Review was published in which Garnaut estimated the optimal emission price as being between $20 to $30 per tonne of carbon dioxide equivalent, rising by four per cent per year thereafter (Crimp et al., 2014). This report became one of the main foundations for designing Australian emissions reduction policies.

In July 2008 the Rudd government announced its cap-and-trade program, the Carbon Pollution Reduction Scheme (CPRS) which was intended to become effective in 2010 (Alexandratos and Bruinsma, 2012). The scheme was designed to reduce emissions to 15 per cent below the 2000 level by 2020. The principle of the scheme was supported by the Liberal-National Coalition led by Malcolm Turnbull. However, it was criticised by industry
and business lobbies who believed that the permits and the assistance packages to decrease the costs imposed by the scheme were inadequate. On the other hand, the environmental lobby argued that the emissions reduction targets specified in the program were inadequate (Adjemian et al., 2014).

The CPRS, however, was rejected by the Senate twice in 2009 which forced the government to defer it to 2013 (Shafik, 1994). Meanwhile, Tony Abbott, who was against the CPRS, deposed Turnbull as Liberal Party leader (UNFCCC, 2016b). Also, Rudd lost his leadership to Julia Gillard in 2010 (Cantore et al., 2016) and she then called a federal election. The Greens Party leader, Bob Brown, announced that if Labor was to win the election the Greens party would assist the government in passing a carbon tax policy in the Senate (Batt, 2015). During the election campaign, however, Gillard announced that she would rule out a carbon tax (Department of Agriculture Fisheries and Forestry, 2011). After the election, and in order to obtain a working majority in the Senate, the Labor Party entered into an agreement with the Greens which included a plan to introduce a carbon tax (Australian Bureau of Agriculture and Resource Economics and Science, 2011).


Shortly after this, the next federal election was held and the Liberal-National Party Coalition, led by Tony Abbott, won the vote and introduced legislation to abolish the carbon pricing
system with effect from 1 July 2014 (Australian Government, 2014a). The repeal was passed by the Senate in July 2014. In order to meet Australia’s international commitment to reducing emissions by 5 per cent compared to the 2000 level by 2012, the government introduced the Emissions Reduction Fund program which came into effect on 13 December 2014. This fund involves the use of government funds to finance emissions reduction activities, including the improvement of energy efficiency standards (Department of the Environment, 2014a).

Prior to the 2016 federal election in which it was narrowly defeated, the Australian Labor party proposed two emissions trading schemes, one for the electricity sector and one for industrial polluters with a total cost of $355.6 million over four years. The program is similar to the one proposed by Malcolm Turnbull in 2009 when he was leader of the Opposition (Taylor, 2016). The proposed industrial ETS includes two phases: phase one specifies a cap, or a certain level of emissions, that industries can produce without any penalty, but they have to buy permits for the extra units of emissions. Phase two is yet to be designed (Borrello, 2016). The program confirms that the Australian Labor Party is pledged to reducing emissions by 45% by 2030 and is committed to shifting Australian electricity generation to renewable sources (Grattan, 2016). In the next two sub-sections the implemented programs, including the Gillard and Abbott government programs, are reviewed in detail.

2.7.1. Gillard’s Clean Energy Program

The Gillard government introduced the ‘Securing a Clean Energy Future, the Australian Government’s Climate Change Plan’ on 10 July 2011. The plan was designed to transit Australia to a clean energy economy through initiatives in four areas: carbon pricing, renewable energy, energy efficiency and land management. Central to the plan was the introduction of a carbon pricing mechanism along with a significant package of complementary measures and assistance for businesses and households (Australian
Government, 2011). In fact, more than 50 per cent of the revenue from the carbon tax was to be returned to households through increasing family payments, cutting other types of taxes and paying higher allowances and pensions. These household support measures covered 90 per cent of all Australian households (Gardiner, 2014).

Under an emissions pricing system a price, such as a tax, is levied on each tonne of GHGs emissions. GHGs include carbon dioxide (CO$_2$), methane (CH$_4$), nitrous oxide (N$_2$O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF$_6$), all of which make the earth warmer. These gases can be found in nature but human activities since the industrial revolution have their atmospheric concentrations resulting in an increase in global temperatures. Carbon dioxide, methane, nitrous oxide and perfluorocarbons from aluminium smelting were included in Australian carbon pricing.

The carbon price mechanism included two phases. The first was a fixed price period. This period commenced on 1 July 2012 and was originally designed to continue until 30 July 2015. The price started at $23 per tonne of carbon rising by 2.5 per cent each year in real terms in the first three years. This was to be followed by the second phase beginning on 1 July 2015 in which the fixed price system was going to transform to a fully flexible price determined in the global carbon market. During this period the government would place a cap on emissions, that is, it would place a limitation on annual greenhouse gas emissions by issuing a fixed number of carbon permits, each one of which would represent one tonne of emissions. Some of the issued permits would be sold by the government at auction while others would be donated freely to businesses to support jobs and competitiveness. Businesses could sell and buy the permits they gained from the government which would lead to the creation of a market. The government would determine the annual caps on emissions from
2015 to 2019 before the beginning of the flexible period. Afterward, annual caps would be
determined annually to make businesses aware of the limits they would face.

The government was planning to set safety values for the system for the first three years of
the flexible price period to avoid price plunges. These safety values included a price ceiling
and floor. The former was to be set $20 higher than the expected international carbon price at
the beginning of the flexible price period and would rise by five per cent in real terms each
year, while the latter would be set at $15 per tonne from 1 July 2015 rising by four per cent
each year in real terms. The price floor would decrease the risk of a sharp price fall which
would lead to a reduction of long-term investment in clean technologies.

It was anticipated that the tax would be paid by industrial plants that emitted over 25,000
tonnes of CO₂ per annum. These plants comprised 315 liable entities which were burning
fossil fuels. They included electricity generation, transportation including rail, domestic
aviation and shipping, cement and steel making which produce industrial emissions, coal and
LNG mining which release greenhouse gases naturally stored underground, and waste
management. Land-based activities like farming, forestry and fishing were not covered by the
carbon price. Households and light commercial vehicles were also exempted from carbon
pricing.

As planned in the Clean Energy Future program, Australian businesses were to be permitted
to enter the global carbon market from July 2015. In the global market they could trade their
permits and buy international permits from other countries if the permit in Australia was
more expensive. This trade could ensure that the Australian permit price would be set at the
global price which was determined by international supply and demand for abatement. To
decrease the negative effects and risks of this new system the government was going to
support enterprises with a number of packages including industry assistance ($11.9 billion),
the Jobs and Competitiveness Program ($8.6 billion), the Clean Technology Program ($1.2 billion), the Steel Transformation Plan ($300 million) and Coal Sector Jobs Package ($1.3 billion).

The Australian emissions program, however, was not implemented as planned since it was not supported by subsequent prime ministers. The first change to the program was made by Kevin Rudd who announced that this fixed price period would finish one year earlier, (Australian Government, 2013). The program was abolished by the Abbott-led Liberal–National government with effect from 1 July 2014 (Australian Government, 2014a). Instead, he introduced the Emissions Reduction Fund program in which emissions reduction activities are financially supported. The next section reviews the program implemented by the Abbott government.

2.7.2. Abbott’s Emissions Reduction Fund Program

In the Emissions Reduction Fund the government set aside $1.55 billion to support emissions reduction programs which could be extended to $2.55 billion in future budgets. The fund was to be allocated to ‘project proponents’ who included landholders, businesses and other organisations with plans to reduce emissions. The program involved four steps, as shown in Figure 2.4 Australian Government (2014b):

Figure 2.4: Emissions Reduction Fund steps

The first step involves proponents of projects estimating emissions reductions and registering their projects. To this end, the government provided guidelines and tools for the proponents to use to estimate the emissions their proposed programs would eliminate. Next, the projects needed to be registered with the Clean Energy Regulator to participate in an auction.

In the second step, the approved projects can sell their proposed emissions reductions on the basis of a price per tonne of carbon dioxide equivalent by submitting a bid at an auction. The successful bidders then go to step three and enter into a contract with the government in which the government commits to purchase the emissions reduction specified by the project. In the fourth step, the proponents commence their project and report to the Clean Energy Regulator. The regulator then evaluates the reports and issues credits based on the reported emissions reductions. Finally, proponents receive payment for the credits at the contract price (Roson, 2013).

To date, three Emissions Reduction Fund auctions have been held, one in April 2015, one in November 2015, and one in April 2016. The auctions together resulted in 348 contracts to purchase 143 million tonnes of abatement at a cost of $2.55 million dollars. The average price of abatement was $13.12 per tonne of abatement, being the average of the auction price in April 2015 ($12.14), the auction price in November 2015 ($12.25) and the auction price in April 2016 ($10.23) (Clean Energy Regulator, 2016). The Emissions Reduction Fund program, however, has been criticised by some environmental economists. For instance, Roson and van der Mensbrugghe (2012) applied a Computable General Equilibrium model and showed that the allocated budget for the Emissions Reduction Fund scheme is half the amount that would be required to meet the target of reducing emissions to 5 per cent below the 2000 level by 2020. Another criticism of the program is that it is designed to continue for only five years (Roson, 2013) while a successful policy, aimed at changing the attitudes of
both consumers and producers, would require the economy to believe that the policy will continue (Stern, 2007). Additionally, a tax system is straightforward, as polluters pay for the actual emissions they produce while in an abatement system it is possible that the government pays for abatements which will occur anyway. For instance, coal fired electricity generators may reduce their emissions due to a decrease in electricity demand, even if the firm does not make any abatement efforts (Roson and van der Mensbrugghe, 2012).

As reviewed in this section, Australia’s emissions reduction policies have been highly influenced by political uncertainty in terms of different policy attitudes and programs. Despite the considerable volatility in the Australian emissions pricing program, however, it remains of research interest and several studies have analysed the costs and benefits of such programs. The next chapter reviews the literature on Australian emissions pricing policy and analysis and of its modelling.

2.8. Summary

In this chapter, the importance of controlling GHG emissions and the approaches adopted to achieve this target were introduced. Concerns over the environmental impact of human activities have increased since the 1990s and attempts have been made to find ways to manage emissions. This led to the establishment of several international agreements, such as the Cancun Agreement and Paris Agreement, with the aims of mitigation and adaptation. The Kyoto Protocol is the most significant climate agreement so far. In this agreement countries committed to reducing their emissions to particular levels. To achieve their targets governments have applied different types of instruments including emissions pricing systems which can be price-based or quantity-based.

On a theoretical level both systems can induce polluters to internalise the social and environmental costs of their pollution. The effectiveness of each policy, however, is
influenced by different types of economic and environmental uncertainty and the sources and
size of those uncertainties can affect the choice of environmental policies (Angelopoulos et al., 2013). These uncertainties emphasise the necessity of dynamic stochastic models to enable researchers to show and track such uncertainties in their analyses.

This chapter also provided an overview of Australian environmental policies. In Australia the first policy introduced was a carbon tax which was imposed on 1 July 2012 for three years. The plan was for it to be in effect for three years, after which it was to be replaced by a flexible emissions system (i.e. a cap and trade). However, the program was abolished on 1 July 2014 and instead an emissions subsidy program, named the Emissions Reduction Fund, was established. The current research provides a policy analysis of these programs using a dynamic stochastic general equilibrium (DSGE) model.

Reviewing the structure of Australia’s emissions also revealed the correlation between emissions fluctuations and Australia’s business cycles. This leads to the question as to which one of the programs so far designed or implemented for Australia would be optimal in terms of reducing emissions and/or lowering costs in the presence of business cycles. This question will be addressed in the current research. To this end the literature on Australia’s emissions pricing policies, as well as the use of DSGE modelling for environmental policy, are reviewed in Chapter 3. Based on the reviewed study, a DSGE model will be applied to the Australian economy in Chapter 4.
Chapter 3

Literature Review

3.1. Introduction

This chapter reviews the literature on emissions pricing systems as climate change policy instruments and their possible impacts on economies. As explained in Chapter 2 Section 2.4 emissions pricing instruments are the instruments most commonly used to reduce emissions. They include price-based instruments or emissions taxes, and quantity-based instruments or cap-and-trade systems. A review of existing studies indicates that the environmental and economic effects of each type of program are wide-ranging, with different results obtained depending on which of a large variety of assumptions and methodologies are applied. Previous studies have primarily concentrated on the short- and long-run impacts of emissions pricing programs for the whole economy (Lu et al., 2010; Fischer and Springborn, 2011; Ghosh et al., 2012; Lim and Kim, 2012; Meng et al., 2013) or for a specific sector (Khanna and Zilberman, 1999; Morgenstern et al., 2004; Goulder et al., 2010; Dissou and Karnizova, 2012; Lehmann, 2013).

In theory, the outcomes of price-based and quantity-based policies will be the same under a full information situation. Under conditions of uncertainty, however, the outcomes of the two systems would be different. This issue was first raised by Weitzman (1974) who developed a static partial equilibrium model for an economy characterised by uncertainty, asymmetric information, costly policy adjustment and second-best policy alternatives. He developed cost and benefit functions as quadratic in the regulated input and linear in uncertainty. He finds that under asymmetric information conditions (i.e. when the regulator cannot observe the firm’s real abatement costs) the relative slope of marginal costs and benefits of emission control play a key role in choices between quantity and price controls, in such a way that a
steeper (flatter) marginal cost and a flatter (steeper) marginal benefit will increase the efficiency of price-based (quantity-based) controls.

This finding was replicated in subsequent research. For instance Hoel and Karp (2002) and Newell and Pizer (2003) conducted two separate but very similar studies to investigate the impacts of price-based controls and quantity-based controls where the stock of pollution damages the environment, and polluters and regulators have asymmetric information about abatement costs. Previous studies prior to Hoel and Karp (2002) mostly assumed that environmental damage depends on the flow of emissions, while Hoel and Karp (2002) consider the damage caused by the stock of pollution. Both Hoel and Karp (2002) and Newell and Pizer (2003) compare the expected benefits from the two types of instruments, where the expected net benefit is a function of the benefits and expected costs of emission abatement. The major difference between these two studies is that Hoel and Karp (2002) assume that the cost shocks are serially uncorrelated while Newell and Pizer (2003) use correlated cost shocks over time.

The initial results of both studies are the same as Weitzman (1974): an increase in the slope of the marginal cost and a decrease in the slope of the marginal benefit curve will increase the efficiency of price-based controls. The choice between the two policies also depends on emission stock decay rates and discount rates so that a higher discount rate and/or a higher decay rate decrease the importance of future stock impacts and, therefore, the regulator would prefer a price-based instrument. Not only are the theoretical results of the two studies the same, but also the empirical results are similar, as Hoel and Karp (2002) suggest that an emissions tax system is more efficient than an emissions quota system while Newell and Pizer (2003) argue that the benefits of price-based polices are greater than those of quantity-based policies.
Weitzman (1974), Hoel and Karp (2002), and Newell and Pizer (2003) along with many other researchers such as Pizer (2002) and Fell et al. (2012) apply a dynamic model of environmental policy in the form of a cost-benefit analysis with uncertainty about the costs of abatement. These studies impose different reduced quadratic forms for the cost function and for the benefit function. Instead, one can apply a DSGE model which involves all sectors of the economy and is more compatible with economic theories. A great advantage of DSGE models is that they are micro-founded models based on the optimisation behaviour of agents with different constraints, technology and equilibriums. These models are able to include sources of uncertainty and to be solved for exogenous shocks or unexpected changes. These advantages of DSGE models have been attracting researchers since Fischer and Springborn (2011), and a few studies have developed a dynamic model to analyse the impact of climate policies using DSGE models.

In the case of Australia all studies, to the best of the author’s knowledge, have applied deterministic approaches which ignore the impact of economic fluctuations on the effectiveness of emissions pricing programs. The main aim of this thesis is to address this gap by exploring how emissions reduction programs that have been used or slated for use in Australia are affected by economic fluctuations. Australian climate policy models have progressed significantly. Computable general equilibrium (CGE) models help policy makers recognise the costs and income distribution effects of emissions pricing policies for different sectors and for the economy as a whole. In order to review the major studies of Australian environmental analysis, this chapter first reviews the CGE models developed and applied to emissions pricing policy analysis in Australia. It then reviews the new, but rapidly increasing, literature on DSGE modelling of emissions pricing policy. Both CGE and DSGE models are general equilibrium models; that is, can be used to examine the effects of a policy on different sectors of an economy when they are in equilibrium. The pros and cons of each
approach are explained in detail in Sections 3.1 and 3.2 but they are summarised here in Table 3.1.

Table 3.1: DSGE vs. CGE models

<table>
<thead>
<tr>
<th>Source: Compiled by the author.</th>
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<tbody>
<tr>
<td>1) The model builder can make decisions about how to show economic relationships and interactions, and about what functions and what variables to use in each relationship and equation.</td>
</tr>
<tr>
<td>2) There are different types of CGE models – short-run or long-run, static or dynamic.</td>
</tr>
<tr>
<td>3) They are consistent with many economic theories.</td>
</tr>
<tr>
<td>4) They can be applied to investigating the impacts of taxes or revenue changes on one or a number of sectors or regions, or a whole economy.</td>
</tr>
</tbody>
</table>

The advantages of CGE models (except number 2), plus:

1) They can consider exogenous shocks and uncertainties.
2) They show the dynamics of a policy in policy analysis.
3) They are appropriate for welfare analysis (Winschel and Kratzig, 2010).

DSGE models are stochastic while CGE modes are deterministic.

Advantages of DSGE models for environmental analysis:

This chapter has four main sections. Section 3.1 is the introduction. Section 3.2 reviews the application of CGE models as one of the most frequently adopted approaches to studying the effects of climate policies, especially for the Australian economy. Section 3.3 focuses on the application of DSGE models in the environmental area, followed by Section 3.4 which summarises the chapter.
3.2. Computable General Equilibrium Models

Computable general equilibrium (CGE) models attempt to represent the widespread interactions between economic agents. The advantages of CGE models are (Charney, 2003):

1) These models are very flexible. In other words the model builder can make decisions about how to show economic relationships and interactions, and about what functions and what variables to use in each relationship and equation. 2) The model builder is able to choose from different types of CGE models: short-run or long-run, static or dynamic. 3) CGE models conform to many economic theories. 4) These models can be applied in investigating the impacts of taxes or revenue changes on either one or a number of sectors or regions, or a whole economy. Due to such advantages, researchers have shown an increased interest in using CGE models to model environmental issues. Below, a number of studies that have applied CGE models to study climate policy worldwide and in Australia are discussed.

To investigate the effects of a price-based policy, Lu et al. (2010) constructed a dynamic recursive CGE model to examine the environmental and economic impacts of two different prices for a tonne of carbon, RMB¥100 and RMB¥200, on the Chinese economy. They also simulate such effects under two scenarios, with and without any complementary policies such as indirect tax cuts or with increased household subsidies. Their results suggest that a carbon tax at the rate of RMB¥100 leads to a reduction in China’s carbon emissions of 12.49 per cent per year at an annual cost of 1 per cent of GDP, while the rate of RMB¥200 reduces emissions by 12.33 per cent at the same cost of 1 per cent of GDP. This small cost in terms of GDP is due to an increase in investment in technology changes, making the carbon tax an effective policy instrument. Their results also indicate that the costs of a carbon tax would decrease if the government also used complementary policies (e.g. monetary and fiscal policy) in conjunction with the carbon tax.
In addition to taxing the units of pollution produced by emitters, some researchers argue that levying a tax on energy is another policy which can achieve environmental goals since the major polluters in all industries are fossil fuels. To show the environmental effects of this policy Wissemé and Dellink (2007) quantify the effects of levying a tax on energy in Ireland. They develop a static CGE model comprising seven energy commodities and 19 other commodities. Their results indicate that imposing a carbon energy tax of €10 to €15 per tonne of carbon dioxide emissions leads to a 25.8 per cent reduction in Ireland’s carbon emissions compared to its 1998 levels. However, they emphasise that their results are very sensitive to the possibility of fuel switching for producers. Furthermore, comparing the impacts of a carbon tax with an energy tax, they find that a carbon tax would be more effective, with less negative impacts on the economy and greater abatement of carbon emissions, since it would increase the incentives to switch from coal and peat to renewable energy resources.

The application of CGE models in environmental studies in Australia is also extensive, to the point that the most popular climate change models are of this type. During the last two decades the number of quantitative investigations of environmental issues in Australia has increased (Asafu-Adjaye, 2004; Asafu-Adjaye and Mahadevan, 2013; Meng et al., 2013). Many of these studies investigate the economic and environmental effects of carbon prices on the whole economy and/or specific sectors. The following sub-sections discuss some of the most prominent climate change models developed for the Australian economy. Table 3.2 provides a summary of the CGE models reviewed in this section.
<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Aim(s)</th>
<th>Region</th>
<th>Method</th>
<th>Scope</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Lu <em>et al.</em>.</td>
<td>To investigate the economic and environmental effects of a price-based policy, with and without complementary policies (e.g. monetary and fiscal policy)</td>
<td>China</td>
<td>A dynamic recursive CGE model</td>
<td>Theoretical contribution (a deterministic simulation).</td>
<td>A carbon tax can reduce emissions (by about 12%) at the cost of 1 per cent of GDP which would decrease if a complementary policy, such as indirect tax cuts or increasing household subsidies, was applied in conjunction with the carbon tax.</td>
</tr>
<tr>
<td>2007</td>
<td>Wissema and Dellink</td>
<td>To study the effects of levying a tax on energy and to compare it with a carbon tax</td>
<td>Ireland</td>
<td>A static CGE model with a social accounting matrix (SAM).</td>
<td>Theoretical contribution (a deterministic simulation).</td>
<td>An energy tax can reduce emissions. However, a carbon tax is more effective and has little impact on welfare, and a significant shift in production and consumption patterns from higher to lower carbon intensity energies.</td>
</tr>
<tr>
<td>1993</td>
<td>McDougall</td>
<td>To simulate the short-run and economy-wide impacts of a carbon tax</td>
<td>Australia</td>
<td>ORANI: a dynamic CGE model</td>
<td>Theoretical contribution (a deterministic simulation).</td>
<td>A carbon tax increases prices, especially the price of energy intensive commodities; decreases export volume, GDP and employment which call for a lower wage policy. Also, an energy tax (except on petroleum products) can be an effective alternative to a carbon tax.</td>
</tr>
<tr>
<td>1998</td>
<td>Kennedy</td>
<td>To simulate the economic and sectoral impacts of Kyoto Protocol commitments with and without an emissions trading scheme</td>
<td>Annex B Countries, including Australia</td>
<td>MEGABARE: a dynamic CGE model</td>
<td>Theoretical contribution (a deterministic simulation).</td>
<td>Kyoto Protocol commitments negatively affect Australian competitiveness by decreasing export volumes. They also affect Australian coal, iron and steel sectors significantly. An emissions trading scheme can reduce such negative effects.</td>
</tr>
<tr>
<td>2004</td>
<td>Ahammad <em>et al.</em></td>
<td>To investigate the effects of a Japanese carbon tax on Japan and Australia at two different rates as well as the effects of a joint emissions trading scheme between these two countries</td>
<td>Japan and Australia</td>
<td>GTEM: a dynamic CGE model</td>
<td>Theoretical contribution (a deterministic simulation).</td>
<td>A high carbon tax at the rate of ¥45000 per tonne of carbon and emissions trading scheme can decrease emissions close to the Kyoto Protocol targets with significant economic effects especially on the consumption and import of energy, which affects Australia as the major energy exporter to Japan.</td>
</tr>
<tr>
<td>Year</td>
<td>Author</td>
<td>Aim(s)</td>
<td>Region</td>
<td>Method</td>
<td>Scope</td>
<td>Findings</td>
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<tr>
<td>2007</td>
<td>Adams et al.</td>
<td>To investigate the effects of a carbon emissions trading scheme</td>
<td>Australia</td>
<td>MMRF-Green: a dynamic CGE model</td>
<td>Theoretical contribution (a deterministic simulation).</td>
<td>The possible cost of an ETS is about 1.3% of income. To decrease the negative effects of the ETS on energy generation the government can use compensations or a free allocation of permits.</td>
</tr>
<tr>
<td>2010</td>
<td>McKibbin et al.</td>
<td>To simulate environmental and economic effects of the Copenhagen Accord’s targets</td>
<td>Australia, Japan, USA, Other OECD, China, LDCs, Eastern Europe</td>
<td>G-cubed: a dynamic CGE model</td>
<td>Theoretical contribution: (a deterministic simulation).</td>
<td>The effects of the Accord’s targets on consumption and GDP are different across countries. A domestic carbon tax also has different impacts domestically, or on international trades, i.e. export and import, of the selected countries.</td>
</tr>
<tr>
<td>2011</td>
<td>Commonwealth of Australia, Treasury</td>
<td>To provide a comprehensive carbon price model for the Australian economy</td>
<td>Australia</td>
<td>A combination of a number of CGE models.</td>
<td>Overall: theoretical contribution (dynamic, deterministic).</td>
<td>A AUD$20 per tonne carbon price will lead to a reduction in emissions to 80% of the 2000 level, and an increase in per capita GNI by 56% and employment will be 53% higher than its 2010 level by 2050.</td>
</tr>
<tr>
<td>2013</td>
<td>Meng et al.</td>
<td>To simulate the environmental and economic impacts of a carbon tax at a rate of AUD$23 per tonne on the Australian economy, with and without a compensation plan</td>
<td>Australia</td>
<td>A static CGE model based on ORANI-G with an environmentally extended social accounting matrix (ESAM).</td>
<td>Theoretical contribution (static, deterministic).</td>
<td>The carbon tax will efficiently mitigate emissions but will negatively impact the economy, and a compensation policy will significantly reduce these impacts with only a very slight effect on emissions mitigation.</td>
</tr>
</tbody>
</table>

Source: Compiled by the author.
3.2.1. ORANI

The ORANI model was first introduced by Dixon et al. (1977) and is a large multi-sectoral CGE model for the Australian economy with more than 100 industry sectors, in which an industry is allowed to produce more than one commodity. The model was initially designed to study the impact of tariff cuts on industries, regions and occupations, but the high flexibility of the model in choosing variables to be endogenous or exogenous makes it appropriate for analysing a wide range of policies.

Application of the ORANI model to climate change analysis occurred in the 1990s when McDougall (1993a) applied an enhanced ORANI multi-sectoral model to simulate the short-run and economy-wide impacts of a carbon tax. He finds that the impact of levying AUD$25 per tonne of carbon emissions increases prices, especially the price of energy intensive commodities. The tax negatively affects Australian international competitiveness and contributes to a 0.6 per cent contraction in export volume which leads to a decrease in GDP by 0.9 per cent with the assumption of fixed domestic absorption, and reduces employment by 1.2 per cent with the assumption of fixed money wages. To decrease these negative effects, especially on employment, he suggests a lower wage policy.

McDougall (1993b) also uses another version of the ORANI model, ORANI-E, to study the effectiveness of an energy tax (i.e. a tax on fossil fuels), and to compare it with a carbon tax in terms of carbon emissions reduction. This model is a version of the ORANI model which was upgraded by embedding several energy-specific enhancements including adding various substitution possibilities in energy production and consumption in the theoretical structure of ORANI, as well as more detail on energy production and consumption to its database. McDougall concludes that an energy tax, except on petroleum products, can be an effective alternative to a carbon tax since, like a carbon tax, it would lead to fuel switching. He also
finds that both carbon and energy taxes decrease real GDP by 0.5 per cent and national consumption by 0.07 per cent.

3.2.2. MEGABARE
The MEGABARE model is a dynamic CGE model introduced by the Australian Bureau of Agricultural Resource Economics and Sciences (ABARES) in 1996. The model is designed to provide a comprehensive framework with which to investigate the impacts on the Australian economy of national and international policies such as trade liberalisation or environmental policies implemented in Australia or other countries. The model comprises 30 regions in the world economy, including Australia, with 37 industries in each region. The structure of industrial production is a function of energy inputs, intermediate inputs and three production factors, labour, capital and land, in which labour and capital are allowed to be substituted. The major contribution of MEGABARE is in the development of a technology bundle approach in modelling iron, steel and electricity production. In this approach, producers are able to choose between energy intensive technologies in response to price changes arising from emission abatement policies.

An aggregated form of the MEGABARE model, with 19 regions and 16 commodity groups, was applied by Kennedy (1998) to analyse the impact of two environmental policies on the Australian economy: an independent emissions abatement program in which each country meets its Kyoto commitments without any international emissions trading scheme, and a program in which countries develop an emissions trading system. Kennedy employs a carbon tax mechanism in this model in which the revenue from the tax is returned to the economy in the form of a lump-sum transfers so that it has a neutral impact on the economy. The results indicate that achieving Kyoto Protocol commitments negatively affects Australian competitiveness by decreasing export volumes while an emissions trading scheme reduces
these economic costs. Moreover, Kennedy finds that coal, non-ferrous metal, and iron and steel production would be less affected under an international emissions trading scheme.

MEGABARE, however, has been criticised in several works. Hamilton and Quiggin (1997) argue that “the principal characteristics of the MEGABARE model ... make it a poor guide to formulating climate change policies”. They categorise these characteristics as ignoring possible technological change in response to environmental policies, emphasising changes occurring in types of fuels as inputs of production which is not consistent with Australian consumption patterns, overstating the degree of carbon leakage, excluding the benefits gained from emissions reductions, and making assumptions such as disregarding non-energy sources of greenhouse gas emissions and the lump-sum transfer nature of the taxes. These critiques led to the development of a new model, the GTEM.

3.2.3. GTEM

ABARE developed the Global Trade and Environment Model (GTEM) which is a dynamic multi-country model derived from the Global Trade Analysis Project (GTAP) model and the MEGABARE model. GTEM includes three major modules in a way that it can show both the positive effects including improving water quality and the negative effects, such as job cuts, of governmental actions. The first module is the economic core in which agents face different optimisation problems subject to particular constraints. The second is the population module which represents changes in the labour force and social structure such as public health. The third is an environmental module representing the greenhouse gas emissions produced from regular lifestyle or economic activities. In other words, GTEM is an economic core model with bilateral linkages with a population module and an environmental module.

The economic core of the model comprises \( r \) economic regions which can be countries, parts of countries or groups of countries. There are \( j \) industries in each region; each of them
employs primarily factors and intermediate inputs, both can either be produced locally or imported in order to produce a single product. In each region households are the owners of all production factors. Hence, the representative household in each region receives the GNP per capita of that region and allocates it to the consumption of private and public goods and savings. The government imposes taxes on almost all transactions and transfers the proceeds to the representative household. The government also provides public goods from locally produced or imported inputs which are funded by the household. Additionally, technological change is assumed to be exogenous except in infant electric power generation technologies and in natural resource extraction.

GTEM was used by Ahammad et al. (2004) to investigate the effects of a Japanese carbon tax on Japan and Australia at two different rates of ¥3400 and ¥45000 per tonne of carbon emissions, as well as the effects of an emissions trading scheme between these two countries. The results indicated that introducing a carbon tax at the rate of ¥3400 would have little negative effect on Japan’s economic growth, energy consumption, imports or greenhouse gas emissions. The rate of ¥45000, however, would decrease emissions to levels close to the Kyoto Protocol targets with significant economic effects. The most important effect would be on the consumption and importation of energy, especially coal, which affects Australia since Japan is the major importer of Australian liquefied natural gas and coal.

3.2.4. MMRF

The Monash Multi-Regional Forecasting (MMRF) model is a dynamic multi-regional model of the Australian economy designed by Adams et al. (2003; 2010). This model has been used in several reports and studies due to its advantages including: a dynamic structure, a strong disaggregated sectoral and regional database, the incorporation of a national labour market and a government finance module (Adams et al., 2010). MMRF is a comparative static CGE
model which includes eight regions, six states and the two territories of Australia. Each region has its own economic characteristics such as region-specific industries, region-specific consumers and region-specific prices. The model has four types of agents: households, producers, government and foreigners. Each region has 58 industries and 63 commodities. Each industry can produce various types of commodities but it can create only one type of capital. Each region has its own specific type of capital, representative household and regional government while all regions have a federal government. The model also has foreigners that supply regional international imports and their demand is equal to regional international exports.

The MMRF model can be run using two methods: a comparative static model or a recursive dynamic model. In the first method the model specifies the short-run and long-run impacts of an indicated policy change. In the second, dynamic relationships like physical capital accumulation indicate the sequences of solutions for every year, and policy analysis is conducted through a comparison of the sequences of solutions with and without the policy. MMRF is a comprehensive model that has been used frequently in Australia to analyse the impacts of fiscal, transport and environmental policies.

The MMRF-Green model is very close to that of MMRF and was designed by the Centre of Policy Studies to analyse Australian carbon emissions-related issues. The model has primarily been applied in carbon emissions trading areas (for instance, Allen Consulting Group, 2000; Adams, 2007) and also in the Treasury modelling of the Australian carbon pricing system. The model was subsequently enhanced to increase its consistency with environmental analysis in three areas. First, MMRF-Green makes it possible to account in detail for greenhouse gas emissions produced by each region and industry in the model. Second, it models the emissions from burning fuels due to fuel usage with equations that
make allowance for inter-fuel substitution in electricity generation by region. Third, the model provides an appropriate framework for the endogenous take-up of mitigation measures due to environmental policy measures.

### 3.2.5. G-Cubed

The G-Cubed model is a dynamic multi-country, multi-sector intertemporal CGE model which was originally developed by McKibbin and Wilcoxen (1992) and updated by McKibbin (1995). The model was designed to simulate policy impacts such as environmental policies, tax reforms, trade liberalisation and macroeconomic policies with a focus on global warming issues. The G-Cubed model was developed in an effort to provide a linkage between econometric general equilibrium modelling, modern macroeconomics and international trade theories. The model comprises eight regions, including Australia; each region has an energy sector and a non-energy sector. There are five industries in the energy sector and seven industries in the non-energy sector. The model includes three types of agents: producers, consumers and investors whose behaviour is based on forward-looking optimisation. At the international level the model allows the regions to have bilateral trade and endogenous capital flows.

However, McKibbin (1995) points out two major limitations of the model. First, the applied constant elasticity of substitution (CES) utility function caused budget shares to be independent of income, which is inconsistent with empirical studies. Second, the parameters used for a number of developing countries, especially for those outside the OECD, are calibrated from US time series estimations. This was due to a lack of time series input-output data for those countries.

In another study, McKibbin et al. (2010) use the G-Cubed model to analyse the Copenhagen Accord’s targets. They estimate the environmental and economic effects of those targets and
also the spillover impact of abatement activities on the countries not adopting those targets. They show that the impacts of the commitments on consumption or GDP loss are different across countries and are affected by their economic situations in the future. They also show that the welfare effects of an overall agreement vary broadly between countries. For instance, the US would not experience a significant loss of consumption, although it would have the third-highest carbon price, while OPEC countries, with no carbon pricing, would have less consumption if other countries levied a tax on OPEC exports and decreased their demands for OPEC products.

3.2.6. Australia’s Treasury Carbon Price Modelling

The Australian Treasury developed the most comprehensive climate change model for Australia on 10 July 2011, and updated it on 21 September 2011. The model integrates a number of CGE models to conduct complex large-scale carbon price modelling for the Australian economy. First, the Treasury model includes the GTEM to take advantage of an international framework for both economic and environmental aspects of the model. Second, the MMRF model is applied to address the effects of a carbon tax at the sectoral, national and regional levels. Third, in order to evaluate the atmospheric concentrations of greenhouse gases the Model of Assessment of Greenhouse Gas Induced Climate Change (MAGICC), which was developed by the Intergovernmental Panel on Climate Change (IPCC), is also employed. Fourth and fifth, to investigate the Australian electricity generation sector using a comprehensive bottom-up approach, the Sinclair Knight Merz Market Model Australia (SKM MMA), provided by the Sinclair Knight Merz group, as well as the ROAM model\textsuperscript{13} developed by the ROAM consulting group, are applied. Sixth, modelling of the road transport sector is done using the Energy Sector Model (ESM) developed by the Commonwealth

\textsuperscript{13} The model’s name is taken from the group that developed it.
Scientific and Industrial Research Organisation (CSIRO). Seventh, in order to study the income distribution effects of a carbon price on households, the Price Revenue Incidence Simulation Model and Distribution Model (PRISMOD.DIST) is employed.

Each of the above models is integrated into the Treasury model with the objective of maintaining consistency at the macroeconomic level for the whole Australian economy, despite the different structures of each model. The results of the study, and the framework of the model, are presented in *Strong Growth, Low Pollution Modelling a Carbon Price* developed by The Treasury (2011). The model compares the Australian economy without any environmental policy and with two carbon prices (AUD$20, the core policy scenario, and AUD$30, the high price scenario) for 2012–13.

The core policy scenario is an analysis of attempting to achieve emissions that are 5 per cent lower than the 2000 level by 2020 and 80 per cent below the 2000 level by 2050, while maintaining economic growth. This scenario assumes that a rate of AUD$20 per tonne of carbon dioxide emissions is set in 2012–13, increasing by 5 per cent per annum thereafter. The high price scenario targets are an emissions reduction of 25 per cent below the 2000 level by 2020 and a reduction of 80 per cent below the 2000 level by 2050. To this end the price would start at AUD$30 per tonne of carbon dioxide emissions in 2012–13 and increase by 5 per cent per annum thereafter.

The findings were significantly encouraging: in the first situation, without an environmental policy, the Australian GNI per capita increases by an average rate of 1.2 per cent per year to 2050, while under a carbon tax policy it will grow by 1.1 and 1 per cent under the core and high price policies respectively. To be more explicit, without an environmental policy, the Australian GNI per capita until 2050 increases by 60 per cent and emissions by 74 per cent with respect to the 2010 level, while in the core policy scenario the GNI per capita increases
by approximately 56 per cent and emissions decrease by 80 per cent. Additionally, in the core policy scenario, employment increases by 14 per cent by 2020, and 53 per cent by 2050. Also, the model analyses the welfare effects of a carbon tax by investigating the short-run impact of a tax at the rate of AUD$23 per tonne of carbon dioxide emissions, and the findings show that household weekly expenditure would increase by 0.7 per cent in 2012-13.

However, as Meng et al. (2011) point out, the iteration process in the integration of MMRF, ROAM and SKM MMA can provide a good approach to finding consistent data on the demand for, and the supply of, road transport and electricity generation, but these results depend to a significant extent on price setting which is not clear in the Treasury model. Meng et al. (2011) mention that although the model indirectly implies that electricity prices are estimated by the partial equilibrium models of ROAM and SKM MMA, a specified endogenous price setting method such as a CGE model like MMRF should have been incorporated.

They also point to another two limitations of the Treasury model: first, the great number of assumptions behind the Treasury model as a whole and, second, the assumptions of the incorporated models and the compatibility of those assumptions. The former refers to the assumptions about global carbon prices, household taste modifications, energy efficiency, productivity and technology changes. The latter refers to the assumptions of the incorporated economic models. For instance, the dynamic characteristics of MMRF require specific assumptions on the future economy and growth trends, while the micro nature of the SKM MMA and ROAM models involve other specific postulates. Hence, the results obtained are sensitive to underlying assumptions.

The models explained above are the main climate change models for the Australian economy, and have been mostly developed and conducted by government-funded research institutes.
Environmental issues in Australia are also of interest to many academic researchers and various papers have been published in these areas. Looking at these works, one can easily perceive the central role of CGE models in both static and dynamic forms in analysing carbon policies. For instance, Meng et al. (2013) use a static CGE model with an environmentally extended social accounting matrix (ESAM) to simulate the environmental and economic impacts of a carbon tax at a rate of AUD$23 per tonne of carbon emissions on Australia with and without a compensation plan. Their results indicate that the carbon tax can have a positive impact on the environment by mitigating emissions and negative effects on the economy. They also show that a compensation policy could significantly reduce the negative economic impacts with a very slight effect on emission mitigation.

To study the dynamic effects of carbon policies, Asafu-Adjaye (2004) employs a dynamic CGE model to simulate the effects of environmental policies on the Australian economy. He analyses the short- and long-run effects of two environmental policies: a forest conservation policy, and a carbon emissions reduction policy, over a seven-year period. The results indicate that in the short run (i.e. years 1-3), both policies impact the economy negatively, while in the long-run (i.e. years 4-7), the emission abatement policy affects the economy positively as real output can increase by 6 per cent, aggregate employment by 6.4 per cent and real consumption by 4.4 per cent. This expansion in the economy is due to input substitution and improvements to productivity in response to the adjustments.

In another study, Asafu-Adjaye and Mahadevan (2013) apply a dynamic CGE model to compare the sectoral and macroeconomic impacts of three environmental policies in Australia: an emissions trading scheme (ETS), a combination of ETS with technological innovation in the renewable energy sector and imposing a levy on fuel as an alternative to the ETS. They find that although all methods had approximately similar impacts on
macroeconomic variables (such as GDP growth, consumption, employment, exports and imports), a fuel tax mechanism would not be as effective as the other methods as it would not reduce emissions to the same extent as the other measures.

The literature reviewed above has focused mostly on climate policy analysis aimed at indicating the effects of carbon policies on an economy and choosing the optimal carbon policy that will have a less negative effect on macroeconomic variables. However, they typically ignore the fact that the affected variables in their models, such as GDP or employment, fluctuate over time and generally in the form of business cycles, and such fluctuations can result in endogenous variations in emissions. This implies that an optimal policy requires establishing integration with economic fluctuations and adaptation to business cycles. To this end one would need to investigate the response of climate policies to business cycles (for example as done by Fischer and Springborn (2011) and Heutel (2012) which will be explained later). This can be done with a DSGE model such as that of Kydland and Prescott (1982) and Long and Plosser (1983) using a real business cycle (RBC) analysis, which has been broadly used in studying the effects of fiscal and monetary policies.

An important feature of DSGE models, which makes them popular, is their ability to consider exogenous shocks and uncertainties based on the stochastic characteristic of these models. This characteristic makes them more complicated, but increases aggregation and decreases the number of variables, especially in higher-order estimations, which are necessary in welfare analysis (Winschel and Kratzig, 2010). A major difference between CGE and DSGE models is that the former are deterministic while the latter are stochastic. This feature of DSGE models makes them appropriate for studies involving uncertainty, including environmental policy analysis. In principle an optimal environmental policy is a policy which balances pollution-related damage with the costs of pollution abatement activities, while both
types of costs are currently uncertain and neither will be accurately recognised for a long time (Webster et al., 2012). This highlights the importance of extending environmental policy analysis to stochastic studies which involve uncertainty, although the objectives of such policies, such as the Kyoto Protocol, are announced well in advance.

Another advantage of having a stochastic model is that it makes the model fit to time series data. On the other hand, CGE models, even dynamic ones, are regularly calibrated to cross-sectional data, and are then used to simulate a balanced growth path based on existing exogenous conditions. In other words, in a CGE model, an equilibrium which is mostly known as a market clearing condition is estimated for each period given existing exogenous conditions such as the supply of labour and capital. Any changes in the supply of labour or capital would lead to a new equilibrium. The sequence of the set of calculated equilibriums can represent the time path of the economy. Hence, augmentations of factors are set in these models, given that equilibrium would happen in each period, instead of being empirically established. This would decrease the suitability of CGE models in forecasting (Partridge and Rickman, 1998). Therefore, DSGE models would be more suitable for the dynamic analysis of aggregate economies and the cyclical impacts of policies, while CGE models are suitable for studying the impacts of long-run policies, such as tax policies or international trade, from a microeconomic point of view. The contribution of DSGE models to environmental policy analysis is discussed in the next section.

3.3. Application of DSGE Models

Generally, there are two schools of DSGE modelling: real business cycle (RBC) and New-Keynesian. The former is built on neoclassical growth theories under the assumption of flexible prices to investigate how an economy can be affected by real shocks. RBC models were first introduced by Kydland and Prescott (1982) who investigated how total factor
productivity shocks can cause business cycle fluctuations. The latter, New-Keynesian models, introduced by Rotemberg and Woodford (1997), were built on RBC models but assume monopolistically competitive markets in which price adjustments involve time and costs. Due to such assumptions, New Keynesian models have been used in monetary policy analysis. The application of DSGE models to environmental studies is not very extensive in the literature and is mostly related to RBC models. However, the modelling features of this approach have recently attracted the interest of a number of researchers.

Environmental analysis using a DSGE model was first introduced by Fischer and Springborn (2011) who apply a real business cycle (RBC) model with productivity shocks to provide a comparison of three emissions reduction policies: an emissions tax, an emissions trading system, and an intensity target policy in which the ratio of emissions to output is held constant. The three policies have the same aim of an exogenous and fixed level of reduction in emissions while emissions are an intermediate input. The authors conduct a cost-effectiveness analysis for a particular abatement target and attempt to indicate labour market responses to policy and productivity shocks for two main reasons. First, the impacts of climate policies on the labour market are always highlighted in climate policy debates. Second, the impulse response of the labour market to productivity shocks in RBC models is usually unique, with a different pattern compared to the impulse response of other economic variables such as investment and production.

In calibrating the model to the US economy, Fischer and Springborn (2011) find that compared to a business-as-usual scenario, under the three climate systems economic variables such as capital, production and consumption fall, except employment under the intensity target policy which remains unchanged. The results also indicate that under a deterministic system, and for a particular level of abatement, an intensity target policy is more efficient and
has higher total output, while the emissions tax and emissions trading system have identical outputs.

In the presence of a productivity shock, however, these results will change. An emissions trading system will decrease the volatility of variables and variations in utility and production due to shocks. A tax policy, on the other hand, will increase the volatility of all variables, including investment, production and household utility. Finally, the sensitivity of variables to shocks will not change significantly under the intensity target policy. Thus, the choice of policy depends on the policy makers’ perspective. An emissions cap is the optimal policy in terms of the expected costs, i.e. the volatility of economic variables. An intensity target can maintain the highest economic growth without any negative impact on employment in the steady state, and a tax can achieve an emissions target with a minimum decrease in welfare.

Another initial study in the environmental DSGE literature was conducted by Heutel (2012) to investigate the impact of emissions pricing mechanisms on the whole economy. He argues that an optimal climate policy should be adapted to business cycles since this would be more acceptable for firms, as it is the first-best response to cost fluctuations. Following this argument, he develops an RBC model with total factor productivity (TFP) shocks in which pollution is a stock variable that can impose damage to the economy in the form of the loss of potential output. He specifies emissions as a function of production and abatement activities, and TFP shocks as an AR(1) process. He conducts a welfare analysis for a centralised economy and for a decentralised economy with asymmetric information concerning TFP shocks. Using US economy data, he examines how carbon dioxide emissions would respond to cyclical fluctuations in monthly GDP data, and finds that emissions are inelastic with respect to output.
However, results from calibrating the model to the US economy indicate that the optimal climate policy should be responsive to business cycles with lower permitted emissions during economic recessions and higher permitted emissions during output expansion. This result is due to the fact that during an expansion (recession) the price effects will be more (less) than the income effects; that is, during an expansion (recession) the demand for clean air is higher (lower) than the costs of achieving a specific level of emissions. Heutel (2012) also develops a decentralised model under the asymmetric information condition in which the government cannot observe the TFP shocks. He finds that under this scenario an emissions tax policy and a cap policy are not equivalent in such a way that the variation of the optimal tax policy is significantly greater than the optimal quantity policy.

Conducting an environmental analysis at the global level, Hassler and Krusell (2012) develop a DSGE model to provide an integrated investigation of climate policies and the global economy, and to analyse the economic impacts of different policy scenarios. They argue that the global nature of pollution means that it is necessary to find a dynamic and global solution, and they adopt a general equilibrium framework which is necessary for analysing the welfare effects of policies. They consider the heterogeneity between different global regions as the main difficulty in establishing international agreements and they attempt to measure the ways that this heterogeneity can affect preferences for different policy options. To this end they investigate the impacts of taxation on oil as an approach to controlling climate changes by applying a Regional Integrated model of Climate and the Economy (RICE) combined with stochastic productivity. The results indicate that levying a tax on oil in oil-importing countries is not a useful climate policy. However, the effects of such taxes in oil-producing countries are significant, especially when the proceeds of the taxes recycle in a lump-sum manner to the payer countries.
In another study, Dissou and Karnizova (2012) use a DSGE model to compare the responses of the economy to TFP shocks under two environmental policies, emissions taxes and emissions permits. They develop a multi-sectoral RBC model to investigate the sectoral and aggregate effects of climate policies in the presence of TFP shocks. To this end their model included six sectors with different sectoral productivity shocks: three energy sectors (coal, electricity, and oil and gas), plus services, energy-intensive goods, and non-energy-intensive goods. The energy input is a CES aggregate of electricity and fossil energy, while the fossil energy itself is a CES combination of coal, and oil and gas intermediate inputs. Burning fossil fuels produces emissions (coal more than oil and gas) while using electricity does not, and firms can substitute between primary and intermediate inputs with different substitution capacities. Since using each type of fossil fuel produces a constant amount of emissions, controlling emissions is equivalent to controlling energy usage.

Climate polices, including emissions taxes or permits, will increase the price of fossil fuels and decrease their usage. Calibrating their model to the US economy, Dissou and Karnizova (2012) find that although the emissions permit policy imposes less volatility, it can lead to asymmetries in economic responses to shocks and, therefore, the emissions tax policy is found to be preferable to emissions permits. However, from a welfare point of view, the influence of each policy depends on the origin of the shocks. A productivity shock originating from non-energy sectors imposes the same welfare costs under both emissions taxes and emissions permit regimes, while for shocks emanating from energy sectors an emissions permit system is costlier than an emissions tax.

The application of DSGE models in environmental analysis is relatively new, but Fischer and Heutel (2013) conducted a survey on the application of two macroeconomic approaches in environmental economics: RBC and directed technological change (DTC). Reviewing the
RBC literature, including the studies mentioned above, they suggest that the literature should be expanded to consider other types of shocks besides TFP shocks. DTC studies investigate how innovation, especially in clean sectors, can be affected by environmental policies. The results of these studies show that supporting innovation in clean technologies, even for a short period, can be sufficient to achieve environmental goals.

Adding other types of uncertainty besides TFP, Angelopoulos et al. (2013) compare the second-most optimal environmental policy (i.e. an emissions tax policy), to first-best allocation, that is a social planner solution without any emissions policy. They develop an RBC model with two sources of uncertainty, productivity and pollution technology (which is measured as emissions per unit of output). The model specifies consumers who derive utility from consumption and environmental quality, which is a stock variable affected by governmental abatement activities and pollution. In this model pollution is a function of output and exogenous stochastic environmental technology. Only the government is involved in abatement activities by allocating the revenue from emissions taxation or permits to these activities. Both productivity and pollution technology follow an AR(1) process. The results of this research indicate that the optimal environmental policy is pro-cyclical when an economic shock occurs, and counter-cyclical in the case of an environmental shock.

Extending the DSGE environmental analysis, Roach (2014) developed a model to demonstrate an optimal emissions tax in line with the cyclical movement of US GDP and the price of energy. He also attempts to find the best way of recycling emissions tax revenues between two choices: a lump-sum transfer to households and reducing the distortionary effects of a labour tax. To this end he develops a New-Keynesian model with monopolistic competition, price-adjustment friction and labour taxation. He specifies emissions as an intermediate input of production which affects household utility. The price of this
intermediate input is equal to the energy price plus an emissions tax. The energy price and TFP are both stochastic and exogenous variables following an AR(1) process. He examines three scenarios: 1) a baseline scenario without any environmental policy, 2) an environment-first tax rule: a tax policy with the target of a specific level of emissions, and 3) a dynamic tax rule: a dynamic tax which increases as output increases, and decreases as energy prices increase. He finds that the optimal tax should be pro-cyclical, and the tax revenue should be recycled to the household sector in both scenarios.

Previous emissions control policy analyses applying DSGE modelling have concentrated on the economic effects of such policies. However, Golosov et al. (2014) consider factors other than macroeconomic ones to estimate the best carbon price. They develop a DSGE model at the global level in which fossil fuel, as an energy input for production, is a source of a negative externality by producing carbon emissions. Their model includes two sources of energy, oil and coal. They attempt to find the optimal rate for an emissions tax by estimating the marginal externality damage due to emissions. The results indicate that the damage is a proportion of GDP and is determined by three factors. The first is, discounting, including an economic discount factor which indicates time preferences and an environmental discount rate which represents how quickly carbon emissions are naturally purified. The second is the expected elasticity of damage indicating the sensitivity of output reduction to an extra unit of carbon emissions in the atmosphere. The third is pollution damage which depends on the structure of carbon depreciation in the atmosphere.

Hence, to estimate the optimal emissions tax one only needs to identify these three factors and one does not need any information about economic variables or the sources of energy that the economy uses, and this is what they point to as the major contribution of their study. Based on these factors, they find that the optimal emissions tax is equal to the marginal
externality. This is higher than the average estimated values of emissions taxes in the literature. They also computed and compare the economy without any climate policy (i.e. laissez-faire) and with an emissions tax and indicated that with an emissions tax the use of coal would decrease significantly, while there would be no change in oil usage. Moreover, with an optimal tax the global temperature, and subsequently total damage caused by emissions, would increase less than with a laissez-faire approach.

As illustrated above, DSGE models have great potential for climate policy analysis, although their contribution to environmental analysis is very new and less than a decade old. For the Australian economy the application of DSGE models remains limited to a few studies. Jaaskela and Nimark (2011) developed an open economy New-Keynesian DSGE model for Australia and found that both domestic and foreign shocks have key roles in driving the economy’s business cycles. Robinson (2013) also investigated the effects of foreign shocks on Australia as a small open economy. Using an RBC model he found that this role is not large, while the results for a BVAR-DSGE model that includes block exogenous restrictions indicated a more significant role.

Rees (2013) also developed an RBC model for Australia as a small open economy in which agents have imperfect information about the persistence of terms of trade shocks – that is, whether a shock is transitory or permanent. He found that under incomplete information conditions, agents responded more cautiously to the shocks and did so in a way that meant the volatility of consumption, output and the trade balance were less than they were under full information. To the best knowledge of this author the current research is the first attempt to apply a DSGE model to analysing emissions pricing policies in Australia. This represents a major contribution to the literature in this context because it investigates the relationship

\[14\text{Bayesian Vector Autoregressive Dynamic Stochastic General Equilibrium}\]
between emissions reduction policies and business cycles in Australia. Table 3.3 provides a summary of the DSGE studies reviewed in this section.

3.4. Summary

In this chapter, the contributions of two general equilibrium models applied to investigate the effects of environmental policies on different sectors of an economy were reviewed. First, computable general equilibrium models were discussed. These models have been used in Australian studies to examine the effects of emission pricing systems, mostly emission taxes, on the economy. Second, the chapter discussed dynamic stochastic general equilibrium models which have not been used for the Australian economy as yet, but which have considerable potential to facilitate the study of the cyclical effects of such policies on the Australian economy. The stochastic feature of DSGE models is the main difference between them and CGE models, and it provides researchers with the opportunity to address environmental or economic uncertainties relating to environmental issues.

Additionally, since pollution remains in the atmosphere for decades and affects environmental and economic variables for a period of time, any abatement activity or environmental policy with the aim of controlling pollution should be investigated in a dynamic framework. The literature on DSGE environmental analysis is still in a preliminary stage and focuses mostly on RBC models showing how environmental policies respond to economic fluctuations. However, as Fischer and Heutel (2013) suggest, these models should be extended to add other types of uncertainties beside those relating to productivity.
## Table 3.3: DSGE Literature Review Summary

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Aim(s)</th>
<th>Region</th>
<th>Method</th>
<th>Scope</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>Hassler and Krusell</td>
<td>To provide an integrated investigation of climate and the global economy through analysing different policy scenarios (taxation on oil) and measuring the ways that heterogeneity between different global regions can affect preferences for different policy options.</td>
<td>US</td>
<td>DSGE model (a RICE model combined with stochastic productivity).</td>
<td>Theoretical contribution (dynamic, stochastic).</td>
<td>A levy on oil usage in oil-importing countries is not a useful climate policy. However, it has significant effects on oil-producing countries, especially when the proceeds of the taxes recycle in a lump-sum manner to the payer countries.</td>
</tr>
<tr>
<td>2012</td>
<td>Heutel</td>
<td>To develop a model with productivity shocks in which pollution is a stock variable that can have negative impacts on the economy.</td>
<td>US</td>
<td>DSGE model: RBC</td>
<td>Theoretical contribution (dynamic, stochastic).</td>
<td>A dynamic climate policy, both carbon tax and cap-and-trade, adjusted with business cycles is more efficient that a static policy with an optimal constant emission target in the long run.</td>
</tr>
<tr>
<td>2011</td>
<td>Fischer and Springborn</td>
<td>To provide a comparison between three climate policies: a carbon tax, a carbon emission trading system, and an intensity target policy that holds the ratio of maximum emissions to output constant</td>
<td>US</td>
<td>DSGE model: RBC</td>
<td>Theoretical contribution (dynamic, stochastic).</td>
<td>Under the three climate systems the economic variables including production and consumption will fall, except labour under the intensity target policy. Additionally, an emissions trading system will decrease while a tax policy will increase the volatility of variables including production and consumption due to the shocks. Finally, the sensitivity of variables to shocks will not change significantly under the intensity target policy.</td>
</tr>
<tr>
<td>2012</td>
<td>Dissou and Karnizova</td>
<td>To investigate the sectoral and aggregate effects of a carbon tax policy and a carbon permit policy</td>
<td>US</td>
<td>DSGE model: RBC</td>
<td>Theoretical contribution (dynamic, stochastic).</td>
<td>Although the emissions permit policy imposes less volatility, it can lead to asymmetries in economic responses to shocks. Also, a productivity shock originating from non-energy sectors imposes the same welfare costs under both emissions tax and emissions permit regimes, while for shocks emanating from energy sectors an emissions permit system is costlier than an emissions tax.</td>
</tr>
<tr>
<td>Year</td>
<td>Author</td>
<td>Aim(s)</td>
<td>Region</td>
<td>Method</td>
<td>Scope</td>
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<tr>
<td>2013</td>
<td>Fischer and Heutel</td>
<td>To conduct a survey on the application of two macroeconomic approaches in environmental economics: RBC and directed technological change (DTC)</td>
<td>–</td>
<td>DSGE and DTC models</td>
<td>A survey.</td>
<td>The RBC literature should be expanded to consider other types of shocks beside TFP shocks. The DTC literature concludes that supporting innovation in clean technologies, even for a short period, can be sufficient to achieve environmental goals.</td>
</tr>
<tr>
<td>2013</td>
<td>Angelopoulos et al.</td>
<td>To compare an optimal emissions tax policy to a social planner solution without any emissions policy under economic and environmental uncertainties</td>
<td>US</td>
<td>DSGE model: RBC</td>
<td>Theoretical contribution (dynamic, stochastic).</td>
<td>An optimal environmental policy is pro-cyclical when an economic shock occurs, and counter-cyclical in the case of an environmental shock.</td>
</tr>
<tr>
<td>2014</td>
<td>Roach</td>
<td>To demonstrate an optimal emissions tax in line with the cyclical movement of GDP and the price of energy. Also, to find the best way of recycling emissions tax revenues.</td>
<td>US</td>
<td>DSGE model: New-Keynesian</td>
<td>Theoretical contribution (dynamic, stochastic).</td>
<td>An optimal tax should be pro-cyclical, and the tax revenue should be recycled to the household in both scenarios.</td>
</tr>
<tr>
<td>2014</td>
<td>Golosov et al.</td>
<td>To estimate the optimal tax on fossil fuel by estimating the marginal externality damage due to emissions.</td>
<td>Global</td>
<td>DSGE model: RBC</td>
<td>Theoretical contribution (dynamic, stochastic).</td>
<td>The pollution damage is a proportion of GDP and is determined by three factors: discounting, the sensitivity of output to an extra unit of carbon emissions and the structure of carbon depreciation in the atmosphere.</td>
</tr>
</tbody>
</table>

Source: Compiled by the author.
The literature on Australian environmental studies can be extended to the application of DSGE approaches to provide a new insight for Australian policy makers by showing the relationship between environmental policies and different types of uncertainties about environmental policies. This issue is the main target of the current thesis which attempts to represent the relationship between economic fluctuations due to business cycles and emissions pricing outcomes. To this end this thesis, in line with the literature reviewed in this section, provides an Australian RBC model for emissions pricing policy analysis to investigate how different types of emissions pricing programs, including a carbon tax and a subsidy, which have been already implemented in Australia, would respond to real business cycle fluctuations. This model is presented in the next chapter.
Chapter 4

Theoretical Framework

4.1. Introduction

This chapter focuses on developing a DSGE model for an analysis of emissions pricing programs in Australia. As reviewed in Chapter 2 Section 2.5 there are several types of environmental and economic uncertainty relating to the costs and outcomes of environmental policies. The source and size of uncertainty can affect optimal choices\(^{15}\) of environmental policies (Angelopoulos et al., 2013). These uncertainties emphasise the necessity of a dynamic stochastic analysis of environmental policies. To this end DSGE models can be applied. These models are still new to environmental economics and were originally introduced by Fischer and Springborn (2011). The existing literature focuses mostly on macroeconomic uncertainty, and mostly in terms of total factor productivity shocks. As Dissou and Karnizova (2012) point out, macroeconomic uncertainty in environmental policies should be considered since, firstly, it results in fluctuations in consumption which influence the costs of emissions policies and secondly, since uncertainty is considered to be the main factor to be considered when choosing between a quantity-based emissions policy and a price-based emissions policy since Weitzman (1974).

This thesis is the first to attempt DSGE modelling for Australian emissions pricing policy analysis. Following the literature, along with the fact that Australia’s emissions follow economic business cycles as shown in Chapter 2 Section 2.6.2, a real business cycle (RBC) model is developed here to investigate how economic fluctuations in terms of business cycles can influence the outcomes of emissions pricing programs. To this end, the main structure of

\(^{15}\) Angelopoulos et al. (2013) specifies the optimal choices of environmental policies in terms of social welfare.
the model, including the sectors and environment, are specified. Then the model is extended to consider three emissions pricing scenarios which are similar to programs already applied in Australia.

The first scenario is a fixed emissions tax system in which a constant emissions tax is levied on each tonne of emissions where the tax rate does not change over time. This system is similar to the Australian carbon tax system introduced in the Clean Energy Program. The second is a variable emissions tax policy in which the regulator chooses a tax rate for each tonne of emissions at the beginning of each period. Based on theory, under perfect certainty where both the regulator and firms have access to the same information, the tax will be set at the market price of a cap and trade system. Thus, the variable emissions tax specified in this thesis can be identified as a proxy for the emissions trading system which was planned as the second emissions pricing phase by the Gillard government in the Clean Energy Program. The third scenario is an abatement subsidy policy in which the regulator pays for the emissions reduction achieved by polluters. This scenario is similar to the current Australian emissions reduction policy, the Emissions Reduction Fund introduced by the Abbott government. A business-as-usual scenario is also specified as a benchmark to evaluate emissions pricing policy. Table 4.1 summarises the scenarios tested in this study.

In addition, in the Australian Carbon Tax program, designed in the Clean Energy Future (Australian Government, 2011), the federal government planned to increase the tax rate by 2.5 per cent per year. The current research is also interested in investigating the environmental and economic impacts of such a program, that is, an augmented fixed tax program, by simulating an increasing fixed emissions tax. To this end the fixed tax scenario developed in this chapter will be used when the tax rate increases by 2.5 per cent in every fourth period, equal to a year. This increase in the emissions tax is pre-announced at the
beginning of the program, so both production and consumption sectors expect the changes and take them into account in their optimisation behaviour.

The model will be applied under different scenarios and the numerical results of each policy will be evaluated and compared in Chapter 6 in order to provide a comparison between these policies. The comparison will be conducted in terms of volatility in economic variables, such as output or social welfare, and environmental variables, such as emissions, as well as cumulative changes in each variable.

<table>
<thead>
<tr>
<th>Emissions Pricing Policy Scenarios</th>
<th>Emissions Pricing Policy Assumptions</th>
<th>Corresponding Australian Policy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business-as-usual</td>
<td>No emissions pricing system</td>
<td></td>
</tr>
<tr>
<td>Fixed emissions price policy</td>
<td>A constant emissions tax is levied on each tonne of emissions. The tax rate does not change over time.</td>
<td>Carbon tax</td>
</tr>
<tr>
<td>Variable emissions price policy</td>
<td>The government levies an emissions tax on each tonne of emissions at the beginning of each period</td>
<td>Emissions trading scheme</td>
</tr>
<tr>
<td>Emissions abatement subsidy policy</td>
<td>The government financially supports firms’ abatement efforts in each period.</td>
<td>Emissions Reduction Fund</td>
</tr>
</tbody>
</table>

Source: compiled by the author.
Following the literature on environmental RBC models the stochastic element of the model is contained in total factor productivity (TFP) shocks. These shocks can create a price effect and an income effect (Heutel, 2012) on all other sectors and variables including production, consumption, emissions and abatement. A positive TFP shock has an income effect by increasing consumers’ budgets, which in turn will lead to higher demand for a cleaner and less polluted environment. Therefore, the income effect from a positive TFP shock will lead to more abatement and thus, lower emissions. On the other hand a positive TFP shock will increase the productivity of inputs, such as capital, and therefore the opportunity cost of spending on abatement instead of increasing outputs, such as investment in capital, will be higher. Hence, abatement will be costlier and the price effects of a positive TFP shock will decrease the demand for abatement and lead to higher emissions.

This thesis will investigate which effect would be greater for the Australian economy. To this end, it will benefit from the contribution of Heutel (2012). However, the model used here will deviate from his model in terms of scenarios to be tested, parameterisation and analysis technique. The first deviation is to make this model more applicable to Australia and then apply it to analyse planned and/or implemented emissions reduction policies, the second difference relates to a technical improvement on his model and the third one is an extension to the ways of using the model for policy analysis. These deviations represent the major contributions of this thesis and are explained further below.

The first deviation relates to the scenarios. Heutel (2012) tested a variable emissions pricing scenario in which the policy (i.e. a tax or a cap) is not constant over time and can be chosen at the beginning of each period. To this end he starts with a centralised decision-making economy in which a representative agent’s choices on consumption, investment and emissions match those of a social planner. Thus, polluters pay the costs of pollution they
produce and all externalities from pollution are internalised. However, as Heutel (2012) also explains, such a model cannot explicitly provide a comparison between different policies since it does not include emissions externalities. In order to make a policy comparison he extends the model to a decentralised economy with asymmetric information about total factor productivity shocks.

An assumption of a centralised economy in which polluters automatically internalise the costs of the emissions they produce, would not be realistic. Thus, the current research starts with a decentralised rather than centralised economy. Moreover, while Heutel (2012) tests only for a variable emissions pricing system where the government chooses the tax or cap at the beginning of each period, the current research analyses a variable emissions price, as well as a fixed emissions tax and an abatement subsidy policy. Investigating the other two scenarios is fundamental here, since the focus of this study is on analysing emissions pricing systems in Australia, and these policies have been the only policies implemented or planned so far in Australia. The outcomes from the fixed emissions pricing policies can be compared with the findings in the literature and this will result in interesting policy implications regarding the outcomes of such policies. Therefore, the effects of both fixed and variable emissions pricing systems on Australia are studied in this research.

The second difference between this thesis and Heutel (2012) concerns the parameterisation of an environmental variable, emissions from the rest of the world. As explained in Chapter 5, Section 5.2, Heutel (2012) specifies the pollution stock at each period as a function of pollution in the previous period, plus domestic emissions and emissions from the rest of the world in the same period. He assumes that total emissions from the rest of the world are three times greater than those of the US. However, assuming emissions from the rest of the world as a fixed coefficient of domestic emissions under emissions pricing policies would provide a
channel to transfer the effects of domestic emissions pricing systems to the rest of the world’s emissions. In other words, such an assumption would imply that an emissions pricing policy could affect not only domestic emissions but also emissions produced by the rest of the world, which is not necessarily true. Moreover, it would contradict the assumption that the emissions from the rest of the world are exogenous to the economy.

To avoid this, the current research assumes that emissions from the rest of the world are fixed under the three scenarios. Given the small size of the Australian economy and of its contribution to global emissions, this assumption is acceptable. This thesis first calculates emissions from the rest of the world under a business-as-usual scenario. Then, the calculated value will be used under the emissions pricing policies. This assumption will keep the rest of the world emissions constant over different policy scenarios. This is an appropriate condition here since the aim of this study is to analyse the domestic effects of a national emissions pricing program on Australia and not on the world economy. Hence, the contribution of this thesis is not only empirical, involving the application of a DSGE model to the Australian economy, but also technical due to the abovementioned differences between this study and Heutel (2012).

The third contribution of this thesis is theoretical and is about the method to be applied to analyse the effects of environmental policies and to make a comparison between different emissions pricing programs. Heutel (2012) only uses the impulse response functions (IRFs) of variables, and chooses the policy which minimises the difference between the IRF of consumption in a scenario where information is asymmetric and the IRF of consumption in a scenario where information is not asymmetric. This research also studies the IRFs of variables under different emissions pricing policies and compares them with those under the business-as-usual scenario to investigate how such programs can influence those variables.
Additionally, this thesis adopts two other approaches for policy analysis. First, it compares the steady state values of variables (i.e. without TFP shocks). Second, it compares the cumulative effect of each policy over time by calculating the area under the IRF of a variable. Multiplying the cumulative effect by the steady state of that variable can express the total effects of the shock under an emissions reduction program. To the best of the author’s knowledge this method has not been applied in an environmental DSGE study before, and is another contribution of this thesis.

The remainder of this chapter proceeds as follows. In Section 4.2 the evolution of DSGE models as macroeconomic and environmental modelling tools is discussed. Then the model to be used in this study is presented in Section 4.3. To this end the main agents of the economy, including the production and consumption sectors and the environment, are specified. The specified equations are extended to different scenarios, including business-as-usual in Section 4.4, a fixed emissions tax policy in Section 4.5, a variable emissions tax policy in Section 4.6 and an emissions abatement subsidy policy in Section 4.7. Finally, the chapter is summarised in Section 4.8.

4.2. The Evolution of DSGE Models

A DSGE model was initially introduced by Kydland and Prescott (1982) to investigate the role of total factor productivity (TFP) shocks in business cycle fluctuations. DSGE models are based upon microeconomic assumptions which specify forward-looking agents. As indicated by their name these models have three characteristics: first, they are dynamic (i.e. they investigate an economy over time); second, they are stochastic, in terms of considering random changes imposed on an economy; and, finally, they are based on general equilibrium
when all sectors are in equilibrium simultaneously. The stochastic feature of DSGE models is the most significant distinguishing feature of these models. It makes them more complex but enables modellers to track the effects of any exogenous shock or uncertainty.

These three features mean that the model can explicitly demonstrate the dynamics arising from the behaviour of different economic agents when it is based on rational expectations. As a result, DSGE models are less likely to suffer from the shortcoming highlighted by the Lucas critique (Lucas, 1976) than traditional econometric models are. The Lucas critique is a criticism of econometric models which utilise historical data in order to predict the future effects of a change in a policy without recognising the optimal decision rules of economic agents.

There are two types of DSGE models: real business cycle (RBC) and New-Keynesian. RBC models were first introduced by Kydland and Prescott (1982) and Long and Plosser (1983). They developed a stochastic model to investigate whether real shocks, in terms of TFP shocks, are the main source of business cycle fluctuations. RBC models are built on neoclassical growth theories under the assumption of flexible prices. These models apply first principles of market clearing, rational expectations and optimising agents and present “a small and coherent dynamic model of [an] economy”, as stated by Fernández-Villaverde (2010, p. 4). The flexibility of the computation and recursive methods offered by Kydland and Prescott (1982) encouraged these economists to develop models of complete markets with fully flexible prices, which made their stochastic neoclassical growth model gain widespread support among researchers and policy makers (Fagiolo and Roventini, 2012; Caldara et al., 2014; Fueki et al., 2016).

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16 A stochastic event is an unpredicted event caused by a random variable.
RBC models, however, were not appropriate for monetary policy analysis due to the predominant role of technology shocks, as well as the absence of frictions (Rickman, 2010). RBC models were therefore extended to address these problems by adding three components (Fernández-Villaverde, 2010). First, monopolistic competition, where firms are not identical and have some market power, was added. Such market power contributes to rigidities in prices and wages. Without market power, a firm must adjust its price to the market price immediately, otherwise it loses its sales and market. Second, an explanation of the role of money was added; this can be illustrated either in the consumer’s utility function or as a cash-in-advance constraint. Third, a monetary authority was included to set monetary policy, usually in accordance with the Taylor rule or a money growth process. These expansions of the RBC model have led to the development of a new school of DSGE modelling: the New-Keynesian school. The New-Keynesian model was introduced by Rotemberg and Woodford (1997) who employ the monopolistically competitive markets assumption in which price adjustments involve time and costs.

Regardless of school, a typical DSGE model consists of a consumer who derives utility from consumption which is usually represented by constant relative risk aversion and a producer with a Cobb-Douglas production function (DeJong and Dave, 2011). For parameterisation, early DSGE models usually employed calibration using long-run averages of variables which made the predictions of DSGE models conflict with actual data (Rickman, 2010). To overcome this problem new parameterisation procedures were developed including Bayesian estimation, generalised methods of moment estimation, full-information maximum likelihood estimation and matching VAR and DSGE dynamic responses to structural shocks (Canova, 2007).
The progress made in DSGE modelling make it suitable for business cycle theory, fiscal and monetary policy analysis, growth analysis and other fields of macroeconomics and international economics to the point that many central banks have developed their own DSGE models for policy analysis. For instance, the US Federal Reserve Board's SIGMA model was developed to investigate the effects of a broad variety of shocks on the US economy, including shocks due to a change in monetary policy, government spending, capital tax rates, productivity growth, risk premiums, foreign demand, consumption demand and the impact of fiscal shocks\textsuperscript{17} on the trade balance (Erceg \textit{et al.}, 2005; 2006). The Central Bank of Chile also employed its MAS model to analyse the role of different shocks on the business cycle, such as foreign shocks and domestic supply shocks (Medina and Soto, 2007a; b). Advances in DSGE modelling since Kydland and Prescott (1982) have been considerable, to the point that these models may eventually be the main competitor or even dominate other macroeconomic models in quantitative macroeconomic forecasting and policy making (Rickman, 2010).

As explained in Chapter 3 Section 3.3 the contribution of DSGE models in environmental economics remains limited, since they have only recently been introduced by Fischer and Springborn (2011), although they have the potential to be a key tool for environmental policy analysis. This is due to the great number of environmental and economic uncertainties relating to environmental issues and policies, as discussed in Chapter 2 Section 2.5, which provide support for the use of stochastic models. The literature on environmental policy comparison under uncertain conditions began with Weitzman (1974), followed by many other researchers (Hoel and Karp, 2002; Pizer, 2002; Newell and Pizer, 2003; Quirion, 2005; Fell \textit{et al.}, 2012) who have used a partial equilibrium approach to investigate the role of

\textsuperscript{17} These shocks are specified as exogenous changes in the demand and/or supply side of the economy which can explain the cyclical fluctuations of economic time series.
uncertainty, usually about abatement cost, in environmental policy. The focus of these studies is usually on the effects of a price-based instrument (i.e. an emissions tax) and a quantity-based instrument (i.e. an emissions permit) on welfare. They usually specify welfare in terms of the costs and benefits of emissions policies where the benefit is shown by less damage from emissions.

A few contributions have also developed general equilibrium models for environmental policy analysis. In a static stochastic general equilibrium model, Kelly (2005) investigated the effects of productivity shocks on environmental policy in a static framework. Investigating environmental economics under conditions of uncertainty and in a dynamic general equilibrium model is still in its primary stage, involving limitations that the early DSGE models had over three decades ago. Reviewing the existing literature presented in Chapter 3 Section 3.3, this research finds four limitations of environmental DSGE models which need to be overcome in future studies:

1. The environmental DSGE contributions mostly emphasise real shocks only, ignoring other economic and environmental shocks including uncertainties related to climate change damage which is the main underlying motivation of environmental policy. This issue is also pointed to by Fischer and Heutel (2013) who review the environmental RBC and Directed Technical Change models and conclude that other types of uncertainties should be added besides productivity to the environmental RBC models.

2. For parameterisation environmental DSGE models mostly rely on calibration rather than estimation. This could negatively affect their ability to fit time series data.

3. As a result of calibration they focus on forecasting deviations from the steady state of macroeconomic variables rather than the levels of such variables.
4. The complexity of environmental DSGE models is usually limited to one integrated sector while an appropriate environmental policy analysis requires a multi-sectoral macroeconomics model based on their carbon intensity. Constructing large-scale multi-sectoral DSGE models can tailor these models to environmental analysis, since the imposed economic costs and the optimal outcome of environmental policies vary across sectors.\(^{18}\)

Despite the abovementioned limitations, DSGE models have great potential to be applied for environmental policy analysis at the national and international levels due to their dynamic and stochastic features. This thesis is the first application of an environmental DSGE model to the Australian economy. The model was developed to compare the economic costs and environmental outcomes of policies implemented in Australia when economic fluctuations due to a TFP shock occurs, and to investigate how to stabilise emissions during business cycles using emissions pricing programs to avoid large fluctuations in emissions. Addressing these questions requires an RBC model and not a New-Keynesian one since, as explained earlier in this section, the New Keynesian models are mostly appropriate when the research focuses on the impacts of monetary policies, or the effects of policy changes on the monetary side of an economy. The RBC mode applied in this research is presented in the next section.

4.3. Model Specification

This section presents the main structure of the DSGE model used in this study and its extensions to different scenarios. Generally, developing a DSGE model involves six main steps as follows (Flotho, 2009):

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\(^{18}\) This research found one study conducted by Bukowski and Kowal (2010) that developed an environmental large scale, multi-sectoral DSGE model for the Polish economy.
1. First, a DSGE modeller needs to develop the model by specifying the representative individual agents including households and firms, and the underlying theoretical assumptions relating to optimisation behaviour.

2. The optimisation behaviour of agents results in first order conditions (FOCs). FOCs, together with structural equations including market clearance conditions and shocks, facilitate the building of a system of dynamic stochastic equations (i.e. with leads and/or lags).

3. This system is usually nonlinear without a closed analytical solution. In order to make the model suitable for empirical analysis the model can be approximated in the neighbourhood of a given point which is mostly the non-stochastic steady state of the system obtained in Step 2.

4. The parameters of the system should be calibrated or estimated.

5. The size and direction of the shock should be specified which is usually set as equal to one standard deviation of the shock. The modeller can now run the model to obtain the impulse response functions.

6. The results obtained from the model are then analysed and evaluated in line with the aims of the study.

This chapter includes the first two steps: specifying the individual sectors and their optimisation problems. Steps 3, 4 and 5 are covered in Chapter 5 and Step 6 is explained in Chapter 6. As explained in Section 4.1 the structure of the model in this section closely follows Heutel (2012) who developed an RBC model to investigate how an emissions pricing policy responds to business cycles. He considers a centralised decision-making economy where a representative agent’s choices on consumption, investment and emissions match those of a social planner. This implies that the polluters are influenced by the costs of pollution they produce and all externalities from pollution are internalised. Then he extends
the model to a decentralised economy with asymmetric information about total factor productivity shocks.

A centralised economy without an emissions externality is not the focus of this study since it cannot include pollution externalities. Here, a decentralised economy model is applied from the beginning in which polluters are not automatically concerned about the costs of the pollution they produce. The model consists of a representative producer and a representative consumer where production generates emissions. The flow of emissions aggregates in the atmosphere and forms the pollution stock and imposes damages on the economy. In the following subsections the environment, production and consumption sectors are explained in Sections 4.3.1, 4.3.2 and 4.3.3 respectively. The functions introduced in these sections are used for testing the BAU scenario in Section 4.4, as well as a fixed emissions tax, a variable emissions tax and an abatement subsidy policy in Sections 4.5, 4.6 and 4.7 respectively.

4.3.1. The Environment

The earlier literature on environmental policy analysis assumed that environmental damage would arise from the flow of emissions (Weitzman, 1974; Malcomson, 1978; Watson and Ridker, 1984; Costello and Karp, 2004). Although the flow of emissions can contribute to several problems such as health problems, major environmental problems including global warming are due to cumulative emissions, or the stock of pollution, rather than the flow of emissions. Recently, many studies have revised the assumption that problems are caused by flows of emissions by including a linkage between the flow of emissions and the stock of pollution, and incorporating the pollution stock in their analysis (Falk and Mendelsohn, 1993; Hoel and Karp, 2002; Petrosjan and Zaccour, 2003; Heutel, 2012; Nordhaus and Sztorc, 2013; Benchekroun and Ray Chaudhuri, 2014). This research also assumes that the stock of pollution $x_t$ in period $t$ imposes negative effects on the economy in terms of damage to output.
This damage function represents the loss of potential output supply due to pollution which indicates the role of damage as it slows down the production process, for example by its negative effects on land, climate, access to water and forests. Thus, \( d(x_t) \) is an increasing function of pollution stock that takes a value between 0 and 1.

The stock of pollution decays at the rate of \( 1-\eta \) which is the share of pollution absorbed naturally by forest and oceans. Therefore, \( \eta \) represents the rate of pollution which is not absorbed naturally and remains in the atmosphere over a period. It is a positive function of domestic emissions \( m_t \) and emissions from the rest of the world \( m_{t,\text{row}} \):

\[
x_t = \eta x_{t-1} + m_t + m_{t,\text{row}}
\]

(4-1)

Emissions arise from production:

\[
m_t = (1 - \mu_t)h(y_t)
\]

(4-2)

where \( y_t \) is production and \( h \) shows the relationship of emissions to output for given technology, with abatement held constant. \( 0 \leq \mu_t \leq 1 \) is the fraction of emissions abated in period \( t \) determined by

\[
g(\mu_t) = z_t / y_t
\]

(4-3)

\( g(\mu_t) \) is the marginal abatement cost which is proportional to output. This implies that total abatement spending \( z_t \) is equal to the marginal cost of emissions reduction multiplied by total output:

\[
z_t = g(\mu_t)y_t
\]

(4-4)
Equations (4-1) to (4-4) represent the environment functions of the model. The next subsection deals with the production sector.

4.3.2. The Production Sector

The model assumes perfect competition with a representative agent who produces a commodity using capital from the last period $k_{t-1}$. Like many other emissions pricing studies (Kelly, 2005; Nordhaus, 2008; Schumacher and Zou, 2008; Nordhaus, 2010; Heutel, 2012; Angelopoulos et al., 2013), for simplicity labour is not included in this study since employment fluctuations are not the focus. The production function is

$$ y_t = (1 - d(x_t))a_t f(k_{t-1}) $$

(4-5)

where $a_t$ is total factor productivity (TFP) and is the main source of economic fluctuations with an expected value of 1. In this situation $a_t$ evolves according to a stationary, first order autoregressive process

$$ \ln a_t = \rho \ln a_{t-1} + \varepsilon_t $$

(4-6)

where $\rho$ is the persistence parameter and $\varepsilon_t$ is an i.i.d. normal random variable with a mean of zero and standard deviation $\sigma$. This random variable may occur in each period which can be observed by agents (i.e. households and businesses) at the beginning of that period. The damage function $d(x_t)$ shows the externality of pollution and pollution is a stock variable that can impose damage to the economy in the form of the loss of potential output (Nordhaus, 2008; 2010; Heutel, 2012). This assumption is plausible in a competitive market in which there are many identical small firms, with each choosing the optimal level of abatement while they incur damage from the aggregate of pollution. In other words, the firm is sufficiently small that it ignores the impact of the emissions it produces on the entire stock of pollution,
and thus on damages, and takes the stock of pollution as given when it chooses abatement. The firm maximises profit by choosing the appropriate level of abatement and capital. The profit function is determined by:

\[ \pi_t = y_t - r_t k_{t-1} - z_t \]  \hspace{1cm} (4-7)

where \( \pi_t \) is profit and \( r_t \) is the rate of return on capital. Assuming the price of output is one, equation (4-7) shows that profit is equal to net output of production and abatement costs.

Equations (4-5) to (4-7) represent the production side. The next section deals with the consumption sector.

### 4.3.3. The Consumption Sector

It is assumed that the economy is inhabited by rational identical households who derive utility from consumption of goods and services \( u(c_t) \). The household can observe productivity (i.e. \( a_t \)) at the beginning of each period and expect future values of \( a_{t+1} \) and thus, the household maximises expected total discounted utility:

\[ E_t \sum_{t=0}^{\infty} \beta^t u(c_t) \]  \hspace{1cm} (4-8)

where the operator \( E_t \) is the expectation of future values of \( a_{t+1} \) at period t. The household sector is the owner of the firm sector and receives a rate of return on capital and profit \( \pi_t \), and chooses between consumption \( c_t \) and investment \( i_t \). The stock of capital depreciates at the rate of \( \delta \):

\[ k_t = (1 - \delta) k_{t-1} + i_t \]  \hspace{1cm} (4-9)

The budget constraint is
Equations (4-8) to (4-10) represent the consumption sector. Additionally, there is a benevolent government that can envisage the behaviour of the firm and the household and chooses the optimal emissions pricing system which maximises total discounted expected utility. Under a business-as-usual scenario, in which there is no environmental policy, the role of government can be ignored, while under an emissions tax or an emissions cap scenario the government’s optimisation problem arises. The business-as-usual scenario is discussed in the next section. The results of this scenario will be used in Chapter 6 as a benchmark for policy analysis.

4.4. Business-As-Usual Scenario

Under a business-as-usual scenario, or no-policy scenario, the government does not implement a specific environmental policy. Thus, there’s no price on pollution and the firm can produce pollution at any desired level. The firm’s profit maximisation problem is

\[
\max_{k_{t+1}, \mu_t} \pi_t = y_t - r_t k_{t-1} - z_t,
\]

subject to the production, TFP and abatement cost function

\[
y_t = (1 - d(x_t)) a_t f(k_{t-1})
\]

\[
z_t = g(\mu_t) y_t
\]

\[
\ln a_t = \rho \ln a_{t-1} + \epsilon_t
\]

Without any emissions policy the profit maximising firm is not motivated to engage in abatement activity and thus, it does not take into account the effects of the emissions it
produces on the pollution stock, since it is free and takes \( x_t \) as given. Hence, the firm sets the costs of abatement as equal to zero, that is, \( z_t = 0 \), by refusing any abatement activities, that is, \( \mu_t = 0 \). Therefore, the firm’s resource constraint is

\[
\pi_t = y_t - r_t k_{t-1}
\]  

(4-11)

Optimising the profit over capital, however, the marginal value product of capital is set equal to the rate of return:

\[
r_t = y_t f'(k_{t-1})/f(k_{t-1})
\]  

(4-12)

The consumer chooses between consumption and investment by maximising expected discounted utility

\[
\max_{c_t, h_t} E_t \beta^t u(c_t)
\]

subject to the budget constraint and capital accumulation functions:

\[
c_t = \pi_t + r_t k_{t-1} - i_t
\]

\[
i_t = k_t - (1 - \delta) k_{t-1}
\]

where \( \beta \) is the discount factor. Both the rate of return to capital and profit are determined by the firm and so are exogenous to the household. Optimising the utility function with respect to consumption will lead to the first order condition representing the Euler equation as follows:

\[
-u'(c_t) + \beta E_t u'(c_{t+1}) [r_{t+1} + (1 - \delta)] = 0
\]  

(4-13)
where \(-u'(c_t)\) is the marginal benefit of an additional unit of consumption which is equal to the marginal cost of an additional unit of investment. Equation (4-13) implies that the total of marginal cost and benefit of an additional unit of investment, which is equal to the marginal benefit of consumption in the next period, should be equal to zero.

The system of equations, therefore, under a business-as-usual scenario includes the firm’s and household’s choices Equations (4-12) and (4-13) respectively, and the firm’s and household’s budget constraints, Equations (4-10) and (4-11) respectively. It also includes capital accumulation, the stock of pollution and TFP equations, Equations (4-9), (4-1) and (4-6) respectively, which represent the dynamics of the system. This system will be calibrated in the next chapter. The numerical results of the calibration will be presented in Chapter 6 as a benchmark to be compared with the results of other emissions tax policies. The outcome of the comparison will show the effects of emissions policy on the Australian economy which is the target of the current study. The model is extended to an emissions tax scenario in the next section where a tax is levied on each tonne of emissions produced.

### 4.5. Fixed Emissions Tax Policy

Under an emissions tax policy the government levies a fixed rate \(p^*\) on each tonne of emissions the firm produces. The government is neutral in the way that it collects the tax and returns the revenue from the tax to the household simply in lump sum transfers. Thus, the firm’s profit function is

\[
\pi_t = y_t - r_t k_{t-1} - p^* m_t - z_t \tag{4-14}
\]

subject to production, Equation (4-5), technology, Equation (4-6), abatement, Equation (4-4), and emissions, Equation (4-2). The profit maximising firm chooses the optimal path of abatement \(\{\mu_t\}\) which maximises its profit. The first order condition for the choice of \(\mu_t\) is
Equation (4-15) shows that the firm chooses abatement to the extent that the marginal cost of emissions abatement equals the marginal cost of the emissions tax, measured as the emissions tax multiplied by the potential emissions per unit of output. Equation (4-15) can be solved for $\mu_t$ to obtain the optimal level of abatement: $\mu_t = \mu(p^*, y_t)$. This implies that an emissions tax can affect abatement and consequently the level of emissions, but the magnitude of such an effect depends not only on the tax but also on production.

Additionally, the firm chooses the optimal level of capital where the marginal value product of capital equals the rental rate. Finding the first order condition for capital, shown by Equation (4-16), reveals that levying a tax on emissions has a negative effect on the rate of return on capital. This is due to the fact that the abatement cost is a function of output, which in turn is a function of capital. So levying a tax on emissions decreases the marginal value product of capital.

$$r_t = y_t f' (k_{t-1}) / f(k_{t-1}) \left[1 - p^*(1 - \mu_t) h'(y_t) - g(\mu_t)\right]$$

Next, consider the behaviour of the household. The household again maximises expected total discounted utility subject to capital accumulation, Equation (4-9), and the budget constraint. As explained before, it is assumed that the government transfers the revenue from an emissions tax, $p^* m_t$, to the household in each period. Thus the household’s budget constraint is

$$\pi_t + r_t k_{t-1} + p^* m_t = c_t + i_t$$

(4-17)
Optimising utility over consumption under a fixed tax policy results in the same Euler equation as the BAU scenario, Equation (4-13), although the budget constraints are different, as shown by Equation (4-17). The Euler equation, Equation (4-13), implies that the utility from consuming today is equal to the expected discounted utility of consumption in the future.

Therefore, the system of equations under a fixed emissions tax scenario includes the outcomes of the firm’s profit optimisation, Equations (4-15) and (4-16), the firm’s resource constraint, Equation (4-14), the household’s utility optimisation behaviour, Equation (4-13), household’s budget constraint, Equation (4-17), the production function, Equation (4-5), technology, Equation (4-6), capital accumulation, Equation (4-9), and other environmental functions, Equations (4-1), (4-2) and (4-4).

Comparing the system of equations under a tax policy with the BAU scenario reveals that levying an emissions tax not only persuades the firm to introduce a path of abatement Equation (4-15), but also indirectly affects the rate of return to capital, Equation (4-16). This system will be calibrated in Chapter 5 and tested in a fixed emissions tax scenario in Chapter 6.

4.6. Variable Emissions Tax Scenario

The optimising of the output of a firm in a variable emissions tax regime is the same as it is in a fixed tax system, while the tax rate $p_t$ changes over time. So Equations (4-17), (4-14), (4-15) and (4-16) can be written as:

$$\pi_t + r_t k_{t-1} + p_t m_t = c_t + i_t$$  \hspace{1cm} (4-18)

$$\pi_t = y_t - r_t k_{t-1} - p_t m_t$$  \hspace{1cm} (4-19)
In this regime the regulator observes the firm’s and household’s optimisation behaviour and chooses an optimal emissions tax path \( \{p_t\} \) which maximises social welfare in terms of total discounted expected utility. The regulator’s optimisation problem can be written as

\[
\max_{p_t, k_t, y_t, r_t} \sum_{t=0}^{\infty} \beta^t E[u(c_t)]
\]

subject to the firm’s and household’s FOCs and budget constraints, Equations (4-18) to (4-21) and (4-13), production and TFP functions, Equations (4-5) and (4-6), capital accumulation, Equation (4-9), and environmental relationships, Equations (4-1), (4-2) and (4-4). Equation (4-20) can be solved to obtain \( \mu_t = \mu(p_t, y_t) \). Substituting this into equation (4-4) results in \( z_t = z(p_t, y_t) \). Substituting these two solutions, the constraints, Equations (4-1), (4-2) and (4-20) can be simplified to one constraint as below:

\[
x_t = \eta x_{t-1} + m_t + m_{t,\text{row}} + m(p_t, y_t)
\]

Likewise, Equations (4-4), (4-9), (4-13), (4-18), (4-19), (4-20) and (4-21) can also be simplified to

\[
-u'(y_t - k_t + (1 - \delta)k_{t-1} - z(p_t, y_t)) + \beta E[u'(y_{t+1} - k_{t+1} + (1 - \delta)k_t - z(p_{t+1}, y_{t+1}))]
\times(r(p_{t+1}, y_{t+1}, k_t) + 1 - \delta)
\]

Using these two simplified constraints the government’s problem can be written as the following Lagrangian equation:
\[ L_t = \sum_{t=0}^{\infty} \beta^t E_u(y_t - k_t + (1-\delta)k_{t-1} - z(p_t, y_t)) + \lambda_t \{ -u'(y_t - k_t + (1-\delta)k_{t-1} - z(p_t, y_t)) \} \\
+ \beta u'(y_{t+1} - k_{t+1} + (1-\delta)k_t - z(p_{t+1}, y_{t+1})) \times (r(p_{t+1}, y_{t+1}, k_t) + 1-\delta) \} \\
+ \zeta_t \{ x_t - \eta x_{t-1} + m_{t+1} + m(p_t, y_t) \} + \omega_t \{ y_t - [1 - d(x_t)] f(k_{t-1}) \} \]  

(4-25)

where \( \lambda_t, \omega_t, \zeta_t \) are the Lagrangian multipliers. To find the optimal tax, the government solves a Ramsey problem by using a so-called dual approach (Brendemoen and Vennemo, 1994; Fankhauser, 1995) and choosing \( \{ p_t \}_{t=0}^{\infty} \) and also \( \{ k_t, x_t, y_t \}_{t=0}^{\infty} \). Optimising the above Lagrangian equation over the emissions tax leads to the first order condition with respect to \( p_t \) as below:

\[ -u'(c_t) z'_p (p_t, y_t) + \lambda_t \{ u''(c_t) z'_p (p_t, y_t) \} \]
\[ + \lambda_{t-1} \{ u''(c_t) (z'_p (p_t, y_t) (r_t + 1-\delta) + u'(c_t) r'_p (p_t, y_t, k_{t-1}) \} + \zeta_t \{ -m'_p (p_t, y_t) \} = 0 \]

(4-26)

Equation (4-26) is the solution of the government’s problem, showing the optimal path of emissions tax \( \{ p_t \} \). The government also optimises social welfare over \( k_t, y_t \) and \( x_t \) as below:

\[ -u'(c_t) + \beta u'(c_t) (1-\delta) + \beta \lambda_{t+1} \{ -u''(c_{t+1}) (1-\delta) \} \]
\[ + \lambda_t \{ u''(c_t) (1-\delta) (r_{t+1} + 1-\delta) + \beta u'(c_{t+1}) r'_x (p_{t+1}, y_{t+1}, k_t) \} \]
\[ + \lambda_{t-1} \{ -u'(c_t) (r_t + 1-\delta) \} - \beta \omega_t \{ 1 - d(x_{t+1}) \} a_{t+1} f'(k_t) = 0 \]

(4-27)

\[ u'(c_t) (1 - z'_p (p_t, y_t)) + \lambda_t \{ -u''(c_t) z'_p (p_t, y_t) \} + \omega_t \]
\[ + \lambda_{t-1} \{ u''(c_t) (1 - z'_p (p_t, y_t)) (r_t + 1-\delta) + u'(c_t) r'_x (p_t, y_t, k_{t-1}) \} + \zeta_t \{ -m'_p (p_t, y_t) \} = 0 \]

(4-28)

\[ \zeta_t - \beta \zeta_{t+1} \eta + \omega_t a_t f(k_{t-1}) d'(x_t) = 0 \]

(4-29)

Equations (4-26) to (4-29) show the government’s social welfare maximising outcomes. These equations, plus the firm’s resource constraints and profit optimisation outcomes, Equations (4-19) to (4-21), the household’s utility optimisation behaviour, Equation (4-13), the household’s budget constraint, Equation (4-18), production function, Equation (4-5),
technology, Equation (4-6), capital accumulation, Equation (4-9), and other environmental functions, Equations (4-1), (4-2) and (4-4) represent the economy under a variable emissions tax system. This system will be calibrated in Chapter 5 and its numerical solution will be presented in Chapter 6. The results will describe the Australian economy under a variable emissions tax policy. In the following section, another emissions control system, an abatement subsidy policy, will be specified.

4.7. Abatement Subsidy Policy

In an abatement subsidy regime the regulator supports abatement by allocating a subsidy of \( s_t \) to a firm for any abatement effort made in each period: \( \mu_t \) is the percentage of emissions abated in each period, holding output constant. Like a variable tax system, it is assumed that the regulator is neutral as they levy a lump-sum tax on consumers and allocate the revenues to subsidise abatement efforts. Thus, the household’s budget constraint is

\[
\pi_t + r_t k_{t-1} - s_t \mu_t = c_t + i_t
\]  
(4-30)

The household maximises expected total utility of consumption subject to a budget constraint, Equation (4-30), and capital accumulation, Equation (4-9) which results in the same Euler equation, Equation (4-13), as the BAU and emissions tax scenarios.

The firm receives the subsidy and, thus, the firm’s budget constraint is

\[
\pi_t = y_t + s_t \mu_t - r_t k_{t-1} - z_t
\]  
(4-31)

The firm maximises this profit subject to production, Equation (4-5), technology, Equation (4-6), abatement, Equation (4-4), and emissions, Equation (4-2). Optimising with respect to capital leads to the optimal level of capital in each period as shown by Equation (4-32). The
firm also chooses the optimal level of abatement which maximises profit which results in Equation (4-33).

\[ r_i = y_i f'(k_{t-1}) / f(k_{t-1}) [1 - g(\mu_i)] \]  
\[ s_i = y_i g'(\mu_i) \]  

Comparing the firm’s choice of capital under a subsidy policy, Equation (4-32), with that of a tax policy, Equation (4-21), reveals that the rate of return to capital can be affected by a tax but not by a subsidy.

Observing the behaviour of households and firms, the regulator chooses the optimal path of subsidy \{s_t\} which maximises social welfare in terms of total discounted expected utility

\[ \max \sum_{t=0}^{\infty} \beta^t Eu(c_t) \]  

subject to the firm’s and household’s budget constraints and optimisation outcomes, Equation (4-13) and Equations (4-30) to (4-33), production and TFP functions, Equations (4-5) and (4-6), capital accumulation, Equation (4-9), and environmental relationships, Equations (4-1), (4-2) and (4-4).

Substituting Equation (4-33) into Equation (4-4) leads to \( z_i = z(s_i, y_i) \). Using this function, Equations (4-4), (4-10), (4-13), (4-30), (4-31), (4-32) and (4-33) can be summarised into one constraint

\[ -u'(y_i - k_i + (1 - \delta)k_{t-1} - z(s_i, y_i)) + \beta E u'(y_{i+1} - k_{i+1} + (1 - \delta)k_i - z(s_{i+1}, y_{i+1})) [r(k_{t-1}, y_i) + (1 - \delta)] = 0 \]  

Therefore, the government’s problem can be written as a Lagrangian problem as below:
\[ L_t = \sum_{i=0}^{\infty} \beta^t E_t u(y_t - k_t, (I - \delta) k_{t-1} - z(s_t, y_t)) + \lambda_t \left\{-u'(y_t - k_t, (I - \delta) k_{t-1} - z(s_t, y_t)) \right\} \]

\[ + \beta u'(y_{t+1} - k_{t+1}, (I - \delta) k_t - z(s_{t+1}, y_{t+1})) \times (r(y_{t+1}, k_t) + I - \delta) \]

\[ + \xi_t \left\{ x_t - \eta x_{t-1} + m_{t+1} + m_t \right\} + \omega_t \left\{ y_t - [I - d(x_t)] f(k_{t-1}) \right\} \]

where \( \lambda_t, \omega_t, \xi_t \) are the Lagrangian multipliers. Optimising this Lagrangian problem with respect to an abatement subsidy leads to

\[ -u'(c_t) z'_t (s_t, y_t) + \lambda_t \left\{ u''(c_t) z''_t (s_t, y_t) \right\} \]

\[ + \lambda_{t-1} \left\{ u''(c_t) \left( -z'_t (s_t, y_t) \right) \left( r_t + 1 - \delta \right) \right\} + \xi_t \left\{ -m'_t (s_t, y_t) \right\} = 0 \]

Additionally, optimising social welfare over \( x_t, k_t \) and \( y_t \) results in

\[ \xi_t - \beta \xi_{t+1} + \omega_t a_t f(k_{t-1}) f'(x_t) = 0 \]

\[ -u'(c_t) + \beta u'(c_t) \left( 1 - \delta \right) + \beta \lambda_{t+1} \left\{-u''(c_{t+1}) \left( 1 - \delta \right) \right\} \]

\[ + \lambda_t \left\{ u''(c_t) + \beta u''(c_{t+1}) \left( 1 - \delta \right) \left( r_{t+1} + 1 - \delta \right) \right\} + \beta u'(c_{t+1}) \left( y_{t+1}, k_t \right) \]

\[ + \lambda_{t-1} \left\{ -u'(c_t) \left( r_{t+1} + 1 - \delta \right) \right\} - \beta \omega_{t+1} \left[ 1 - d(x_{t+1}) \right] a_{t+1} f'(k_t) = 0 \]

\[ u'(c_t) \left( 1 - z'_{y} (s_t, y_t) \right) + \lambda_t \left\{ -u''(c_t) z''_{y} (s_t, y_t) \right\} + \omega_t \]

\[ + \lambda_{t-1} \left\{ u''(c_t) \left( 1 - z'_{y} (s_t, y_t) \right) \left( r_t + 1 - \delta \right) + u'(c_t) r'_y (y_t, k_{t-1}) \right\} + \xi_t \left\{ -m'_y (s_t, y_t) \right\} = 0 \]

Using these equations the system of equations describing the economy under a variable emissions cap includes the outcomes of the firm’s and household’s optimisation behaviour and budget constraints, Equation (4-13) and Equations (4-30) to (4-33), production and TFP functions, Equations (4-5) and (4-6), capital accumulation, Equation (4-9), environmental relationships, Equations (4-1), (4-2) and (4-4) and government’s social welfare optimisation outcomes, Equations (4-37) to (4-40). This system will be calibrated in Chapter 5 and the numerical solution of the system will be represented in Chapter 6. The results will be compared with those of the BAU scenario to show the effects of an abatement subsidy policy on the Australian economy. The results will also be compared with other scenarios, that is,
fixed and flexible emissions taxes, in order to find the optimal emissions pricing system in Australia.

4.8. Summary

In this chapter a DSGE model of emissions reduction for policy analysis under different scenarios was presented. To this end, the evolution of DSGE models and their applications in macroeconomics were explained. Additionally, the extension of DSGE modelling into environmental areas was also clarified. As clarified in Section 4.2, these models are known as modern macroeconomic models specifying macroeconomic relationships based upon micro-founded assumptions. Partial equilibrium models focus only on one or a few economic agents, while the general equilibrium nature of DSGE models makes them suitable for representing the relationships between all sectors of an economy. The dynamic feature of these models enables modellers to track the transitional effects of policy changes on different sectors over various time periods. Additionally, as a result of being stochastic, these models provide an appropriate framework to study the effects of uncertainties on the economy. Due to such advantages, DSGE models have been recently applied in environmental policy analysis since they can facilitate investigating the effects of any economic or environmental uncertainty in environmental policy analysis.

This research is the first attempt to apply DSGE models for emissions pricing policy analysis in the case of Australia. This chapter specified the general equations of the model and extended them to four scenarios: first, a business-as-usual scenario (i.e. with no emissions pricing policy) as a benchmark; second, a fixed emissions tax policy in which a constant emissions tax is levied which does not change over time; third, a variable emissions tax scenario where the government choses the optimal emissions tax at the beginning of each period; and, fourth, an emissions abatement policy in which the government financially
supports firms’ abatement efforts in each period. These scenarios are specified in such a way that they resemble the emissions reduction policies that have been implemented in Australia.

The model applied here closely followed the model developed by Heutel (2012). However, it deviated from his model in two ways. Firstly, it tested different scenarios: Heutel (2012) starts with a centralised economy in which polluters automatically internalised the externalities arising from pollution, to investigate the responses of an economy only under a variable emissions pricing system to TFP shocks. While the centralised model was the main focus of his study, he extended it to a decentralised economy where an emissions pricing policy motivates the polluter to reduce their emissions in order to provide a comparison between different policies. The current research, however, applied a decentralised model from the beginning. The model included emissions externalities and tested not only a variable emissions tax, but also a fixed emissions tax and an emissions abatement subsidy since the aim of this study is emissions reduction policy analysis in Australia, and these three scenarios are the policies which have so far been developed for Australia. This chapter specified the relationships between economic and environmental variables under each scenario. These relationships are summarised in Table 4.2.

The second deviation of the current research is regarding the specification of one of the environmental variables, emissions from the rest of the world. This deviation will be explained in detail in the next chapter. Finally, the third difference between this study and Heutel (2012) is related to analysing the outcomes of the model, as this thesis applies a new approach to study the effects of emissions pricing systems. This new approach is explained in Chapter 6. These three differences are the technical contributions of the current research. In addition, this thesis makes the empirical contribution of applying the model to the Australian economy while Heutel (2012) calibrated his model to the US economy and, thus, his
numerical results were based on the US. The calibration and parametrisation of the current research will be presented in the next chapter.
Table 4.2: Systems of equations describing the economy under a business-as-usual, a fixed and a variable emissions tax and an abatement subsidy scenario

<table>
<thead>
<tr>
<th>Function</th>
<th>BAU</th>
<th>Fixed Emissions Tax</th>
<th>Variable Emissions Tax</th>
<th>Abatement Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>$y_t = (1 - d(x_t))a_t f(k_{t-1})$</td>
<td>$y_t = (1 - d(x_t))a_t f(k_{t-1})$</td>
<td>$y_t = (1 - d(x_t))a_t f(k_{t-1})$</td>
<td>$y_t = (1 - d(x_t))a_t f(k_{t-1})$</td>
</tr>
<tr>
<td>Pollution stock</td>
<td>$x_t = \eta p_{t-1} + m_t + m_t^{\text{cum}}$</td>
<td>$x_t = \eta p_{t-1} + m_t + m_t^{\text{cum}}$</td>
<td>$x_t = \eta p_{t-1} + m_t + m_t^{\text{cum}}$</td>
<td>$x_t = \eta p_{t-1} + m_t + m_t^{\text{cum}}$</td>
</tr>
<tr>
<td>Capital accumulation</td>
<td>$k_t = (1 - \delta)k_{t-1} + i_t$</td>
<td>$k_t = (1 - \delta)k_{t-1} + i_t$</td>
<td>$k_t = (1 - \delta)k_{t-1} + i_t$</td>
<td>$k_t = (1 - \delta)k_{t-1} + i_t$</td>
</tr>
<tr>
<td>TFP</td>
<td>$ln a_t = \rho \ln a_{t-1} + \varepsilon_t$</td>
<td>$ln a_t = \rho \ln a_{t-1} + \varepsilon_t$</td>
<td>$ln a_t = \rho \ln a_{t-1} + \varepsilon_t$</td>
<td>$ln a_t = \rho \ln a_{t-1} + \varepsilon_t$</td>
</tr>
<tr>
<td>Household’s budget constraint</td>
<td>$\pi_t + r_t k_{t-1} = c_t + i_t$</td>
<td>$\pi_t + r_t k_{t-1} + p^* m_t = c_t + i_t$</td>
<td>$\pi_t + r_t k_{t-1} + p^* m_t = c_t + i_t$</td>
<td>$\pi_t + r_t k_{t-1} - s_t \mu_t = c_t + i_t$</td>
</tr>
<tr>
<td>Household’s choice of investment</td>
<td>$- u'(c_t) + \beta E u'(c_{t+1}) \left[ r_{t+1} + (1 - \delta) \right] = 0$</td>
<td>$- u'(c_t) + \beta E u'(c_{t+1}) \left[ r_{t+1} + (1 - \delta) \right] = 0$</td>
<td>$- u'(c_t) + \beta E u'(c_{t+1}) \left[ r_{t+1} + (1 - \delta) \right] = 0$</td>
<td>$- u'(c_t) + \beta E u'(c_{t+1}) \left[ r_{t+1} + (1 - \delta) \right] = 0$</td>
</tr>
<tr>
<td>Firm’s resource constraint</td>
<td>$\pi_t = y_t - r_t k_{t-1}$</td>
<td>$\pi_t = y_t - r_t k_{t-1} - p^* m_t - z_t$</td>
<td>$\pi_t = y_t - r_t k_{t-1} - p^* m_t$</td>
<td>$\pi_t = y_t + s_t \mu_t - r_t k_{t-1} - z_t$</td>
</tr>
<tr>
<td>Firm’s choice of capital</td>
<td>$r_t = y_t f^*(k_{t-1}) / f(k_{t-1})$</td>
<td>$r_t = y_t f^*(k_{t-1}) / f(k_{t-1})$</td>
<td>$r_t = y_t f^*(k_{t-1}) / f(k_{t-1})$</td>
<td>$r_t = y_t f^*(k_{t-1}) / f(k_{t-1}) \left[ 1 - g(\mu_t) \right]$</td>
</tr>
<tr>
<td>Function</td>
<td>BAU</td>
<td>Fixed Emissions Tax</td>
<td>Variable Emissions Tax</td>
<td>Abatement Subsidy</td>
</tr>
<tr>
<td>--------------------------------</td>
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<td>------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Firm’s choice of abatement</td>
<td>0</td>
<td>$g'(\mu) = \frac{h(y)}{y}$</td>
<td>$g'(\mu) = \frac{h(y)}{y}$</td>
<td>$g'(\mu) = \frac{s}{y}$</td>
</tr>
<tr>
<td>Emissions</td>
<td>$m_t = h(y)$</td>
<td>$m_t = (1 - \mu) h(y)$</td>
<td>$m_t = (1 - \mu) h(y)$</td>
<td>$m_t = (1 - \mu) h(y)$</td>
</tr>
<tr>
<td>Abatement cost</td>
<td>0</td>
<td>$z_t = g(\mu) y_t$</td>
<td>$z_t = g(\mu) y_t$</td>
<td>$z_t = g(\mu) y_t$</td>
</tr>
<tr>
<td>Government’s choice of tax/subsidy</td>
<td></td>
<td>$-u'(c_t) z'_p (s_t, y_t) + \lambda_t [u''(c_t) z''_p (s_t, y_t)]$</td>
<td>$-u'(c_t) z'_s (s_t, y_t) + \lambda_t [u''(c_t) z''_s (s_t, y_t)]$</td>
<td>$-u'(c_t) z'_s (s_t, y_t) + \lambda_t [u''(c_t) z''_s (s_t, y_t)]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ \lambda_t [u''(c_t) (-z'_p (s_t, y_t)) (r_t + 1 - \delta)]$</td>
<td>$+ \lambda_t [u''(c_t) (-z'_s (s_t, y_t)) (r_t + 1 - \delta)]$</td>
<td>$+ \lambda_t [u''(c_t) (-z'_s (s_t, y_t)) (r_t + 1 - \delta)]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ u'(c_t) r'<em>p (p_t, y_t, k</em>{t-1})] + \xi_t [-m'_p (p_t, y_t)]$</td>
<td>$+ \xi_t [-m'_s (s_t, y_t)] = 0$</td>
<td>$+ \xi_t [-m'_s (s_t, y_t)] = 0$</td>
</tr>
<tr>
<td>Government’s choice of capital</td>
<td></td>
<td>$-u'(c_t) + \beta u'(c_t) (1 - \delta) + \beta \lambda_{t-1} [-u''(c_{t-1}) (1 - \delta)]$</td>
<td>$-u'(c_t) + \beta u'(c_t) (1 - \delta) + \beta \lambda_{t-1} [-u''(c_{t-1}) (1 - \delta)]$</td>
<td>$-u'(c_t) + \beta u'(c_t) (1 - \delta) + \beta \lambda_{t-1} [-u''(c_{t-1}) (1 - \delta)]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$(r_{t-1} + 1 - \delta) + \beta u'(c_{t-1}) (1 - \delta)$</td>
<td>$+ \lambda_t [u''(c_t) + \beta u''(c_{t-1}) (1 - \delta) (r_{t-1} + 1 - \delta)]$</td>
<td>$+ \lambda_t [u''(c_t) + \beta u''(c_{t-1}) (1 - \delta) (r_{t-1} + 1 - \delta)]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ \lambda_t [-u'(c_t) (-z'_p (s_t, y_t)) (r_t + 1 - \delta)]$</td>
<td>$+ \lambda_t [-u'(c_t) (-z'_p (s_t, y_t)) (r_t + 1 - \delta)]$</td>
<td>$+ \lambda_t [-u'(c_t) (-z'_p (s_t, y_t)) (r_t + 1 - \delta)]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- \beta \omega_{t-1} [1 - d(x_{t-1})] a_{t-1} f'(k_t) = 0$</td>
<td>$- \beta \omega_{t-1} [1 - d(x_{t-1})] a_{t-1} f'(k_t) = 0$</td>
<td>$- \beta \omega_{t-1} [1 - d(x_{t-1})] a_{t-1} f'(k_t) = 0$</td>
</tr>
<tr>
<td>Function</td>
<td>BAU</td>
<td>Fixed Emissions Tax</td>
<td>Variable Emissions Tax</td>
<td>Abatement Subsidy</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Government’s choice of output</strong></td>
<td>$u'(c_i) {1 - z'_y(p_i, y_i)} + \lambda_i {-u''(c_i) }$</td>
<td>$u'(c_i) {1 - z'_y(p_i, y_i)} + \lambda_i {-u''(c_i) }$</td>
<td>$u'(c_i) {1 - z'_y(s_i, y_i)} + \lambda_i {-u''(c_i) }$</td>
<td>$u'(c_i) {1 - z'_y(s_i, y_i)} + \lambda_i {-u''(c_i) }$</td>
</tr>
<tr>
<td></td>
<td>$z'<em>y(p_i, y_i) + \omega_t + \lambda</em>{i,t} {u''(c_i) }$</td>
<td>$(1 - z'_y(p_i, y_i))(r_i + l - \delta) + u'(c_i)r'<em>y(p_i, y_i, k</em>{i,t})$</td>
<td>$z'<em>y(s_i, y_i) + \omega_t + \lambda</em>{i,t} {u''(c_i) }$</td>
<td>$z'<em>y(s_i, y_i) + \omega_t + \lambda</em>{i,t} {u''(c_i) }$</td>
</tr>
<tr>
<td></td>
<td>$ {l - z'_y(p_i, y_i)}(r_i + l - \delta)$</td>
<td>$+u'(c_i)r'<em>y(p_i, y_i, k</em>{i,t})$</td>
<td>$+ \lambda_{i,t} {u''(c_i) }(l - z'_y(s_i, y_i))(r_i + l - \delta) + u'(c_i)r'_y(s_i, y_i)$</td>
<td>$+ \lambda_{i,t} {u''(c_i) }(l - z'_y(s_i, y_i))(r_i + l - \delta) + u'(c_i)r'_y(s_i, y_i)$</td>
</tr>
<tr>
<td></td>
<td>$+ \varsigma_i {m'_y(p_i, y_i)}$</td>
<td>$+ \varsigma_i {m'_y(s_i, y_i)}$</td>
<td>$+ \varsigma_i {m'_y(s_i, y_i)}$</td>
<td>$+ \varsigma_i {m'_y(s_i, y_i)}$</td>
</tr>
</tbody>
</table>

$\varsigma_i - \beta \varsigma_{i,t} \eta + \omega_t a_t f(k_{i,t}) d'(x_i) = 0$

Source: Author’s configuration.
Chapter 5

Data Collection and Calibration

5.1. Introduction

In Chapter 4 the structure of the environmental dynamic general equilibrium model used in this study was presented. The model comprises a representative consumer and a representative profit maximising producer. Production leads to emissions which accumulate in the atmosphere and impose an externality by reducing total output. A scenario in which a government attempts to internalise the externality by setting a price on emissions was also considered. The optimisation behaviour of each sector, as well as the relationships between them, were specified in Chapter 4 and extended to four scenarios: (1) business-as-usual (i.e. with no environmental policy), (2) a fixed emissions tax policy in which the emissions tax does not change over time, (3) a flexible emissions tax policy where the government chooses the optimal rate of emissions tax at the beginning of each period which maximises social welfare and (4) an abatement subsidy policy where the government chooses the optimal subsidy at the beginning of each period which maximises social welfare. The outcomes for each policy were summarised in Chapter 4, Table 4.2.

Table 4.2 is the outcome of (1) specification and (2) optimisation of different sectors of the Australian economy under different emissions reduction scenarios. As explained in Chapter 4, Section 4.3, these steps are the first two of the six steps required to apply DSGE models. This chapter describes the next three steps, Steps 3, 4 and 5:

3. The parameters of the system are calibrated or estimated.
4. The size and direction of the shock are specified. The size of the shock is usually set as equal to one standard deviation of the shock.

5. The model is usually nonlinear without a closed analytical solution. In order to make the model suitable for empirical analysis, in this step the model can be approximated in the neighbourhood of a given point which is mostly the non-stochastic steady state of the system obtained in Step 2.

Thus, the model developed in Chapter 4 is calibrated here for the purpose of scenario analysis. To this end the general relationships, or functions, of the model, such as the utility and production functions, are specified. Like Heutel (2012) the current research utilises the Dynamic Integrated Climate-Economy (DICE) model (Nordhaus, 2008) to specify the functions. However, it deviates from Heutel (2012) in calibrating one of the environmental variables, the emissions from the rest of the world. Calibrating his research to the US economy, Heutel (2012) assumes that the emissions from the rest of the world are three times greater than the domestic emissions produced by the US. However, tying the emissions from the rest of the world to domestic emissions at a constant rate under emissions pricing policies would not be appropriate since it would provide a channel to transfer the effects of domestic emissions pricing policy to the rest of the world’s emissions.

In other words, according to this assumption, if an emissions pricing policy affects domestic emissions its effect multiplied by three will be equal to the emissions produced by the rest of the world which is not necessarily true. Instead of making such an assumption, the current research calculates the rest of the world’s emissions under a BAU scenario and assumes that emissions from the rest of the world under the various emissions pricing policies are equal to those under a BAU scenario. This assumption is consistent with the aim of this study which is
to analyse the economic effects of emissions pricing policies on Australia, not on the world economy.

After specifying the functions, the model is parameterised to the Australian economy. To this end, Australian RBC literature, such as Rees (2013), Gomez-Gonzalez and Rees (2013), and Jaaskela and Nimark (2011), is used here since the model of the current research is of the RBC type. The calibrated equations are substituted into the model under different emissions pricing policy scenarios. As explained in Step 5 the nonlinear model does not have a closed-form solution, however a numerical solution can be found. The solution is used via three approaches to conduct a comparison between different pricing policies in Chapter 6. These three approaches are explained below.

First, the steady state values of economic and environment variables are found and compared in order to investigate the non-stochastic effects of each policy. Second, the fluctuations occurring in environmental and economic variables due to total factor productivity (TFP) shocks are presented and analysed to study the effects of each policy on Australian business cycles. Third, the cumulative effect of each policy is calculated to present the cumulative changes in each variable over time when a shock happens. But first, the model needs to be calibrated and log-linearised around the steady state values in this chapter. The numerical results will be presented, compared and discussed in the next chapter.

This chapter is organised as follows. First, the equations and parameters are calibrated in Section 5.2. The calibration of the damage function is explained separately in Section 5.3. In Section 5.4 the calibrated equations are substituted into the model. In Section 5.5 the steady state of the model is obtained and the model is log-linearised around the steady state. Section 5.6 summarises the chapter.
5.2. Calibration

In this section the model specified in Chapter 4 Section 4.3 is calibrated to the Australian economy. As explained in Section 5.1 the functions are calibrated to the DICE model (Nordhaus, 2008) which is the most distinguished integrated assessment model. The DICE model is a global integrated model which is disaggregated to the Regional Integrated model of Climate and the Economy (RICE) model and applied to different regions to analyse different national environmental strategies (Nordhaus and Yang, 1996). In the latest model, RICE-2010, 198 countries in the global economy are divided into 12 regions: the United States, the European Union, Japan, Russia, Eurasia, China, India, Middle East, Africa, Latin America, Other High Income (OHI) countries and Other Asia, where Australia is in the OHI group. Hence, the parameters of the OHI group countries will be used here to calibrate the environmental coefficients, including the damage and abatement function for Australia.

As explained in Section 5.1 the macroeconomic variables are parameterised to the Australian macroeconomic literature, especially RBC studies (Jaaskela and Nimark, 2011; Gomez-Gonzalez and Rees, 2013; Rees, 2013), since the model of this thesis is also RBC. These studies are used to parameterise the production function, the discount factor, the utility function, the capital decay rate and the productivity shock. Also, one of the parameters, the coefficient of output, which is not available in the literature, is estimated using Australian databases including the Australian National Accounts (Australian Bureau of Statistics, 2014) and Australia’s National Greenhouse Accounts (Department of the Environment, 2014b).

To calibrate the model each period of time is set as equal to a quarter. To calibrate the utility discount factor $\beta$, that is the rate at which the consumer discounts the utility gained from future consumption, Jaaskela and Nimark (2011), Gomez-Gonzalez and Rees (2013) and Rees (2013) are used, and they estimated it to be equal to 0.99. The capital depreciation rate $\delta$
is set at 0.02 (Rees, 2013) which implies that Australian capital depreciates by 2 per cent per quarter. The consumer utility function is \( u(c_t) = \frac{c^{1-\zeta}}{1-\zeta} \) where \( \zeta \) represents the constant coefficient of relative risk aversion and is set to 1.66\(^{19}\) based on Hodge \textit{et al.} (2008).

Total abatement spending \( z_t \) is equal to the marginal cost of emissions reduction multiplied by total output:

\[
z_t = g(\mu_t) y_t, \quad (5-1)
\]

where \( g(\mu_t) \) represents the marginal abatement cost. Nordhaus (2008) assumes that \( g(\mu_t) \) is highly convex and thus the marginal costs of emissions abatement rises more than linearly with the abatement rate. Therefore, he specifies \( g(\mu_t) = \theta_1 \mu_t^{\theta_2} \) where \( \theta_2 = 2.8 \) and \( \theta_1 \) is a function of time with the initial value of 0.05607. These values, however, are related to the global economy in the DICE model. In order to calibrate them to the Australian economy the current research uses the RICE–2010 model. In RICE–2010, \( \theta_2 = 2.8 \) while \( \theta_1 \) is estimated to be 0.07 for the OHI countries. \( \theta_1 \) represents a higher cost of emissions abatement for these countries including Australia. This is consistent with the costly abatement structure of Australia since its production sector heavily relies on fossil fuels – 86.9% of Australian electricity was generated by fossil fuels in 2012-13 (Bureau of Resources and Energy Economics, 2014). Thus, the Australian abatement cost function is parametrised to \( \theta_1 = 0.07 \) and \( \theta_2 = 2.8 \).

As represented in Chapter 4, Section 4.2 the stock of pollution function is

\[
x_t = \eta x_{t-1} + m_t + m_t^{new} \quad (5-2)
\]

\(^{19}\) This can be interpreted as the elasticity of the marginal utility of consumption and is set to equal 1.66.
in which $\eta$ represents the persistence of pollution in the atmosphere. This value can be estimated from the half-life of atmospheric carbon dioxide, but it is not precisely estimated. For instance, Reilly and Anderson (1992) estimate that the half-life of atmospheric carbon dioxide is 83 years and is equivalent to 0.9979 quarterly. This value implies that 99.79 per cent of emissions produced in each period will remain in the atmosphere in the next period (i.e. the next quarter), while 0.21 per cent of emissions are absorbed naturally, via forests and oceans for instance (Heutel, 2012).

Additionally, the emissions arising from production are shown by:

$$m_t = (1 - \mu_t)h(y_t)$$  \hspace{1cm} (5-3)

where $h(y_t)$ indicates the relationship of emissions with output which can be specified as $h(y_t) = y_t^{1-\gamma}$. This research assumes that $1 - \gamma \leq 1$ which implies that the rate of increase in emissions is less than or equal to the rate of increase in output, but not greater than it. $1 - \gamma$ can be estimated as the coefficient of the log of emissions on the log of output. To find this coefficient, this research used quarterly data on emissions for Australia from September 2001 to December 2013 from Australia’s National Greenhouse Accounts (Department of the Environment, 2014b). Quarterly data on Australian GDP for September 2001 to December 2013 is also collected from the Australian National Accounts (Australian Bureau of Statistics, 2014). Both emissions and GDP data is in seasonally adjusted terms. The GDP data is in millions of dollars and the emissions data is in millions of metric tons of carbon dioxide equivalents (Mt CO$_2$-e). To find 1-$\gamma$ the regression of the log of emissions on the log of output is calculated. The regression coefficient is $I - \gamma$ which is estimated to be equal to 0.0975. The collected data and the regression results are presented in the Appendix A.1.
Table 5.1: Summary of model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.33</td>
<td>Output elasticity of capital</td>
<td>Rees (2013), Gomez-Gonzalez and Rees (2013)</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>1.66</td>
<td>Risk aversion coefficient</td>
<td>Hodge et al. (2008)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.99</td>
<td>Discount factor</td>
<td>Jaaskela and Nimark (2011), Gomez-Gonzalez and Rees (2013), Rees (2013)</td>
</tr>
<tr>
<td>$\delta$</td>
<td>0.02</td>
<td>Capital depreciation rate</td>
<td>Rees (2013)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.98</td>
<td>Autocorrelation parameter of the productivity shock</td>
<td>Rees (2013)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.007</td>
<td>Standard deviation of $\varepsilon_i$</td>
<td>Rees (2013)</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.9979</td>
<td>Autocorrelation parameter of pollution</td>
<td>Heutel (2012)</td>
</tr>
<tr>
<td>$d_0$</td>
<td>-0.0011</td>
<td>Intercept of damage function</td>
<td>Estimated by the author for Australia from Nordhaus (2010) model</td>
</tr>
<tr>
<td>$d_1$</td>
<td>$-5.6629e^{-10}$</td>
<td>Linear coefficient of the damage function</td>
<td>Estimated by the author for Australia from Nordhaus (2010) model</td>
</tr>
<tr>
<td>$d_2$</td>
<td>$1.2261e^{-8}$</td>
<td>Quadratic coefficient of the damage function</td>
<td>Estimated by the author for Australia from Nordhaus (2010) model</td>
</tr>
<tr>
<td>$\theta_1$</td>
<td>0.07</td>
<td>Abatement cost function coefficient</td>
<td>Nordhaus (2010)</td>
</tr>
<tr>
<td>$\theta_2$</td>
<td>2.8</td>
<td>Abatement cost function exponential coefficient</td>
<td>Nordhaus (2010)</td>
</tr>
<tr>
<td>$1-\gamma$</td>
<td>0.0975</td>
<td>Emissions elasticity of output</td>
<td>Estimated by the author from the Australian emissions and GDP data over the period Q2, 2001- Q4, 2013</td>
</tr>
</tbody>
</table>

Source: compiled by the author.

The output function is:

$$y_t = (1 - d(x_t))a_t f(k_{t-1})$$

(5-4)
where $a_t$ is a total factor productivity (TFP) shock with an expected value of 1. It is assumed that the TFP shock evolves according to a Markov process as $\ln a_t = \rho \ln a_{t-1} + \epsilon_t$. The symbol $\rho$ represents the persistence of the shock which is equal to 0.98 and $\epsilon_t$ is a normally distributed i.i.d shock with a mean of 0 and standard deviation, $\sigma$, of 0.0069 according to Rees (2013).

The production function is calibrated to be $f(k) = k^\alpha$ where $0 < \alpha < 1$ shows the output elasticity of capital. Calibrating to Rees (2013) and Gomez-Gonzalez and Rees (2013), $\alpha = 0.33$. The damage function $d(x_t)$ is set to be a quadratic function: $d(x_t) = d_0 + d_1 x_t + d_2 x_t^2$. This function is calibrated using the DICE and RICE models and leads us to obtain $d_0 = -0.0011$, $d_1 = -5.6629 \times 10^{-6}$ and $d_2 = 1.2261 \times 10^{-8}$. The calibration of the damage function is explained in detail in the next section. Table 5.1 summarises all the parameters explained above.

### 5.3. Damage Function Calibration

In order to calibrate the environmental damage function due to pollution the current research uses from Dynamic Integrated model of Climate and the Economy (DICE) to specify the damage function. While the DICE model provides a large, complicated environmental-economic model, this thesis simplifies the relationships between environmental variables to a quadratic damage function. To this end the DICE model is first explained and then a simplification process is presented. In both the DICE and RICE models the climate change damage function is specified in terms of output lost due to global warming. In the DICE model, Nordhaus (2008) specifies three reservoirs for the carbon cycle: carbon in the atmosphere $M_{AT}(t)$, in the upper oceans $M_{UP}(t)$ and in the deep oceans $M_{LO}(t)$. Carbon can flow between these adjacent reservoirs.
Nordhaus (2008) specifies the relationships between these three reservoirs as follows:

\[ M_{AT}(t) = E(t) + \varphi_{11}M_{AT}(t-1) + \varphi_{21}M_{UP}(t-1) \]  
\[ (5-5) \]

\[ M_{UP}(t) = \varphi_{12}M_{AT}(t-1) + \varphi_{22}M_{UP}(t-1) + \varphi_{32}M_{LO}(t-1) \]  
\[ (5-6) \]

\[ M_{LO}(t) = \varphi_{23}M_{UP}(t-1) + \varphi_{33}M_{LO}(t-1) \]  
\[ (5-7) \]

where \( E(t) \) represents the emissions produced in period \( t \) and \( \varphi_{ij} \) are the parameters between the reservoirs. Then the relationships between the reservoirs, or the accumulation of carbon, and the resulting climate change are specified. The accumulation of GHGs increases radiative forcing\(^{20}\) which leads to warming of the earth’s surface.

\[ F(t) = \eta \log_{2} \left[ \frac{M_{AT}(t)}{M_{AT}(1750)} \right] + F_{EX}(t) \]  
\[ (5-8) \]

where \( F(t) \) represents the change in total radiative forcing of GHGs since 1750 (which is taken to be the beginning of the industrial period) from anthropogenic sources such as carbon dioxide. \( F_{EX}(t) \) is the exogenous forcing from other long-lived greenhouse gases. The radiative forcing warms the atmosphere, which in turn warms the upper ocean layers and then, gradually, the deep oceans.

\[ T_{AT}(t) = T_{AT}(t-1) + \xi_{1}[F(t) - \xi_{2}T_{AT}(t-1) - \xi_{3}[T_{AT}(t-1) - T_{LO}(t-1)]] \]  
\[ (5-9) \]

\[ T_{LO}(t) = T_{LO}(t-1) + \xi_{4}[T_{AT}(t-1) - T_{LO}(t-1)] \]  
\[ (5-10) \]

---

\(^{20}\) Radiative forcing represents the perturbation in the radiative energy of the climate system which results in changes in the climate parameters and leads to a new equilibrium state of the climate system (IPCC, 1990; 1992; 1994).
$T_{AT}(t)$ and $T_{LO}(t)$ are respectively the mean surface temperature and the temperature of deep oceans. Finally, the economic impact of climate change or damage, $\Omega$, arises from the mean surface temperature.

$$\Omega(t) = \psi_1 T_{AT}(t) + \left[ \psi_2 T_{AT}(t) \right]^2$$  \hspace{1cm} (5-11)

As Nordhaus (2008) explains, this damage function is estimated for a temperature increase in the range of 0-3°C which is related to the pollution stock being equal to between 600 and 1200 Giga tons of carbon (GtC). Nordhaus (2008) explained that the damage function cannot be calculated for warming above 3°C as there is little evidence available about the impacts of warming of this magnitude.

Equations (5-5) to (5-11) represent carbon dioxide contributions to global warming damage. In order to obtain the damage as a direct function of the stock of pollution, this research summarises the above relationships. To this end the DICE (2008) equations of radiative forcing, the atmospheric temperatures, ocean temperatures and damage function, Equations (5-8), (5-9), (5-10) and (5-11) respectively, are used to find the damage caused by the pollution stock when the pollution stock is between 600 and 1200 GtC. Finally, in order to calibrate the parameters $\psi_1$ and $\psi_2$ to Australia, this research uses RICE–2010 in which the damage coefficients are $\psi_1=0$ and $\psi_2=0.1564$.

Plotting such a damage function over the carbon mass of 600 to 1200 GtC leads to obtaining the relationship between the damage function and the carbon mass as presented in Figure 5.1. As the figure shows, it is assumed that there is a quadratic relationship between the carbon mass and output such as that given by $d(x_i) = d_0 + d_1x_i + d_2x_i^2$. This leads to obtaining $d_0=-0.0011$, $d_1=5.6629\times10^{-6}$ and $d_2=1.2261\times10^{-8}$. These parameters represent the fraction of
output lost due to a 1GtC increase in the stock of pollution which can be interpreted as the effects of pollution on the Australian economy.

Figure 5.1: Economic damage from the stock of pollution in Australia

![Graph showing the relationship between percentage of output lost and global carbon mass.]

Source: configured by the author and inspired by Nordhaus (2008), Nordhaus (2010) and Heutel (2012)

The equations specified in this section and Section 5.2 are substituted into the model under different scenarios in the next section.

5.4. Calibrating the Model under Different Scenarios

This section calibrates the model under the four emissions reduction scenarios specified in Chapter 4 to the functions and parameters described in the above sections. The model was
summarised in Table 4.2. As the table shows, some equations, including production, capital, pollution accumulation and technology are assumed to be the same for the four scenarios while others, such as the firm’s resource constraints and its choice over capital and abatement as well as the household’s budget constraint and choice of investment, are different as result of different emissions reduction programs. In this section the calibrated relationships specified in Section 5.2 are substituted into the model. The calibrated model based upon these relationships is presented in Table 5.2.

The model is now ready for policy analysis. However, as explained in Section 5.1 in relation to the fifth step of DSGE modelling, the model first needs to be log-linearised around the new steady state. The next section presents the log-linearised version of the model.

5.5. Log-Linearising the Model under Different Scenarios

As the calibrated model in Table 5.2 shows the model consists of several complex nonlinear equations, representing production, emissions, abatement cost and the government’s choice of tax or subsidy which makes the model too complex to enable an analytical solution. Instead, a numerical approximation of the model can be made. To this end, the log-linearisation method is broadly applied in DSGE models (Fischer and Springborn, 2011; Heutel, 2012; Angelopoulos et al., 2013; Iiboshi et al., 2015) in which the model is linearised in the neighbourhood of the non-stochastic steady state values of variables. Thus, it is a local approximation method in which the approximation point is the steady state value which implies that, first, the steady state values should be found. The steady state points are the long-term non-stochastic values of variables. In order to meet the non-stochastic condition, the random variable in the model of this research \( \varepsilon_t \), is set to be equal to 0 and \( a_t \) is set to be equal to its expected value of 1. The steady state of a variable \( \bar{v} \) is the value that does not change over time. That is, \( v_t = v_{t+1} \).
Table 5.2: Calibrated systems of equations describing the economy under a business-as-usual, a fixed and a variable emissions tax and an abatement subsidy scenario

<table>
<thead>
<tr>
<th>Function</th>
<th>BAU</th>
<th>Fixed Emissions Tax</th>
<th>Variable Emissions Tax</th>
<th>Abatement Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production</strong></td>
<td>$y_i = \left(1 - d_{10} - d_{11} - d_{12}\right) \cdot k_{i, t}$</td>
<td>$y_i = \left(1 - d_{10} - d_{11} - d_{12}\right) \cdot k_{i, t}$</td>
<td>$y_i = \left(1 - d_{10} - d_{11} - d_{12}\right) \cdot k_{i, t}$</td>
<td>$y_i = \left(1 - d_{10} - d_{11} - d_{12}\right) \cdot k_{i, t}$</td>
</tr>
<tr>
<td><strong>Pollution stock</strong></td>
<td>$x_i = n \cdot p_{x_{i-1}} + m_i + m_{i}^{\text{new}}$</td>
<td>$x_i = n \cdot p_{x_{i-1}} + m_i + m_{i}^{\text{new}}$</td>
<td>$x_i = n \cdot p_{x_{i-1}} + m_i + m_{i}^{\text{new}}$</td>
<td>$x_i = n \cdot p_{x_{i-1}} + m_i + m_{i}^{\text{new}}$</td>
</tr>
<tr>
<td><strong>Capital accumulation</strong></td>
<td>$k_i = (1 - \delta) \cdot k_{i-1} + i_i$</td>
<td>$k_i = (1 - \delta) \cdot k_{i-1} + i_i$</td>
<td>$k_i = (1 - \delta) \cdot k_{i-1} + i_i$</td>
<td>$k_i = (1 - \delta) \cdot k_{i-1} + i_i$</td>
</tr>
<tr>
<td><strong>TFP</strong></td>
<td>$\ln a_i = \rho \ln a_{i-1} + \varepsilon_i$</td>
<td>$\ln a_i = \rho \ln a_{i-1} + \varepsilon_i$</td>
<td>$\ln a_i = \rho \ln a_{i-1} + \varepsilon_i$</td>
<td>$\ln a_i = \rho \ln a_{i-1} + \varepsilon_i$</td>
</tr>
<tr>
<td><strong>Household’s budget constraint</strong></td>
<td>$\pi_i + r \cdot k_{i-1} = c_i + i_i$</td>
<td>$\pi_i + r \cdot k_{i-1} + p^* \cdot m_i = c_i + i_i$</td>
<td>$\pi_i + r \cdot k_{i-1} + p^* \cdot m_i = c_i + i_i$</td>
<td>$\pi_i + r \cdot k_{i-1} = c_i + i_i$</td>
</tr>
<tr>
<td><strong>Household’s choice of investment</strong></td>
<td>$-c_i^* + \beta E_c e_{i+1}^*$</td>
<td>$-c_i^* + \beta E_c e_{i+1}^*$</td>
<td>$-c_i^* + \beta E_c e_{i+1}^*$</td>
<td>$-c_i^* + \beta E_c e_{i+1}^*$</td>
</tr>
<tr>
<td><strong>Firm’s resource constraint</strong></td>
<td>$\pi_i = y_i - r k_{i-1}$</td>
<td>$\pi_i = y_i - r k_{i-1} - p^* \cdot m_i - z_i$</td>
<td>$\pi_i = y_i - r k_{i-1} - p^* \cdot m_i$</td>
<td>$\pi_i = y_i + s^* \cdot k_{i-1} - z_i$</td>
</tr>
<tr>
<td>Function</td>
<td>BAU</td>
<td>Fixed Emissions Tax</td>
<td>Variable Emissions Tax</td>
<td>Abatement Subsidy</td>
</tr>
<tr>
<td>--------------------------</td>
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</tr>
<tr>
<td>Firm’s choice of capital</td>
<td>( r_i = \alpha y_i k_i^{-\gamma} )</td>
<td>( r_i = \alpha y_i k_i^{-\gamma} (1 - p_i (1 - \mu_i)) )</td>
<td>( r_i = \alpha y_i k_i^{-\gamma} (1 - p_i (1 - \mu_i) (1 - \gamma) y_i^{-\gamma} - \theta_i \mu_i^\theta) )</td>
<td>( r_i = \alpha y_i k_i^{-\gamma} (1 - \theta_i \mu_i^\theta) )</td>
</tr>
<tr>
<td>Firm’s choice of abatement</td>
<td>0</td>
<td>( p_i y_i^{-\gamma} = \theta_i \theta_i \mu_i^\theta) )</td>
<td>( p_i y_i^{-\gamma} = \theta_i \theta_i \mu_i^\theta) )</td>
<td>( s_i = \theta_i \theta_i \mu_i^\theta y_i )</td>
</tr>
<tr>
<td>Emissions</td>
<td>( m_i = y_i^{-\gamma} )</td>
<td>( m_i = (1 - \mu_i) y_i^{-\gamma} )</td>
<td>( m_i = (1 - \mu_i) y_i^{-\gamma} )</td>
<td>( m_i = (1 - \mu_i) y_i^{-\gamma} )</td>
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<tr>
<td>Abatement cost</td>
<td>0</td>
<td>( z_i = \theta_i \mu_i^\theta y_i )</td>
<td>( z_i = \theta_i \mu_i^\theta y_i )</td>
<td>( z_i = \theta_i \mu_i^\theta y_i )</td>
</tr>
<tr>
<td>Government’s choice of tax/subsidy</td>
<td></td>
<td>( -c_i^{-\gamma} \frac{\theta_i}{\theta_i - 1} p_i + \zeta_i c_i^{-\gamma} \frac{\theta_i}{\theta_i - 1} p_i )</td>
<td>( -c_i^{-\gamma} \frac{\theta_i}{\theta_i - 1} p_i + \zeta_i c_i^{-\gamma} \frac{\theta_i}{\theta_i - 1} p_i )</td>
<td>( -c_i^{-\gamma} \frac{\theta_i}{\theta_i - 1} p_i + \zeta_i c_i^{-\gamma} \frac{\theta_i}{\theta_i - 1} p_i )</td>
</tr>
<tr>
<td>Government’s choice of capital</td>
<td></td>
<td>( + \lambda_i [-\zeta_i c_i^{-\gamma} \frac{\theta_i}{\theta_i - 1} p_i + \alpha (1 - \gamma) y_i^{-\gamma} k_{i-1}^{-\gamma}] )</td>
<td>( + \lambda_i [-\zeta_i c_i^{-\gamma} \frac{\theta_i}{\theta_i - 1} p_i + \alpha (1 - \gamma) y_i^{-\gamma} k_{i-1}^{-\gamma}] )</td>
<td>( + \lambda_i [-\zeta_i c_i^{-\gamma} \frac{\theta_i}{\theta_i - 1} p_i + \alpha (1 - \gamma) y_i^{-\gamma} k_{i-1}^{-\gamma}] )</td>
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\( \xi_i \frac{\mu_i y_i^{-\gamma}}{p_i} = 0 \)

\( \xi_i \frac{\mu_i y_i^{-\gamma}}{p_i} = 0 \)

\( \xi_i \frac{\mu_i y_i^{-\gamma}}{p_i} = 0 \)

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\( \xi_i \frac{\mu_i y_i^{-\gamma}}{p_i} = 0 \)
<table>
<thead>
<tr>
<th>Function</th>
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<th>Variable Emissions Tax</th>
<th>Abatement Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government’s choice of output</td>
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<td></td>
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<td></td>
<td></td>
<td>( c_i^{-\gamma} (1 - \frac{(1 - \gamma) \theta_2 - 1}{\theta_2 - 1} \frac{z_i}{y_i}) + \lambda_i [\xi_i c_i^{-\gamma}] )</td>
<td>( (1 - \frac{(1 - \gamma) \theta_2 - 1}{\theta_2 - 1} \frac{z_i}{y_i}) + \lambda_i [-\xi_i c_i^{-\gamma}] )</td>
<td>( c_i^{-\gamma} (1 + \frac{1}{\theta_2 - 1} \frac{z_i}{y_i}) + \lambda_i [\xi_i c_i^{-\gamma}] )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( (1 - \frac{(1 - \gamma) \theta_2 - 1}{\theta_2 - 1} \frac{z_i}{y_i}) ) ( r_{i+1} + 1 - \delta )</td>
<td>( (1 - \frac{(1 - \gamma) \theta_2 - 1}{\theta_2 - 1} \frac{z_i}{y_i}) ) ( r_{i+1} + 1 - \delta )</td>
<td>( (1 + \frac{1}{\theta_2 - 1} \frac{z_i}{y_i}) ) ( r_{i+1} + 1 - \delta )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( c_i^{-\gamma} \left[ ak_{i-1}^{-\gamma} - \alpha (1 - \gamma)^2 p_i, y_i k_{i-1}^{-\gamma} + \alpha (1 - \gamma) (1 - \gamma - \frac{\gamma}{\theta_2 - 1}) p_i y_i k_{i-1}^{-\gamma} \right] )</td>
<td>( c_i^{-\gamma} \left[ ak_{i-1}^{-\gamma} - \alpha (1 - \gamma)^2 p_i, y_i k_{i-1}^{-\gamma} + \alpha (1 - \gamma) (1 - \gamma - \frac{\gamma}{\theta_2 - 1}) p_i y_i k_{i-1}^{-\gamma} \right] )</td>
<td>( c_i^{-\gamma} \left[ ak_{i-1}^{-\gamma} - \alpha \theta_2 (1 - \gamma) k_{i-1}^{-\gamma} \mu_i \right] )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( - \alpha \theta_2 (1 - \gamma) k_{i-1}^{-\gamma} \mu_i ) ] ( - \xi_i y_i^{-\gamma} ) [ ( 1 - \gamma - (\frac{\gamma}{\theta_2 - 1} + \gamma - 1) \mu_i ]</td>
<td>( - \xi_i y_i^{-\gamma} ) [ ( 1 - \gamma - (\frac{\gamma}{\theta_2 - 1} + \gamma - 1) \mu_i ]</td>
<td>( - \xi_i y_i^{-\gamma} ) [ ( 1 - \gamma - (\frac{\gamma}{\theta_2 - 1} + \gamma - 1) \mu_i ]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( [1 - \gamma - (\frac{\gamma}{\theta_2 - 1} + \gamma - 1) \mu_i ] + ( \omega_\mu = 0 )</td>
<td>( \omega_\mu = 0 )</td>
<td>( \omega_\mu = 0 )</td>
</tr>
<tr>
<td>Government’s choice of pollution stock</td>
<td>( \xi_i - \beta \xi_{i-1} \eta + \omega_\eta \alpha k_{i-1}^{\eta} (d_i + 2d_j x_j) = 0 )</td>
<td>( \xi_i - \beta \xi_{i-1} \eta + \omega_\eta \alpha k_{i-1}^{\eta} (d_i + 2d_j x_j) = 0 )</td>
<td>( \xi_i - \beta \xi_{i-1} \eta + \omega_\eta \alpha k_{i-1}^{\eta} (d_i + 2d_j x_j) = 0 )</td>
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</tbody>
</table>

Source: Compiled by the author.
Additionally, as explained in Section 5.1, this research provides a contribution to the calibration approach provided by Heutel (2012) by assuming that the variable for emissions from the rest of the world, $m_{t \text{row}}$, is exogenous and is not affected by Australian emissions reduction policies. Instead of making this assumption the current research calculates $m_{t \text{row}}$ under the BAU scenario first and then this calculated value is used as a constant for all the other emissions reduction policies. In order to calculate $m_{t \text{row}}$ under the BAU scenario, the current research collects the global and Australian carbon dioxide equivalent emissions data from the Carbon Dioxide Information Analysis Centre (CDIAC) over the period 1950–2010. This period is before the implementation of a carbon pricing policy in Australia began in 2012, and is, therefore suitable for the BAU scenario. The data reveals that emissions from the rest of the world are about 30 times greater than Australia’s. Thus, the rest of the world’s emissions are set as equal to 30 times the steady state value of $m$: $\omega \bar{m}$ where $\omega$ is equal to 30. This value is calculated and used as a constant under all the emissions reduction policies. Thus, $m_{t \text{row}}$ under all scenarios, including emissions reduction policies and BAU, is the same.

The steady state of variables $v$ is given by $\bar{v}$, and the steady state equations of the model are presented in Table 5.4. After finding the steady state values of the variables the model can then be log-linearised around those non-stochastic steady state values to show how different variables will react to a shock. This can be done by displaying the deviations of variables from their steady state points when a shock occurs. The log-linearisation approach is explained in detail in Appendix 5.A.2. Using $\tilde{v}$ to show the proportional deviation from the steady state of variable $v$, the model can be log-linearised as shown in Table 5.5. To reduce clutter the expectation operator is suppressed in the log-linearisation model, but the expected value of that variable in period $t+1$ is taken into account.
Table 5.3: Steady state of the system of equations describing the economy under the business-as-usual, fixed emissions tax, variable emissions tax and abatement subsidy scenarios

<table>
<thead>
<tr>
<th>Function</th>
<th>BAU</th>
<th>Fixed Emissions Tax</th>
<th>Variable Emissions Tax</th>
<th>Abatement Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Production</strong></td>
<td>$\bar{y} = (1 - d_0 - d_1 \bar{x} - d_2 \bar{x}^2) \bar{y}^\alpha$</td>
<td>$\bar{y} = (1 - d_0 - d_1 \bar{x} - d_2 \bar{x}^2) \bar{y}^\alpha$</td>
<td>$\bar{y} = (1 - d_0 - d_1 \bar{x} - d_2 \bar{x}^2) \bar{y}^\alpha$</td>
<td>$\bar{y} = (1 - d_0 - d_1 \bar{x} - d_2 \bar{x}^2) \bar{y}^\alpha$</td>
</tr>
<tr>
<td><strong>Pollution stock</strong></td>
<td>$\bar{x}(1 - \eta) = \bar{m} + \omega \bar{m}$</td>
<td>$\bar{x}(1 - \eta) = \bar{m} + \bar{m}^{cov}$</td>
<td>$\bar{x}(1 - \eta) = \bar{m} + \bar{m}^{cov}$</td>
<td>$\bar{x}(1 - \eta) = \bar{m} + \bar{m}^{cov}$</td>
</tr>
<tr>
<td><strong>Capital accumulation</strong></td>
<td>$\delta \bar{k} = \bar{i}$</td>
<td>$\delta \bar{k} = \bar{i}$</td>
<td>$\delta \bar{k} = \bar{i}$</td>
<td>$\delta \bar{k} = \bar{i}$</td>
</tr>
<tr>
<td><strong>Household’s budget constraint</strong></td>
<td>$\pi + \bar{r} \bar{k} = \bar{c} + \bar{i}$</td>
<td>$\pi + \bar{r} \bar{k} + \bar{p} \bar{m} = \bar{c} + \bar{i}$</td>
<td>$\pi + \bar{r} \bar{k} + \bar{p} \bar{m} = \bar{c} + \bar{i}$</td>
<td>$\pi + \bar{r} \bar{k} - \bar{s} \bar{m} = \bar{c} + \bar{i}$</td>
</tr>
<tr>
<td><strong>Household’s choice of investment</strong></td>
<td>$-1 + \beta (\pi + (1 - \delta)] = 0$</td>
<td>$-1 + \beta (\pi + (1 - \delta)] = 0$</td>
<td>$-1 + \beta (\pi + (1 - \delta)] = 0$</td>
<td>$-1 + \beta (\pi + (1 - \delta)] = 0$</td>
</tr>
<tr>
<td><strong>Firm’s resource constraint</strong></td>
<td>$\pi = \bar{y} - \bar{r} \bar{k}$</td>
<td>$\pi = \bar{y} - \bar{r} \bar{k} - \bar{p} \bar{m} - \bar{z}$</td>
<td>$\pi = \bar{y} - \bar{r} \bar{k} - \bar{p} \bar{m} - \bar{z}$</td>
<td>$\pi = \bar{y} + \bar{s} \bar{m} - \bar{r} \bar{k} - \bar{z}$</td>
</tr>
<tr>
<td><strong>Firm’s choice of capital</strong></td>
<td>$\bar{r} = \alpha \bar{y} \bar{k}^{-1}$</td>
<td>$\bar{r} = \alpha \bar{y} \bar{k}[1 - \bar{p} (1 - \bar{m})]$</td>
<td>$\bar{r} = \alpha \bar{y} \bar{k}[1 - \bar{p} (1 - \bar{m})]$</td>
<td>$\bar{r} = \alpha \bar{y} \bar{k}[1 - \bar{p} (1 - \bar{m})]$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$(1 - \gamma) \bar{y}^{-\gamma} - \theta \bar{m}^{\theta}$</td>
<td>$(1 - \gamma) \bar{y}^{-\gamma} - \theta \bar{m}^{\theta}$</td>
<td>$(1 - \gamma) \bar{y}^{-\gamma} - \theta \bar{m}^{\theta}$</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Function</th>
<th>BAU</th>
<th>Fixed Emissions Tax</th>
<th>Variable Emissions Tax</th>
<th>Abatement Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firm’s choice of abatement</td>
<td>0</td>
<td>( p \bar{y}^{−}\gamma = \theta_1 \theta_2 \bar{y}^{−\gamma} )</td>
<td>( \bar{p} \bar{y}^{−}\gamma = \theta_1 \theta_2 \bar{y}^{−\gamma} )</td>
<td>( s_i = \theta_1 \theta_2 \mu_i^{\alpha + 1} y_i )</td>
</tr>
<tr>
<td>Emissions</td>
<td>( \bar{m} = \bar{y}^{−}\gamma )</td>
<td>( \bar{m} = (1 - \bar{p}) \bar{y}^{−}\gamma )</td>
<td>( \bar{m} = (1 - \bar{p}) \bar{y}^{−}\gamma )</td>
<td>( \bar{m} = (1 - \bar{p}) \bar{y}^{−}\gamma )</td>
</tr>
<tr>
<td>Abatement cost</td>
<td>0</td>
<td>( \bar{z} = \theta_1 \bar{y}^{\theta} )</td>
<td>( \bar{z} = \theta_1 \bar{y}^{\theta} )</td>
<td>( \bar{z} = \theta_1 \bar{y}^{\theta} )</td>
</tr>
<tr>
<td>Government’s choice of tax/</td>
<td></td>
<td>( -\zeta^{-\gamma} \frac{\theta_2}{\theta_2 - 1} \bar{z} - \zeta_0 \bar{z}^{\gamma - 1} - \frac{\theta_2}{\theta_2 - 1} \bar{y}^{\gamma - 1} (F - \delta) )</td>
<td>( -\zeta^{-\gamma} \frac{\theta_2}{\theta_2 - 1} \bar{z} - \zeta_0 \bar{z}^{\gamma - 1} - \frac{\theta_2}{\theta_2 - 1} \bar{y}^{\gamma - 1} (F - \delta) )</td>
<td>( -\zeta^{-\gamma} \frac{\theta_2}{\theta_2 - 1} \bar{z} - \zeta_0 \bar{z}^{\gamma - 1} - \frac{\theta_2}{\theta_2 - 1} \bar{y}^{\gamma - 1} (F - \delta) )</td>
</tr>
<tr>
<td>subsidy</td>
<td></td>
<td>( + \lambda \bar{z}^{\gamma - 1} \left[-\alpha(1 - \gamma) \bar{y}^{\gamma - 1} - \alpha(1 - \gamma)(1 + \frac{1}{\theta_2 - 1}) \right] )</td>
<td>( + \lambda \bar{z}^{\gamma - 1} \left[-\alpha(1 - \gamma) \bar{y}^{\gamma - 1} - \alpha(1 - \gamma)(1 + \frac{1}{\theta_2 - 1}) \right] )</td>
<td>( + \lambda \bar{z}^{\gamma - 1} \left[-\alpha(1 - \gamma) \bar{y}^{\gamma - 1} - \alpha(1 - \gamma)(1 + \frac{1}{\theta_2 - 1}) \right] )</td>
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<td>( + \frac{\bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1}}{\theta_2 - 1} - \alpha \frac{\theta_2}{\theta_2 - 1} \bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1} )</td>
<td>( + \frac{\bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1}}{\theta_2 - 1} - \alpha \frac{\theta_2}{\theta_2 - 1} \bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1} )</td>
<td>( + \frac{\bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1}}{\theta_2 - 1} - \alpha \frac{\theta_2}{\theta_2 - 1} \bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1} )</td>
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<td>( + \frac{1}{\theta_2 - 1} \bar{y}^{\gamma - 1} \bar{p} = 0 )</td>
<td>( + \frac{1}{\theta_2 - 1} \bar{y}^{\gamma - 1} \bar{p} = 0 )</td>
<td>( + \frac{1}{\theta_2 - 1} \bar{y}^{\gamma - 1} \bar{p} = 0 )</td>
</tr>
<tr>
<td>Government’s choice of capital</td>
<td></td>
<td>( \bar{z}^{-\gamma} + (-1 + \beta(1 - \delta)) \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
<td>( \bar{z}^{-\gamma} + (-1 + \beta(1 - \delta)) \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
<td>( \bar{z}^{-\gamma} + (-1 + \beta(1 - \delta)) \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
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<td>( - \beta(1 - \delta) \left(F - \delta \right) \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
<td>( - \beta(1 - \delta) \left(F - \delta \right) \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
<td>( - \beta(1 - \delta) \left(F - \delta \right) \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
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<td>( + \alpha(1 - \gamma) \bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1} ) ( \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
<td>( + \alpha(1 - \gamma) \bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1} ) ( \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
<td>( + \alpha(1 - \gamma) \bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1} ) ( \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
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<td>( + \alpha \left[\bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1} \mu^{\theta_2} \right] \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
<td>( + \alpha \left[\bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1} \mu^{\theta_2} \right] \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
<td>( + \alpha \left[\bar{y}^{\gamma - 1} \bar{k}^{\gamma - 1} \mu^{\theta_2} \right] \lambda \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
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<td>( + \bar{y}^{\gamma - 1} \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
<td>( + \bar{y}^{\gamma - 1} \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
<td>( + \bar{y}^{\gamma - 1} \bar{z}^{\gamma - 1} \left[-1 + \beta(1 - \delta) \lambda \bar{z}^{\gamma - 1} \right] )</td>
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<td>( - \beta \bar{y} \bar{k}^{\gamma - 1} \alpha \bar{k}^{\gamma - 1} = 0 )</td>
<td>( - \beta \bar{y} \bar{k}^{\gamma - 1} \alpha \bar{k}^{\gamma - 1} = 0 )</td>
<td>( - \beta \bar{y} \bar{k}^{\gamma - 1} \alpha \bar{k}^{\gamma - 1} = 0 )</td>
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</tr>
<tr>
<td>Government’s choice of output</td>
<td></td>
<td>$\bar{c}^{\gamma} (1 - (1 - \gamma)\theta_2 - 1 - \frac{\pi}{\bar{y}}) + \bar{\lambda} \zeta \bar{c}^{\gamma - 1}$</td>
<td>$(1 - (1 - \gamma)\theta_2 - 1 - \frac{\pi}{\bar{y}})(\bar{r} - \delta)$</td>
<td>$\bar{c}^{\gamma} (1 + \frac{1}{\theta_2 - 1 - \frac{\pi}{\bar{y}}}) - \bar{\lambda} \zeta \bar{c}^{\gamma - 1}$ $(1 + \frac{1}{\theta_2 - 1 - \frac{\pi}{\bar{y}}})(r - \delta)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$(1 - (1 - \gamma)\theta_2 - 1 - \frac{\pi}{\bar{y}})[(\bar{r} - \delta)] + \bar{\lambda} \zeta \bar{c}^{\gamma - 1} [ \alpha k^{\gamma - 1} - \alpha (1 - \gamma)^2 \bar{p}_y k^{\gamma - 1} ]$</td>
<td>$+ \bar{\lambda} \zeta \bar{c}^{\gamma - 1} [ \alpha k^{\gamma - 1} - \alpha \theta_j (1 - \frac{\theta_j}{\theta_2 - 1}) k^{\gamma - 1} \bar{p}^\gamma ]$</td>
<td>$- \bar{\lambda} \zeta \bar{c}^{\gamma - 1} (1 - \gamma - (\frac{1}{\theta_2 - 1}) + \gamma - 1) \bar{p}$ $+ \bar{\omega} = 0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ \alpha (1 - \gamma) (1 - \gamma - \frac{\gamma}{\theta_2 - 1}) \bar{p}_y \bar{k}^{\gamma - 1} \bar{p}$</td>
<td>$- \bar{\lambda} \zeta \bar{c}^{\gamma - 1} (1 - \gamma - (\frac{1}{\theta_2 - 1}) + \gamma - 1) \bar{p}$</td>
<td>$+ \bar{\omega} = 0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$- \alpha \theta_j (1 - \frac{\gamma \theta_j}{\theta_2 - 1}) \bar{k}^{\gamma - 1} \bar{p}^\gamma ] - \bar{\zeta} \bar{y}^{\gamma - 1}$</td>
<td>$+ \bar{\omega} = 0$</td>
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<td></td>
<td></td>
<td>$[1 - \gamma - (\frac{\gamma}{\theta_2 - 1} + \gamma - 1) \bar{p}] + \bar{\omega} = 0$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Government’s choice of pollution stock</td>
<td>$\xi (1 - \beta \eta) + \bar{\omega} k^{\alpha} (d_1 + 2 d_2, \bar{x}) = 0$</td>
<td>$\xi (1 - \beta \eta) + \bar{\omega} k^{\alpha} (d_1 + 2 d_2, \bar{x}) = 0$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Compiled by the author.
Table 5.4: Log-linearised system of equations describing the economy under the business-as-usual, fixed emissions tax, variable emissions tax and abatement subsidy scenarios

<table>
<thead>
<tr>
<th>Function</th>
<th>BAU</th>
<th>Fixed Emissions Tax</th>
<th>Variable Emissions Tax</th>
<th>Abatement Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>( \tilde{y}_i - \tilde{a}<em>i - \alpha \tilde{k}</em>{i-1} )</td>
<td>( \tilde{y}_i - \tilde{a}<em>i - \alpha \tilde{k}</em>{i-1} )</td>
<td>( \tilde{y}_i - \tilde{a}<em>i - \alpha \tilde{k}</em>{i-1} )</td>
<td>( \tilde{y}_i - \tilde{a}<em>i - \alpha \tilde{k}</em>{i-1} )</td>
</tr>
<tr>
<td></td>
<td>( + (d_i + 2d_j) \frac{\pi \tilde{x}}{\tilde{y}} \tilde{x}_i = 0 )</td>
<td>( + (d_i + 2d_j) \frac{\pi \tilde{x}}{\tilde{y}} \tilde{x}_i = 0 )</td>
<td>( + (d_i + 2d_j) \frac{\pi \tilde{x}}{\tilde{y}} \tilde{x}_i = 0 )</td>
<td>( + (d_i + 2d_j) \frac{\pi \tilde{x}}{\tilde{y}} \tilde{x}_i = 0 )</td>
</tr>
<tr>
<td>Pollution stock</td>
<td>( \tilde{x}<em>i - \eta \tilde{x}</em>{i-1} - (1 - \eta) \tilde{m}_i = 0 )</td>
<td>( \tilde{x}<em>i - \eta \tilde{x}</em>{i-1} - (1 - \eta) \tilde{m}_i = 0 )</td>
<td>( \tilde{x}<em>i - \eta \tilde{x}</em>{i-1} - (1 - \eta) \tilde{m}_i = 0 )</td>
<td>( \tilde{x}<em>i - \eta \tilde{x}</em>{i-1} - (1 - \eta) \tilde{m}_i = 0 )</td>
</tr>
<tr>
<td></td>
<td>( - (1 - \eta - \frac{\eta \pi \tilde{m}}{\tilde{x}} ) \tilde{m}_i = 0 )</td>
<td>( - (1 - \eta - \frac{\eta \pi \tilde{m}}{\tilde{x}} ) \tilde{m}_i = 0 )</td>
<td>( - (1 - \eta - \frac{\eta \pi \tilde{m}}{\tilde{x}} ) \tilde{m}_i = 0 )</td>
<td>( - (1 - \eta - \frac{\eta \pi \tilde{m}}{\tilde{x}} ) \tilde{m}_i = 0 )</td>
</tr>
<tr>
<td>Capital accumulation</td>
<td>( \tilde{k}<em>i - (1 - \delta) \tilde{k}</em>{i-1} - \tilde{i}_i = 0 )</td>
<td>( \tilde{k}<em>i - (1 - \delta) \tilde{k}</em>{i-1} - \tilde{i}_i = 0 )</td>
<td>( \tilde{k}<em>i - (1 - \delta) \tilde{k}</em>{i-1} - \tilde{i}_i = 0 )</td>
<td>( \tilde{k}<em>i - (1 - \delta) \tilde{k}</em>{i-1} - \tilde{i}_i = 0 )</td>
</tr>
<tr>
<td>TFP</td>
<td>( \tilde{a}<em>i - \rho \tilde{a}</em>{i-1} - \tilde{e}_i = 0 )</td>
<td>( \tilde{a}<em>i - \rho \tilde{a}</em>{i-1} - \tilde{e}_i = 0 )</td>
<td>( \tilde{a}<em>i - \rho \tilde{a}</em>{i-1} - \tilde{e}_i = 0 )</td>
<td>( \tilde{a}<em>i - \rho \tilde{a}</em>{i-1} - \tilde{e}_i = 0 )</td>
</tr>
<tr>
<td>Household’s budget constraint</td>
<td>( \pi \tilde{z}_i + r \tilde{k} (\tilde{r}<em>i + \tilde{k}</em>{i-1}) ) + ( p^m \tilde{m}_i - \tilde{c}_i - \tilde{i}_i = 0 )</td>
<td>( \pi \tilde{z}_i + r \tilde{k} (\tilde{r}<em>i + \tilde{k}</em>{i-1}) ) + ( p^m \tilde{m}_i - \tilde{c}_i - \tilde{i}_i = 0 )</td>
<td>( \pi \tilde{z}_i + r \tilde{k} (\tilde{r}<em>i + \tilde{k}</em>{i-1}) ) + ( p^m \tilde{m}_i - \tilde{c}_i - \tilde{i}_i = 0 )</td>
<td>( - s \pi (\tilde{z}_i + \tilde{\mu}_i) - \tilde{c}_i - \tilde{i}_i = 0 )</td>
</tr>
<tr>
<td>Household’s choice of investment</td>
<td>( \pi \tilde{z}_i - \beta \tilde{c}<em>i (\sigma + 1 - \delta) ) + ( \beta \pi \tilde{r}</em>{i-1} = 0 )</td>
<td>( \pi \tilde{z}_i - \beta \tilde{c}<em>i (\sigma + 1 - \delta) ) + ( \beta \pi \tilde{r}</em>{i-1} = 0 )</td>
<td>( \pi \tilde{z}_i - \beta \tilde{c}<em>i (\sigma + 1 - \delta) ) + ( \beta \pi \tilde{r}</em>{i-1} = 0 )</td>
<td>( \pi \tilde{z}_i - \beta \tilde{c}<em>i (\sigma + 1 - \delta) ) + ( \beta \pi \tilde{r}</em>{i-1} = 0 )</td>
</tr>
<tr>
<td>Firm’s resource constraint</td>
<td>( \pi \tilde{z}_i - \tilde{y} \tilde{y}_i ) + ( \pi \tilde{k} (\tilde{r}<em>i + \tilde{k}</em>{i-1}) + \tilde{y} \tilde{z}_i = 0 )</td>
<td>( \pi \tilde{z}_i - \tilde{y} \tilde{y}_i + \tilde{p}^m \tilde{m}_i + \pi \tilde{k} (\tilde{r}<em>i + \tilde{k}</em>{i-1}) + \tilde{z}_i = 0 )</td>
<td>( \pi \tilde{z}_i - \tilde{y} \tilde{y}_i + \tilde{p}^m (\tilde{\mu}_i + \tilde{m}_i) + \pi \tilde{k} (\tilde{r}<em>i + \tilde{k}</em>{i-1}) + \tilde{z}_i = 0 )</td>
<td>( \pi \tilde{z}_i - \tilde{y} \tilde{y}_i + \tilde{p}^m (\tilde{\mu}_i + \tilde{m}_i) + \pi \tilde{k} (\tilde{r}<em>i + \tilde{k}</em>{i-1}) + \tilde{z}_i = 0 )</td>
</tr>
<tr>
<td>Function</td>
<td>BAU</td>
<td>Fixed Emissions Tax</td>
<td>Variable Emissions Tax</td>
<td>Abatement Subsidy</td>
</tr>
<tr>
<td>--------------------------</td>
<td>------------------------------------------</td>
<td>-----------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>Firm’s choice of capital</td>
<td>$\vec{y}_t - \vec{y}<em>r + \vec{k}</em>{t-1} = 0$</td>
<td>$\vec{r}_t + \alpha \vec{y}_t \vec{k}^{-1} \left[ -1 + \vec{p} (1 - \vec{p}) (1 - \gamma)^2 \vec{y}_r - p (1 - \vec{p}) (1 - \gamma)^2 \vec{y}_r \right] + \alpha \vec{y}_t \vec{k}^{-1} \left[ -1 + \vec{p} (1 - \vec{p}) (1 - \gamma)^2 \vec{y}_r \right]$</td>
<td>$\vec{r}_t + \vec{y}_t \vec{k}^{-1} \left[ -1 + \vec{p} (1 - \vec{p}) (1 - \gamma)^2 \vec{y}_r - p (1 - \vec{p}) (1 - \gamma)^2 \vec{y}_r \right] + \alpha \vec{y}_t \vec{k}^{-1} \left[ -1 + \vec{p} (1 - \vec{p}) (1 - \gamma)^2 \vec{y}_r \right]$</td>
<td>$-\vec{r}_t + \alpha \vec{y}_t \vec{k}^{-1} \left( \vec{y}<em>t - \vec{k}</em>{t-1} \right)$</td>
</tr>
<tr>
<td>Firm’s choice of abatement</td>
<td>0</td>
<td>$\vec{y}_t + \left( \delta x - \gamma \right) \vec{y} = 0$</td>
<td>$\vec{y}_t - \left( \delta x - \gamma \right) \vec{y} = 0$</td>
<td>$\vec{y}_t - \left( \delta x - \gamma \right) \vec{y} = 0$</td>
</tr>
<tr>
<td>Emissions</td>
<td>$\vec{m}_t - \left( \gamma \right) \vec{y} = 0$</td>
<td>$\left( \gamma \right) \vec{y} \vec{k}^{-1} \left( \gamma \right) \vec{y} = 0$</td>
<td>$\left( \gamma \right) \vec{y} \vec{k}^{-1} \left( \gamma \right) \vec{y} = 0$</td>
<td>$\left( \gamma \right) \vec{y} \vec{k}^{-1} \left( \gamma \right) \vec{y} = 0$</td>
</tr>
<tr>
<td>Abatement cost</td>
<td>0</td>
<td>$\vec{z}_t - \left( \delta x \right) \vec{y} = 0$</td>
<td>$\vec{z}_t - \left( \delta x \right) \vec{y} = 0$</td>
<td>$\vec{z}_t - \left( \delta x \right) \vec{y} = 0$</td>
</tr>
<tr>
<td>Function</td>
<td>BAU</td>
<td>Fixed Emissions Tax</td>
<td>Variable Emissions Tax</td>
<td>Abatement Subsidy</td>
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<td>-------------------</td>
</tr>
<tr>
<td>Government’s choice of tax/subsidy</td>
<td></td>
<td></td>
<td>$-\pi^{-i} \frac{\partial}{\partial s} \frac{\pi}{\theta z-1} (-\zeta \tilde{c}_1 + \tilde{z}_i - \tilde{p}_i) - \zeta \tilde{c}^{-i} \tilde{c}$</td>
<td>$-\pi^{-i} \frac{\partial}{\partial s} \frac{\pi}{\theta z-1} (-\zeta \tilde{c}_1 + \tilde{z}_i - \tilde{p}_i) - \zeta \tilde{c}^{-i} \tilde{c}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\frac{\partial}{\partial s} \frac{\pi}{\theta z-1} (\tilde{c}_1 - (\zeta + 1)\tilde{c}_1 + \tilde{z}_i - \tilde{p}_i)$</td>
<td>$\frac{\partial}{\partial s} \frac{\pi}{\theta z-1} (\tilde{c}_1 - (\zeta + 1)\tilde{c}_1 + \tilde{z}_i - \tilde{p}_i)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$+ \lambda \zeta \tilde{c}^{-i} \frac{\partial}{\partial s} \frac{\pi}{\theta z-1} (\tilde{c}_1 - (\zeta + 1)\tilde{c}_1 + \tilde{z}_i - \tilde{p}_i)$</td>
<td>$+ \lambda \zeta \tilde{c}^{-i} \frac{\partial}{\partial s} \frac{\pi}{\theta z-1} (\tilde{c}_1 - (\zeta + 1)\tilde{c}_1 + \tilde{z}_i - \tilde{p}_i)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$+ \tilde{z}_i - \tilde{p}_i) + \lambda \zeta \tilde{c}^{-i} \frac{\partial}{\partial s} \frac{\pi}{\theta z-1} \tilde{c}_1$</td>
<td>$+ \tilde{z}_i - \tilde{p}_i) + \lambda \zeta \tilde{c}^{-i} \frac{\partial}{\partial s} \frac{\pi}{\theta z-1} \tilde{c}_1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$- \lambda \tilde{c}^{-i} \alpha(1-\gamma)\tilde{y}^{i} \tilde{c}_1 (\tilde{c}_1 - (\zeta + 1)\tilde{c}_1 + \tilde{z}_i - \tilde{p}_i); \tilde{y}<em>i - \tilde{k}</em>{i-1} - \tilde{s}_i$</td>
<td>$- \lambda \tilde{c}^{-i} \alpha(1-\gamma)\tilde{y}^{i} \tilde{c}_1 (\tilde{c}_1 - (\zeta + 1)\tilde{c}_1 + \tilde{z}_i - \tilde{p}_i); \tilde{y}<em>i - \tilde{k}</em>{i-1} - \tilde{s}_i$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$+ \tilde{y}<em>i - \tilde{k}</em>{i-1} - \tilde{s}_i$</td>
<td>$+ \tilde{y}<em>i - \tilde{k}</em>{i-1} - \tilde{s}_i$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$+ (1-\gamma)\tilde{y}_i - \tilde{p}_i) = 0</td>
<td>+ (1-\gamma)\tilde{y}_i - \tilde{p}_i) = 0</td>
</tr>
<tr>
<td>Function</td>
<td>BAU</td>
<td>Fixed Emissions Tax</td>
<td>Variable Emissions Tax</td>
<td>Abatement Subsidy</td>
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<td>------------------</td>
</tr>
<tr>
<td>Government’s choice of capital</td>
<td>$\bar{\tau}(\bar{\xi}) - \bar{\beta}(1 - \delta)(\bar{\xi})^{i-1} + \bar{\beta}(1 - \delta)(\bar{\xi})^{i-1}$</td>
<td>$\bar{\tau}(\bar{\xi}) - \bar{\beta}(1 - \delta)(\bar{\xi})^{i-1} + \bar{\beta}(1 - \delta)(\bar{\xi})^{i-1}$</td>
<td>$\bar{\tau}(\bar{\xi}) - \bar{\beta}(1 - \delta)(\bar{\xi})^{i-1} + \bar{\beta}(1 - \delta)(\bar{\xi})^{i-1}$</td>
<td>$\bar{\tau}(\bar{\xi}) - \bar{\beta}(1 - \delta)(\bar{\xi})^{i-1} + \bar{\beta}(1 - \delta)(\bar{\xi})^{i-1}$</td>
</tr>
</tbody>
</table>

160
<table>
<thead>
<tr>
<th>Function</th>
<th>BAU</th>
<th>Fixed Emissions Tax</th>
<th>Variable Emissions Tax</th>
<th>Abatement Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Government’s choice of output</td>
<td>$\pi^{0} (-\varphi) \left(\frac{1 - \gamma}{\theta_2 - 1}\right) + \frac{\pi}{\nu} (-\varphi + \zeta)$</td>
<td>$-\bar{y}_2 + \frac{\pi}{\nu} \psi^{1} (-\varphi - \bar{y}_2 - \bar{y}_3)$</td>
<td>$\frac{\pi}{\nu} \psi^{1} (-\bar{y}_2 - \bar{y}_3) - \frac{\pi}{\nu} \psi^{0} \psi^{1}$</td>
<td>$\frac{\pi}{\nu} \psi^{1} (-\bar{y}_2 - \bar{y}_3)$</td>
</tr>
<tr>
<td></td>
<td>$\frac{\pi}{\nu} \psi^{1} (-\bar{y}_2 - \bar{y}_3)$</td>
<td>$-\bar{y}_2 + \frac{\pi}{\nu} \psi^{1} (-\varphi - \bar{y}_2 - \bar{y}_3)$</td>
<td>$\frac{\pi}{\nu} \psi^{1} (-\bar{y}_2 - \bar{y}_3) - \frac{\pi}{\nu} \psi^{0} \psi^{1}$</td>
<td>$\frac{\pi}{\nu} \psi^{1} (-\bar{y}_2 - \bar{y}_3)$</td>
</tr>
<tr>
<td></td>
<td>$\frac{\pi}{\nu} \psi^{0} \psi^{1}$</td>
<td>$\left(\frac{1 - \gamma}{\theta_2 - 1}\right)$</td>
<td>$\frac{\pi}{\nu} \psi^{1} (-\bar{y}_2 - \bar{y}_3) - \frac{\pi}{\nu} \psi^{0} \psi^{1}$</td>
<td>$\frac{\pi}{\nu} \psi^{1} (-\bar{y}_2 - \bar{y}_3)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ \varphi_{i} - \bar{y}_2 - \bar{y}_3 + \tilde{p}_i$</td>
<td>$-\bar{y}_2 + \frac{\pi}{\nu} \psi^{1} (-\varphi - \bar{y}_2 - \bar{y}_3)$</td>
<td>$\frac{\pi}{\nu} \psi^{1} (-\bar{y}_2 - \bar{y}_3) - \frac{\pi}{\nu} \psi^{0} \psi^{1}$</td>
</tr>
<tr>
<td>Function</td>
<td>BAU</td>
<td>Fixed Emissions Tax</td>
<td>Variable Emissions Tax</td>
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</tr>
<tr>
<td>--------------------------------</td>
<td>------------------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Government’s choice of pollution stock</td>
<td></td>
<td>$\xi_i \eta - \beta \eta \xi_{i+1} + \omega k \omega_i (d_i + 2d_j \bar{y})(\bar{\omega}_i + \bar{a}<em>i + \bar{a}k</em>{i-1}) = 0$</td>
<td>$\xi_i \eta - \beta \eta \xi_{i+1} + \omega k \omega_i (d_i + 2d_j \bar{y})(\bar{\omega}_i + \bar{a}<em>i + \bar{a}k</em>{i-1}) = 0$</td>
<td></td>
</tr>
</tbody>
</table>

Source: Compiled by the author.
Table 5.4 presents the non-stochastic values of the economic and environmental variables, $\bar{v}$, under different emissions reduction scenarios. This system of equations is coded and then solved in Matlab to obtain the numerical steady state values of each variable. Using the results of the BAU scenario and comparing the values under different emission reduction policies makes it possible to show the long-term effects of each policy on the Australian economy.

Table 5.5 displays the linearised version of the model in the neighbourhood of steady state values. Therefore, any changes in the log-linearised variables, $\tilde{v}$, due to a technology shock will resemble exactly the changes that will occur due to long-term values of variables. In order to obtain such changes the system contained in Table 5.5 is coded in Matlab and the results will show how the Australian economic and environmental variables will respond to a technology shock. These results, as well as the stochastic results, are presented in the next chapter.

5.6. Summary

To investigate the effects of emissions pricing policies on the Australian economy a dynamic general equilibrium model was developed in Chapter 4 and extended to four different scenarios: business-as-usual, a fixed emissions tax policy, a flexible emissions tax policy and an abatement subsidy policy. The model under these scenarios was calibrated in this chapter. The economic parameters, including the discount factor, the production function, the utility function, the capital decay rate and the productivity shock were calibrated using Australian RBC studies (Jaaskela and Nimark, 2011; Gomez-Gonzalez and Rees, 2013; Rees, 2013). The damage function was calibrated using the DICE and RICE models. Additionally, this thesis collected quarterly and seasonally adjusted data for Australian emissions and GDP to
calculate the coefficient of output in the emissions function. The emissions abatement cost function was calibrated to the RICE model. Finally, the decay rate of pollution in the atmosphere was assumed to be identical around the world and calibrated using Heutel (2012).

This research modified the calibration method specified by Heutel (2012) for emissions from the rest of the world. This alteration, in addition to differences related to the scenarios to be tested, and the analysis approach, are the technical contributions of this thesis into the model. Moreover, this research is the first attempt at DSGE modelling for environmental policy analysis in Australia and this can be considered to be a practical contribution. In order to provide the policy analysis the steady state and log-linearised model presented in this chapter will be coded into Matlab and solved, and the results will be presented and compared in the next chapter. This process can be conducted via three approaches: first, by finding and comparing the steady state values of economic and environment variables which will present the non-stochastic outcomes of policies; second, by presenting and comparing the short-term response paths of variables to technology shocks under different policies; and third, by finding and comparing the cumulative changes in each variable which will display the cumulative gain or loss of variables under each policy over time. These results are presented and discussed in the next chapter.
Chapter 6
Numerical Results and Scenario Analysis

6.1. Introduction

This chapter presents simulation results derived from the dynamic stochastic general equilibrium model developed in Chapter 4 and calibrated in Chapter 5. As explained in Chapter 4, Section 4.1, the model was developed for four scenarios including: business-as-usual scenario without any environmental policy, a fixed emissions tax system in which a constant emissions tax is levied on each tonne of emissions where the tax rate does not change over time, a variable emissions tax policy in which the regulator chooses a tax rate on each tonne of emissions at the beginning of each period, and an abatement subsidy policy in which the regulator pays polluters for each unit of emissions reduction they achieve. The BAU scenario with no environmental policy is also developed and is used as a benchmark case to compare with the results of emissions reduction policies. These policies were designed to be similar to the emissions pricing programs implemented in Australia including fixed emissions tax and abatement subsidy programs, while a variable emissions tax is used as a proxy for the cap-and-trade scheme which was planned to be applied in Australia.

Additionally, as explained in Chapter 4 Section 4.1, this thesis is also interested in investigating the environmental and economic impacts of an augmenting fixed tax program, similar to the Australian Carbon Tax program which was originally designed to increase by 2.5 per cent per year. To this end the fixed tax scenario developed in Chapter 4 Section 4.5 is used where the tax rate increases by 2.5 per cent every four periods, equivalent to a year. This increase in emissions tax is pre-announced at the beginning of the program, so that both
production and consumption sectors expect the changes and take them into account in their optimisation behaviour.

In order to obtain the results from the various emissions pricing scenarios and the augmenting scenario, the model was calibrated to the Australian economy in Chapter 5. The current chapter presents the numerical results from each scenario. As explained in Chapter 5 Section 5.5 the model presented in this research consists of several nonlinear equations which make it too complex to derive analytically unambiguous solutions. Therefore, instead, a numerical solution is presented. This use of a numerical approach for DSGE models with nonlinear equations has been widely used since Kydland and Prescott (1982) first applied it. For instance, it has been used by Fischer and Springborn (2011), Heutel (2012) and Annicchiarico and Di Dio (2015).

After the calibration described in Chapter 5, a policy analysis consisting of three stages is conducted. First, a numerical solution of the non-stochastic steady-state values (when the values of variables do not change over time and no shocks occur) is provided. The solutions of the different emissions reduction scenarios are then compared to the benchmark BAU scenario. Second, results from a stochastic shock, specifically a TFP shock, are presented graphically to show the response paths of different economic and environmental variables to such a shock. Third, the cumulative effects of a TFP shock under each emissions policy for different economic and environmental variables are derived numerically. To the best of the author’s knowledge, this method has not been applied in any other environmental DSGE model before, and is another contribution of the current research. The numerical cumulative analysis enables a better understanding of the effects of the three specified emissions reduction policies over time on the Australian economy, while the steady state and the
graphic results indicate the non-stochastic and the short run dynamics of each policy respectively.

The chapter proceeds as follows. Section 6.2 presents the numerical results from the model under all scenarios and provides a comparison between the steady state values of environmental and economic variables. In Section 6.2 the graphical results of the model under different policies are presented and compared to investigate the impacts of emissions control policies on business cycles. The cumulative effects are provided in Section 6.3 to identify the gain or loss in economic and environmental variables over time. Section 6.4 presents the results of an increasing emissions tax system, and Section 6.5 concludes the chapter.

6.2. Steady State Numerical Results

This section presents the steady state solution of the model under different scenarios. Results from the BAU scenario are used as the benchmark case with which to evaluate and compare outcomes from the implementation of various emissions pricing policies. The steady state value of a variable $v$ is the value that does not change over time, that is, $v_t = v_{t+1}$. This requires the model to be deterministic. To meet this condition the value for TFP should be set to a constant. For simplicity, it is assumed in this analysis that the TFP is equal to 1. A stability test is also conducted to ensure that the dynamics of the model are stable.

First, the steady state solutions of selected economic and environmental variables under a variable emissions tax system are calculated. The results include the steady state emissions tax rate. As explained in Chapter 4 Section 4.6 the government chooses an optimal emissions tax path $\{p_t\}$ which maximises social welfare in terms of total discounted expected utility.
Thus, the tax rate represents the optimal emissions tax which maximises social welfare constrained to the behaviour of consumers and firms.21

Thus, the tax rate takes account of all the benefits it would provide, and all the costs it would impose, for all sectors when there is no asymmetric information in the economy. This calculated tax is then used as a constant tax rate in the fixed tax regime. This approach can facilitate a comparison of fixed vs. variable tax policies since it imposes the same steady state tax rate on both fixed and variable emissions tax system scenarios, excluding any effects of a higher or lower fixed tax on the results, and, thereby, just shows the effects of a more rigid tax policy.

Table 6.1 summarises the steady state levels of economic and environmental variables when the TFP is set equal to 1 under various policy scenarios. In order to conduct a comparison between various emissions pricing policies, BAU is considered as the baseline scenario and the others show deviations (in percentages) from this baseline scenario.22 Thus, the table shows the percentage differences of variables under various emissions tax and abatement subsidy policies relative to BAU. For example, the steady state of emissions under a fixed tax scenario (1.0357) is 6.48% less than that for the steady state of emissions under a BAU scenario (1.1075). The simulation results indicate that both of the flexible policies (i.e. a variable emissions tax and abatement subsidy) result in the same steady state outcomes. This finding is in line with existing theories when considering subsidies as negative taxes (Perman

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21 As explained in Chapter 4 Section 4.6, the regulator observes the firm’s and household’s optimisation behaviour and chooses an optimal emissions tax path which maximises social welfare in terms of total discounted expected utility. This implies perfect foresight and complete information which are the underlying assumptions of this model.

22 The numbers are just the solution and cannot be interpreted directly. This is why in DSGE modelling they calculate the percentage of deviation and interpret them. This helps to remove the effects of a large or small unit.
et al., 2003; Arimura and Iwata, 2015; Perman, 2015). Table 6.1 shows that while all emissions reduction policies can result in emissions reductions, emissions decline by more under a fixed emissions tax scenario. Emissions decrease by 6.45 per cent under the variable emissions tax (and subsidy policies) compared with the emissions steady state under a BAU scenario, and 6.48 per cent under the fixed tax policy in steady state compared with the emissions steady state under a BAU scenario.

Thus, a rigid tax policy can result in better environmental outcomes in the new steady state. From this finding it can be concluded that a fixed tax policy can provide higher motivation to undertake emissions abatement, for example by shifting to renewable energies. A possible explanation for this is that in a variable tax (subsidy) regime the government sets an optimal tax (subsidy) based on the behaviour of the household and firm at the beginning of each period. Thus, the optimal tax (subsidy) internalises not only the damage cost but also the abatement cost that the firm will encounter in that period. This can provide a cost saving motivation for the firm to decrease abatement costs by decreasing the abatement level, and, instead, focus on production. The numerical results also confirm that the abatement level is lower under the variable tax (subsidy) scenario: the percentage of emissions abated by the firm is 6.25 compared with 6.28 in a fixed emissions tax policy.

The desired outcome of such policies, emissions reduction, comes at an economic cost. For example, the better environmental outcome under a fixed tax policy is achieved at a higher economic cost (lower output, capital and consumption). The steady state outcomes reveal that under a fixed tax policy, capital has the highest reduction relative to the BAU scenario, decreasing by 4.77 per cent compared to a decreases of 4.70 per cent under a variable emissions tax (subsidy) program. As explained above, the values in brackets in Table 6.1
present the deviations (in percentages) of each economic and environmental variable from those of the BAU scenario.

The larger reduction of capital under the fixed tax scenario is due to higher abatement, $\mu$, which imposes higher abatement costs on the firm. As a result the firm has less resources to allocate to capital. The higher level of capital, as an input, in the flexible programs results in higher output. As the table shows, output experiences the lowest reduction relative to the BAU scenario under the variable tax (subsidy) policy, reducing by 1.53 per cent, while it drops by 1.55 per cent under the fixed tax policy. The lower GDP reduction in the variable tax (subsidy) regime results in higher income for households, and therefore the highest consumption, as GDP decreases by 0.61 compared to a 0.62 per cent reduction for the fixed tax regime.

This research is also interested in finding the welfare costs of the three emissions reduction systems. To this end it follows the DSGE literature (Stockman, 2001; Lucas, 2003; Fischer and Springborn, 2011; Dissou and Karnizova, 2012; Annicchiarico and Di Dio, 2015) by calculating welfare costs as the percentage reduction in consumption which is needed under a given policy to make the consumer indifferent between a BAU scenario and that policy scenario. This definition is similar to the percentage change in consumption from the steady state value here, since utility is only a function of consumption. This leads us to obtain the highest welfare costs of 0.62 per cent under the fixed tax system, followed by 0.61 per cent for the variable tax (subsidy) policy.
Table 6.1: Steady-state levels when TFP equals 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>BAU</th>
<th>Fixed Tax (% change from BAU)</th>
<th>Variable Tax (% change from BAU)</th>
<th>Emissions Reduction Subsidy (% change from BAU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions (m)</td>
<td>1.1075</td>
<td>1.0357 (-6.48%)</td>
<td>1.0361 (-6.45%)</td>
<td>1.0361 (-6.45%)</td>
</tr>
<tr>
<td>Abatement ((\mu))</td>
<td>0</td>
<td>0.0628</td>
<td>0.0625</td>
<td>0.0625</td>
</tr>
<tr>
<td>Output ((y))</td>
<td>2.8335</td>
<td>2.7895 (-1.55%)</td>
<td>2.7902 (-1.53%)</td>
<td>2.7902 (-1.53%)</td>
</tr>
<tr>
<td>Capital ((k))</td>
<td>32.0936</td>
<td>30.562 (-4.77%)</td>
<td>30.585 (-4.70%)</td>
<td>30.585 (-4.70 %)</td>
</tr>
<tr>
<td>Consumption ((c))</td>
<td>2.1917</td>
<td>2.1782 (-0.62%)</td>
<td>2.1784 (-0.61%)</td>
<td>2.1784 (-0.61%)</td>
</tr>
<tr>
<td>Welfare Cost</td>
<td>0</td>
<td>0.62%</td>
<td>0.61%</td>
<td>0.61%</td>
</tr>
</tbody>
</table>

Notes: The values in brackets present the deviations (in percentages) of each economic and environmental variable from those of the BAU scenario.

Source: Author’s calculations.

Overall, the difference in results seems very minor in percentage terms. Such differences, however, are significant in terms of levels. For instance, the difference between the steady state solution of output in a fixed tax and a subsidy policy is 0.02 per cent. Converting this
small percentage into Australia’s GDP in 2015 sets it equal to about $325.8 million based on data published by Jegou and Rubini (2011).

The above results can be summarised as follows: from an environmental point of view a fixed emissions tax should be chosen, while from a welfare and economic point of view a flexible system, such as a variable tax which is a proxy for a cap-and-trade scheme or an abatement policy, is a preferred instrument. Such a ranking is for the deterministic case when TFP is equal to 1 and no shock occurs. In order to obtain a solution in the presence of TFP shocks the model is log-linearised around the steady state values and the solutions are presented in the next section. The log-linearised model will be a good approximation of the original model which facilitates showing small fluctuations around steady state caused by a shock.

6.3. Results with a Stochastic Shock

In this section the model is solved by log-linearising around its steady state and the system of linear equations is solved analytically. To this end the Anderson-Moore Algorithm (AMA) is used which is a method for solving complex problems, including models that assume agents have perfect foresight and for asymptotic constraints on nonlinear models. The models used in the current study have these features. The AMA was developed at the Federal Reserve Board by Anderson and Moore (1985) and evaluated by Anderson (2008) and Anderson (2010). It is verified by them as an accurate and fast method of obtaining solutions. The log-linearised model is coded to Matlab which is widely used in empirical studies in economics.

The solution results can be shown graphically via two approaches: first, by using impulse response functions (IRFs) which show the response paths of economic and environmental variables over a period of time when a TFP shock occurs in the first period; second, by simulating business cycles in the economy by introducing a series of TFP shocks over a
period of time and analysing the responses of variables to those shocks. Both approaches are presented in this research.

6.4. Impulse Response Function Simulation Results

Figure 6.1 displays the response paths of four economic variables: TFP, the stock of productive capital for production purposes, output and consumption after a one-time transitory shock to TFP under all emissions reduction policies. As explained in Chapter 5, Section 5.2 the shock occurs exogenously in period one at the size of one standard deviation of $\varepsilon_t$, 0.0069, and decays at the rate of 0.98. As shown by Figure 6.1 such a positive shock results in a positive deviation of economic variables from their steady state values. The path of TFP is exogenous since the assumed innovation shock occurs exogenously. The simulation is run for 200 periods, equal to 50 years\textsuperscript{23} to investigate the effects of the shock on variables. The simulation results demonstrate that the responses of economic variables to a one period shock overlap under the variable emissions tax and subsidy scenarios and so are exactly the same. The figure also shows that the responses of economic variables to a TFP shock are pro-cyclical; that is, they follow the same direction as the shock.

The shock occurs in the first period and increases the productivity of capital which results in higher output at the same level of input. Thus, the peak of output happens in the same period as the TFP – the first period. The increase in the productivity of capital raises the firm’s demand for capital. However, the peak of capital does not occur during the first period since TFP is a flow variable while capital is a stock variable and, thus, it takes more time to adjust, about 45 periods which is equal to 11 years to reach its peak. The resource constraint

\textsuperscript{23} As explained in Chapter 5 Section 5.2 each time period is equivalent to a quarter of a year.
\[ y_t = c_t + i_t + z_t \] and capital accumulation \( k_t = (1-\delta)k_{t-1} + i_t \) result in consumption being highly affected by output, capital and abatement costs: \[ c_t = y_t - k_t + (1-\delta)k_{t-1} - z_t. \]

Figure 6.1: Impulse responses of economic variables to a TFP shock under a fixed emissions tax (FixedTax), variable emissions tax (VarTax) and abatement subsidy scenarios.

As shown by Figure 6.1 a positive TFP shock leads to an increase in consumption which highlights the key role of income in influencing consumption: an increase in income will increase consumption regardless of the direction of changes in other expenses (i.e. investment and abatement costs). Unlike output, however, the peak of consumption does not occur in the
first period but around period 30, equivalent to year 7, which shows that the dynamics of consumption change is affected by the adjustment path of capital stock. The results for the fixed tax scenario are a bit different from those of the variable emissions tax or subsidy due to a different response of the environmental variables. This is explained further below.

The environmental effects of a positive TFP shock are presented in Figure 6.2. The figure shows the response path of abatement, emissions, abatement costs, variable emissions tax rate and abatement subsidy rate when the same TFP shock occurs. Like the economic effects, the environmental effects of a shock are the same under both the variable tax and subsidy programs but different under the fixed emissions pricing policy. The figure also shows that the impulse response function of abatement is pro-cyclical under the variable tax system and the subsidy system; that is, they follow the same direction as the shock, while it is countercyclical under a fixed tax policy; that is, it follows the opposite direction to the shock. This is because under a fixed emissions tax scenario the only variable that affects the firm’s choice of abatement is the level of output in each period as the tax is a constant, $\gamma \theta m t \theta - = t t 1 t 2 1 0 2 \gamma y 2 p$. In such a nonlinear function the signs of $\gamma$, $\theta_1$, and $\theta_2$ specify the direction of the relationship since the tax rate $p$ is always positive. As explained in Chapter 5, Section 5.2, $1-\gamma$ represents the emissions elasticity of output, and thus, it is strongly positive and, calculated as 0.0975. Also, $\theta_1$ and $\theta_2$ determine the relationship between abatement and abatement cost and both are positive, calibrated to be 0.007 and 2.8 respectively. These positive parameters result in a negative relationship between abatement and output which means that a positive TFP shock, which increases output, leads to a decrease in abatement.

Under a variable emissions tax scenario, however, the firm’s choice of abatement is affected not only by output but also by the emissions tax, as $\theta_1 \theta_2 \mu t \gamma = p y i \gamma$. As is the case for the fixed tax, the relationship between abatement and output is negative. That is, abatement
decreases when output increases, while the abatement and tax relationship is positive. To investigate how the variable tax would be affected by a shock, the IRF of tax is simulated and also displayed in Figure 6.2. As shown by the figure, the response path of tax is pro-cyclical. Also, since the tax is a function of current and expected future consumption, it follows the consumption path and peaks in period 30, year 7. Therefore, an increase in TFP leads to an increase in output and tax. The tax increase motivates firms to decrease emissions by increasing abatement while the increase in productivity, and consequently output, signals firms to allocate resources to production rather than abatement. Thus, analytically, the change in abatement is ambiguous but the simulation result is remarkable: the output stimulus is more significant as soon as the shock occurs and the abatement decreases. As time passes the increase of the tax motivates firms to reduce their emissions and abatement increases to a positive deviation from steady state and peaks in period 60, year 15.

Likewise, in a subsidy system, the relationship between abatement and output is negative while there is a positive relationship between abatement and the subsidy rate as \( \theta_1, \theta_2, \mu_i^0, y_i = s_i \) (see Figure 6.2). This simulation result reveals that the response path of abatement to a positive TFP shock is the same as it is in the case of a subsidy and a variable emissions tax system. Additionally, the response path to a subsidy is similar to that of a variable tax. That is, when a positive TFP shock occurs, the subsidy increases and peaks in period 30, in year 7, as it depends on consumption. The only difference is that the subsidy rate increases to a higher level than that of the tax rate. Also, like a variable tax regime, abatement drops sharply in period 1 as a result of the increase in output, but the increase in subsidy motivates firms to increase abatement and the rise in abatement continues to period 60, year 15, when it peaks.

The response paths of abatement costs are also different for the three policies. In a fixed emissions tax system a positive TFP shock increases capital productivity which motivates the
firm to apply more units of capital. This implies that spending on abatement is more costly after the shock than before, though the tax rate has not been changed, and thus, the profit maximising firm would be motivated to spend more on capital and less on abatement. So abatement and, consequently, abatement costs, decrease. The simulation results show that under a variable emissions tax policy, the tax increases when a positive shock occurs.

The higher tax rate motivates firms to decrease tax costs by reducing emissions, which can be done by increasing abatement at the same level of output, \( m_t = (1 - \mu_t) y_t^{1-r} \). Also, the abatement response path follows the tax path peaks in period 30, year 7. The response of abatement costs under a subsidy policy is the same as it is under the variable emissions tax policy. A positive TFP shock increases the subsidy which motivates the firm to increase revenue from the abatement subsidy by increasing the abatement level. Thus, the abatement costs increase and peaks in period 30.

The response of emissions in all regimes is determined by the responses of output and abatement. As explained above, while output increases under all scenarios, abatement decreases under the fixed emissions tax but increases under the variable emissions tax and subsidy scenarios. The simulation results show that emissions increase under all scenarios. This finding points to the important role of output in emissions. The higher abatement effort in the variable emissions tax and subsidy policies, however, results in a smaller emissions increase than under the fixed emissions tax policy. Emissions rise to a 0.07 per cent deviation from steady state in the variable emissions tax and subsidy policies compared with 0.09 per cent in the fixed emissions tax policy.

Therefore, it can be concluded that a positive TFP shock highly motivates firms to increase production. A fixed emissions tax system loses its motivation as firms increase production
regardless of the environmental consequences, while a variable emissions tax or abatement subsidy system can significantly provide environmental incentives for firms to implement abatement efforts besides increasing production. This is due to the fact that in a fixed tax system the marginal cost of emissions remains unchanged, thus firms can increase pollution at the same cost while in a variable tax system a positive TFP shock increases the tax rate which persuades firms to decrease emissions.

In summary, the outcomes in a stochastic framework and in the presence of a TFP shock provided significant results. The response paths of environmental variables under different emissions reduction scenarios were different in such a way that in a flexible system, such as for an emissions subsidy or variable tax policy, higher abatement efforts and, consequently, higher abatement costs and lower emissions can result. Higher abatement costs led to lower outputs under the flexible scenarios compared with those under a fixed tax policy. The difference between the IRF of output under a fixed tax scenario and under a variable tax (subsidy) was small which points to a minor role of abatement cost in total output, so that different abatement levels under different policies do not lead to noticeable changes in total outputs.

**6.5. Real Business Cycle Simulation Results**

Section 6.4 presented IRFs which indicated the responses of the economy under emissions tax and abatement subsidy policies when an exogenous and transitory shock occurs to TFP. In this section real business cycles are presented in which a series of exogenous shocks happen to TFP that produces output business cycles (i.e. expansions and recessions). Figure 6.3 presents the simulation time paths of outputs in response to a series of TFP shocks. The simulation results include an expansion from period 20 to period 50 followed by a recession from period 50 to period 80 to cover both boom and recessionary periods in a business cycle.
In Figure 6.3 output levels in all scenarios are normalised to the BAU steady state level of output in order to facilitate policy comparison. As Figure 6.3 shows, implementing an emissions tax or an abatement subsidy policy affects the steady state level of output but not the path of its fluctuation. As shown previously in Figure 6.1 the output IRFs under a variable tax and subsidy overlap and is only marginally different from that under a fixed tax scenario.
Figure 6.2: Impulse responses of environmental variables to a TFP shock under fixed emissions tax (Fixed Tax), a variable emissions tax (FlexTax) and abatement subsidy scenarios.

- **Abatement (μ)**
  - Fixed Tax
  - FlexTax
  - Subsidy

- **Emissions (m)**
  - Fixed Tax
  - Variable Tax
  - Subsidy
Likewise, the differences between the output business cycle simulations under a variable tax (and subsidy) and under a fixed tax scenario are very small as they overlap in Figure 6.3.

**Figure 6.3: Business cycle simulation of output under business-as-usual (BAU), fixed emissions tax (FixedTax), variable emissions tax (VarTax) and abatement subsidy (Sub) scenarios when levels are normalised to the BAU steady state level of output**

![Graph showing business cycle simulation of output](image)

Figure 6.4 displays the cyclical simulation results for emissions. Again, the levels are normalised using the BAU steady state level of emissions. Three remarkable findings can be observed in the figure. First, the emissions path follows output under all scenarios. That is, emissions increase during expansion and decrease during recession. This is due to the fact that emissions are a by-product of production, and thus they follow output fluctuations. Second, all emissions reduction policies result in levels of emissions that are lower than those for BAU. Third: the path of emissions under emissions policies varies more than under BAU. To make the fluctuations easy to observe, for all scenarios, the emissions paths in terms of the
percentage deviations from steady state levels, rather than their actual levels, are shown in Figure 6.5.

Figure 6.4: Business cycle simulation of emissions under BAU, fixed emissions tax (FixedTax), variable emissions tax (VarTax) and abatement subsidy (Sub) scenarios when levels are normalised to the BAU steady state level of emissions.

Note that the fluctuations of emissions are the same in Figure 6.4 and Figure 6.5. The scale of the vertical axis in the former is much wider, from 0.92 to 1.01, compared to the latter which range from -1% to 1%, making emissions fluctuations in Figure 6.4 look flatter. As Figure 6.5 shows, emissions cyclical paths are exactly the same in both the variable emissions tax and abatement subsidy systems. However, the emissions path fluctuates more in a fixed tax system. This is due to the fact that during an output expansion, under a fixed tax policy, the marginal cost of producing emissions does not change, and firms would not be motivated to
make abatement efforts. In a variable emissions tax (or abatement subsidy) system, however, the tax (subsidy), or the cost of producing emissions (the benefit of making abatement), increases during an expansion. This motivates firms to decrease costs (increase benefits) by making abatement efforts. Therefore, emissions increase to a smaller extent in a variable tax or subsidy system than they do in the case of a fixed emissions tax system.

The policy implications of such findings are significant: first, a variable emissions tax policy should be adjusted pro-cyclically to business cycles: the tax rate increases during expansions and decreases during recessions. This finding is consistent with Heutel (2012). A similar pattern is apparent for the abatement subsidy policy: the authority should adjust the subsidy to increase during expansions and decrease during recessions. Second, in order to achieve a lower emissions outcome the regulator can implement a variable emissions tax or abatement subsidy policy during periods of expansion and a fixed emissions tax during periods of recession.

This section has indicated the response path of different environmental and economic variables to a one-time TFP shock. It has also shown how different emissions policies would affect Australia’s real business cycles and its emissions fluctuations. This research is also interested in calculating the cumulative effect of a TFP shock on economic and environmental variables under each emissions policy. Section 6.2 provided steady state values for each variable and this section described the responses of variables to the shock in terms of deviations from these steady state values. The next section provides a new approach to emissions pricing policy analysis when TFP shocks happen, by bringing Sections 6.2 and 6.3 together and numerically calculating the cumulative gain or loss of each variable under different emissions pricing systems.
6.6. Numerical Results for Cumulative Effects

This section attempts to calculate the total effects on key economic and environmental variables (in a dynamic context) of each emissions policy when a TFP shock happens. After presenting the IRFs of variables under the different emissions reduction programs, this section numerically calculates and compares graphically the changes shown by the IRFs. This is an issue not previously modelled or evaluated in other studies, and evaluating it is another major contribution of this study. To this end the cumulative effects of a positive TFP shock (i.e. the cumulative percentage deviation from steady state) on the economic and environmental variables are calculated. Such a cumulative effect is equal to the area under the IRF of a variable. Multiplying the cumulative effect by the steady state of that variable can express the total effects of the shock under an emissions reduction program.
This approach can capture not only the effects of emissions reduction programs on the steady state values of key variables, but also on the cumulative percentage deviation of those variables from their initial steady state values. As explained in Section 6.1, comparing the steady state values of variables under emissions reduction policies with those of BAU can reveal the long-term, deterministic impact of the policies. However, under uncertainty there is an adjustment process in which economic sectors adjust their decisions to the uncertainty and the cumulative impact of such an adjustment cannot be captured by just comparing the steady states.

Table 6.2 shows the total, or cumulative, effects of various emissions reduction programs on economic and environmental variables when a positive, but temporary, TFP shock occurs. Using the BAU scenario as the benchmark, the difference between the cumulative effect of a TFP shock on a variable under various emissions reduction policies and the effect under BAU is displayed in brackets and shows the entire impact of the emissions reduction policy, not only in the steady state situation but also throughout the entire adjustment process. As Table 6.2 shows, the cumulative effects under various emissions reduction policies over the entire adjustment period are significantly different from their steady state values, as presented in Table 6.1. To facilitate ease of comparison the steady state and cumulative results are jointly presented in Table 6.2.
<table>
<thead>
<tr>
<th>Variable</th>
<th>BAU</th>
<th>Fixed tax (% change from BAU)</th>
<th>Variable tax (% change from BAU)</th>
<th>Abatement subsidy (% change from BAU)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Emissions (m)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steady state</td>
<td>1.1075</td>
<td>1.0357</td>
<td>1.0361</td>
<td>1.0361</td>
</tr>
<tr>
<td></td>
<td>(-6.48%)</td>
<td>(-6.45%)</td>
<td>(-6.45%)</td>
<td></td>
</tr>
<tr>
<td>Cumulative</td>
<td>0.0259</td>
<td>0.0214</td>
<td>0.0184</td>
<td>0.0184</td>
</tr>
<tr>
<td></td>
<td>(-17.37%)</td>
<td>(-28.96%)</td>
<td>(-28.96%)</td>
<td></td>
</tr>
<tr>
<td><strong>Output (y)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steady state</td>
<td>2.8335</td>
<td>2.7895</td>
<td>2.7902</td>
<td>2.7902</td>
</tr>
<tr>
<td></td>
<td>(-1.55%)</td>
<td>(-1.53%)</td>
<td>(-1.53%)</td>
<td></td>
</tr>
<tr>
<td>Cumulative</td>
<td>0.6795</td>
<td>0.6529</td>
<td>0.6469</td>
<td>0.6469</td>
</tr>
<tr>
<td></td>
<td>(-3.91%)</td>
<td>(-4.80%)</td>
<td>(-4.80%)</td>
<td></td>
</tr>
<tr>
<td><strong>Consumption (c)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steady state</td>
<td>2.1917</td>
<td>2.1782</td>
<td>2.1784</td>
<td>2.1784</td>
</tr>
<tr>
<td></td>
<td>(-0.62%)</td>
<td>(-0.61%)</td>
<td>(-0.61%)</td>
<td></td>
</tr>
<tr>
<td>Cumulative</td>
<td>0.5599</td>
<td>0.5503</td>
<td>0.5457</td>
<td>0.5457</td>
</tr>
<tr>
<td></td>
<td>(-1.71%)</td>
<td>(-2.54%)</td>
<td>(-2.54%)</td>
<td></td>
</tr>
</tbody>
</table>

Source: Author’s calculations.

As discussed in Section 6.4 and shown in Figure 6.2, when a positive TFP shock happens the variable tax (subsidy) policy results in the highest abatement and thus the lowest emissions.
compared to those under the fixed tax policy. This makes the accumulated changes in emissions (i.e. the area under the IRFs multiplied by the steady state of emissions) under the variable tax (subsidy) scenario smaller than the fixed tax scenario: -28.96% under a variable tax (subsidy) compared with -17.37% under a fixed tax. Therefore, although the variable tax (subsidy) leads to higher long-term steady state emissions, this policy can help the economy have the greatest cumulative emissions reduction when a positive TFP shock happens (i.e. during an output boom).

The increase in abatement under a variable tax (subsidy) scenario results in an increase in abatement cost, $z_t$, and, based on the resource constraint, $y_t = c_t + i_t + z_t$, results in a reduction in output. Thus, the cumulative decrease in output is highest under the variable tax (subsidy) policy, -4.80%, compared with that of the fixed tax policy of -3.91%. The higher cumulative output loss under the variable tax (subsidy) policy leads to a higher cumulative consumption loss of -2.54% compared to that of the fixed tax policy of -1.71%.

Comparing the cumulative and steady state results provides a significant result: a fixed tax policy can result in the largest emissions reduction but this occurs at a higher cost in terms of output loss when the economy is in a steady state situation. Allowing for economic fluctuations in the presence of TFP shocks, however, the flexible emissions pricing options, (a variable emissions tax or subsidy program), can result in a larger cumulative emissions reduction during an output expansion period. This finding confirms the importance of considering the relationship between emissions and output business cycles in emissions reduction policy analysis, since the results for the deterministic steady state, which showed that a fixed emissions tax program results in the highest output loss, is different when one takes such a relationship into account. This is also consistent with Angelopoulos et al. (2010) who emphasised the importance of considering uncertainty in environmental policy analysis,
and that the choice of an environmental policy can be affected by the size as well as the sources of uncertainty. Having now provided a comparison between the emissions pricing programs applied in Australia the next section simulates the model under a fixed emissions tax policy when the tax increases incrementally each year.

6.7. Increasing Fixed Tax Scenario Results

The aim of this section is to simulate impacts arising from the Australian carbon tax program under which the previous Labor government planned to increase the tax rate by 2.5 per cent per year (Australian Government, 2011). The results can show the effects of a gradual and foreshadowed change in the tax rate in a fixed tax policy. The tax rate starts at the same rate as that for the fixed emissions tax policy used in the above section, which is equal to the steady state tax in a variable system as explained in Section 6.2. Since each period is set to a quarter the tax will rise by 2.5 per cent every four periods, or one year. The main difference between the fixed emissions tax model of the above sections and the model described here is that in the above model the source of variation was an unanticipated change in TFP, while here it is an anticipated change in the tax rate. It is anticipated since, as with the Australian carbon tax program, such changes were planned and publicly announced in the first period. This type of DSGE model is usually called a deterministic DSGE model in which the system is in an equilibrium state when agents learn about a change that is announced by the government, and they respond to such changes (Adjemian et al., 2014).

In this section the model under a fixed tax scenario is used in which the tax is not constant over time and increases as a step function by 2.5 per cent every four periods, or one year. The simulation results arising from such an increase in the tax rate are presented in Figure 6.6

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24 In this thesis uncertainty is specified as economic uncertainty in terms of TFP shocks which are the main source of economic fluctuations.
covering 16 periods, where each period is three months (i.e. a quarter of a year). Figure 6.6 shows the path of three economic variables including emissions tax, capital and output, and the two environmental variables of abatement and emissions. The periods are shown on the horizontal axis and solution level of the variables is shown on the vertical axis. In order to display the responses of economic and environmental variables to such changes the levels are normalised by the first period value for each variable.

The tax rate is normalised to 1 in the first period and increases by 2.5 per cent every four periods thereafter. This will increase the tax rate from 1 in the first period to about 1.09 at the end of period 16, in year 4, as shown by the figure. The rise in tax increases emissions costs which motivate the producer to decrease emissions by decreasing output and/or increasing abatement effort, since emissions are a function of output and abatement effort and therefore, the higher are tax rates the higher is the output reduction. Consequently, the demand for capital as a production input decreases and, thus, the capital response to the increase in the emissions tax follows the same pattern of output. The tax increase also results in abatement rising in the form of a step function like that of the tax, in which each step takes four periods or one year. This means that the increase in the tax rate can provide a greater incentive for firms to increase their abatement effort. The higher abatement results in a reduction in emissions.

While a pre-announced increase in the emissions tax rate results in lower emissions and lower output, the size of reductions in output and emissions are notable: the reduction in output over four years is negligible from 1 to 0.9999992, which equals \(-8\times10^{-5}\) of one per cent. Similarly, the decrease in capital is also very small from 1 to 0.9999962 or \(-3.8\times10^{-4}\) of one per cent. The increase in abatement, however, is 4.75 per cent from 1 to 1.0475. This significant increase in abatement leads to a remarkable emissions decrease of -0.33 per cent, from 1 to
From the negligible reduction in economic variables and the remarkable changes in environmental variables, it can be concluded that an increase in the emissions tax rate can significantly motivate polluters to decrease emissions and increase their abatement efforts, such as shifting to cleaner technologies and renewable energies, with very low additional costs for the economy in terms of output reduction. This is a significant finding of this thesis which implies that an increasing tax rate system can be considered as an effective instrument to meet international pledges.

6.8. Summary

This chapter has compared the impact of three emissions reduction policies: a fixed emissions tax, a variable emissions tax and an abatement subsidy, on the steady state values of selected economic and environmental variables using a numerical approach. The results for a stochastic case, when a TFP shock occurs, were also presented. In addition, this chapter used a new technique for policy analysis by numerically estimating the cumulative change in each variable under the different emissions pricing programs when a TFP shock happens. This technique has not previously been applied in any environmental DSGE study before and represents an important contribution of this thesis. Using this technique, the current research can provide a more accurate estimate of the costs of different emissions policies by capturing the dynamic nature of the adjustment process. Ignoring the impacts of economic shocks and simply focusing upon steady state results gives a limited and perhaps inaccurate indication of the impact of alternative emissions policies.
Figure 6.6: Path of variables when the tax rate is increased by 2.5% every four periods
The steady state results showed that a fixed emissions tax policy leads to larger emissions reduction but at the cost of greater output reduction and welfare cost than a variable emissions tax or abatement subsidy. In a stochastic situation, and in the presence of a TFP shock, the results are different. When a positive TFP shock occurs, the variable tax or subsidy policies can indeed encourage polluters to move to cleaner technologies such as renewable energies, while a fixed emissions tax system loses its motivating power as firms increase production regardless of the environmental consequences. This means that a variable tax or subsidy results in the highest cumulative emissions reduction during output expansion periods. This highlights the importance of considering the impacts of uncertainty in terms of TFP shocks in policy analysis. Therefore, the policy choice depends on the regulator’s perspective and priorities. If the regulator’s priority is to gain emissions reduction over a boom period, a flexible system such as an emissions subsidy or a variable emissions tax, a proxy for a cap-and-trade scheme, is the better option.

The real business cycle results also showed that implementing an emissions tax or an abatement subsidy policy only affects the steady state level of output and not the path of output fluctuation, since all policies result in almost the same real business cycles. From an environmental point of view, however, they impact emissions fluctuations differently. Emissions fluctuate by more in a fixed tax regime than they do under a variable tax or subsidy regime. This implies that the regulator should set the variable emissions tax or subsidy to be pro-cyclical to business cycles: they increase during expansionary periods and decrease during recessionary periods. Also, in order to achieve the lowest emissions, the regulator can implement a variable emissions tax or abatement subsidy during expansion and a fixed tax during recessions.
This chapter also investigated the impact of an increasing emissions tax regime in which the tax increases by 2.5 per cent each year. This scenario was specified as being similar to the Australian carbon tax program under which the tax which was to increase by 2.5 per cent each year. The results indicated that the increase in the tax rate would lead to a decrease in output and higher tax rate levels would result in a sharper reduction in output. The size of reduction, however, is very low and almost equals zero. On the other hand, an increase in tax results in an increase in abatement and a reduction in emissions. Thus, a step function increasing the fixed tax can encourage producers to decrease emissions by increasing abatement effort, for example by shifting to cleaner energies, at negligible economic costs in terms of output reduction.

The results presented in this chapter were based on the calibrated parameters specified in Chapter 5. The next chapter will conduct a sensitivity analysis to investigate the dependence of the findings on the values one of the key parameter, the emissions elasticity of output, which was the only parameter analysed by this research. Additionally, the policy implications of the findings from this chapter will be further elaborated in the next chapter.
Chapter 7

Sensitivity Analysis and Policy Implications

7.1. Introduction

This research has indicated that emissions pricing programs can result in lower emissions by changing the abatement attitudes of firms. Without such a program, a profit maximising firm only considers the economic aspects of its activities and ignores the environmental side arising from emissions produced during production. With an emissions pricing policy, however, the government internalises the externality cost from emissions within the firm. In fact, with an emissions price policy the government can motivate the firm to take the environmental effects of their actions into account. The incentive is created by the cost that polluters must pay for each tonne of emissions they produce in an emissions tax system or the benefit the firm receives for reducing its emissions under an emissions reduction subsidy system. Thus, the cost effect of the emissions price can provide an incentive for polluters to reduce emissions.

Additionally, this research discussed that the correlation between emissions and output, presented in Chapter 2 Section 2.6.2, transfers the economic fluctuations to emissions and results in emissions variation. Ignoring the fluctuations in emissions that inevitably occur as a consequence of economic fluctuations, and setting emissions reduction policies based only on the currently observed economic and environmental situation, the government may face undesired levels of emissions, and increase the risk of failing to reach emissions targets. To avoid this possibility the government should take emissions variations into consideration when setting policies and attempting to control and stabilise emissions.
The main purpose of this study has been to take cognisance of Australian emissions fluctuations due to economic changes and to examine the impact of different emissions taxes and subsidies. To this end a Real Business Cycle (RBC) model was applied under different emissions reduction scenarios in Chapter 6, focusing on the Australian economy. These scenarios were specified to imitate Australian emissions reduction programs over the past five years including: a business-as-usual (BAU) or no policy change scenario, a fixed emissions tax, a flexible emissions tax and abatement subsidy. Additionally, the impact of changes in the tax rate in a fixed tax policy were presented in Chapter 6 which resembled the former Australian carbon tax system, in which the carbon tax rate was designed to increase by 2.5 per cent per year.

This chapter discusses further how the results presented in Chapter 6 can be practically applied to stabilise emissions and obtain lower emission levels. Additionally, since the relationship between emissions and output strongly depends on the carbon intensity of production, it is expected that besides the emissions pricing policies, moving to less polluting, green production technologies can also help the government achieve its emissions reduction targets. In order to investigate how changes in the carbon intensity of production can assist in controlling and stabilising emissions, this chapter presents a sensitivity analysis relating to one of the model parameters, the elasticity of emissions to output (the \( \gamma \) parameter in the model presented in Chapter 6). A lower value of this elasticity indicates the adoption of production technology which is less polluting – that is, it produces the same level of output but at a lower emissions level.

The numerical solution of the model presented in Chapter 6 Section 6.2 is represented here in Table 7.1, including the steady state solutions and cumulative changes in each variable. In order to conduct a comparison between emissions pricing policies, BAU is considered as the
baseline scenario and the others show deviations (in percentage terms) from this baseline scenario. As the table indicates, under all emissions pricing scenarios in the steady state situation abatement increases, output decreases and, as a result, the emissions level decreases. The findings in the table indicate that the outcomes of a deterministic emissions policy analysis are completely different from the outcomes when the effects of business cycles are taken into account. Based on the deterministic steady state solution, a fixed emissions tax system can result in a lower emissions level than a flexible system. This applies to both variable taxes and an abatement subsidy programs. During a boom period as a result of a positive and transitory TFP shock, however, a flexible system can result in the highest cumulative emissions reduction.

This is due to the fact that when economic variations as a result of a TFP shock occur, the responses from a variable tax or abatement subsidy follow the same direction as the shock. This issue is also shown in Figure 6.2. That is, a variable tax or subsidy rate increases (decreases) when a positive (negative) shock occurs. This implies that the regulator should set the variable emissions tax or subsidy to be pro-cyclical to business cycles, so that they increase during expansions and decrease during recessions. When a positive shock occurs, output and consequently emissions, tend to increase, and if the government increases the tax or subsidy it can provide an incentive for a firm to get involved in emissions reduction activities. On the other hand, under the fixed tax program, the tax rate, or the marginal cost of emissions, remains unchanged when a TFP shock happens which means that the firm can increase its emissions without incurring greater costs. Therefore, the firm does not have an incentive to increase abatement efforts and emissions increase to a higher level than they would under a variable tax or subsidy policy. In other words, as shown by Table 7.1, although

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25 Recall that emissions are a function of output and abatement, \( m_t = (1 - \mu_t) y_t \), in which \( 0 \leq \mu_t \leq 1 \) is the fraction of emissions abated in period \( t \).
a fixed tax system leads to the lowest steady state level of emissions, in the presence of a positive TFP shock it results in the highest cumulative emissions over boom periods.

Table 7.1: Cumulative effect of a positive TFP shock

<table>
<thead>
<tr>
<th>Variable</th>
<th>BAU</th>
<th>Fixed tax (% change from BAU)</th>
<th>Variable tax (% change from BAU)</th>
<th>Abatement subsidy (% change from BAU)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Emissions (m)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steady state</td>
<td>1.1075</td>
<td>1.0357 (-6.48%)</td>
<td>1.0361 (-6.45%)</td>
<td>1.0361 (-6.45%)</td>
</tr>
<tr>
<td>Cumulative</td>
<td>0.0259</td>
<td>0.0214 (-17.37%)</td>
<td>0.0184 (-28.96%)</td>
<td>0.0184 (-28.96%)</td>
</tr>
<tr>
<td><strong>Output (y)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steady state</td>
<td>2.8335</td>
<td>2.7895 (-1.55%)</td>
<td>2.7902 (-1.53%)</td>
<td>2.7902 (-1.53%)</td>
</tr>
<tr>
<td>Cumulative</td>
<td>0.6795</td>
<td>0.6529 (-3.91%)</td>
<td>0.6469 (-4.80%)</td>
<td>0.6469 (-4.80%)</td>
</tr>
<tr>
<td><strong>Consumption (c)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steady state</td>
<td>2.1917</td>
<td>2.1782 (-0.62%)</td>
<td>2.1784 (-0.61%)</td>
<td>2.1784 (-0.61%)</td>
</tr>
<tr>
<td>Cumulative</td>
<td>0.5599</td>
<td>0.5503 (-1.71%)</td>
<td>0.5457 (-2.54%)</td>
<td>0.5457 (-2.54%)</td>
</tr>
</tbody>
</table>

Source: Author’s calculations.
The simulation of emissions in real business cycles\textsuperscript{26} was shown in Chapter 6 Section 6.2 and is displayed here again in Figure 7.1. The figure reveals that emissions fluctuate more in a fixed tax regime than they do under a variable tax or subsidy. As explained above, this is because under a variable emissions tax or subsidy program the change in the tax and subsidy rate will provide more of an incentive for firms to control emissions than a fixed tax program, and so emissions fluctuate less under a variable tax or subsidy scenario. Thus, during expansion (recession), emissions would increase (decrease) to the highest (lowest) value under a fixed emissions tax scenario. This implies that in order to stabilise emissions a variable emissions tax or an abatement subsidy can help. Additionally, if the government’s target is to achieve the lowest emissions the regulator should implement a variable emissions tax or abatement subsidy during periods of expansion and a fixed tax during periods of recession. How can this approach be implemented in practice by the government to stabilise emissions? This question is addressed in this chapter.

The remainder of chapter is structured as follows. Section 7.2 provides a sensitivity analysis of the results presented in Chapter 6 relating to the emissions intensity parameter. Section 7.3 discusses the main policy implications of the current study, including an explanation of the difference between environmental policy rules and discretion. Section 7.4 summarises the chapter.

\textsuperscript{26} Real business cycles are generated by a series of exogenous TFP shocks which result in economic expansions and recessions.
Figure 7.1: Emissions during expansion and recession periods under BAU, fixed emissions tax (FixedTax), variable emissions tax (VarTax) and abatement subsidy (Subsidy) scenarios

7.2. Sensitivity Analysis

As explained in Section 7.1 this chapter provides a sensitivity analysis relating to the elasticity of emissions to output in order to investigate whether changes to this parameter can help in emissions stabilisation. This section presents a sensitivity analysis only for the elasticity of emissions to output, since only this parameter can capture the effects of moving to less polluting technologies, such as renewable energies and green technologies, and emissions stabilisation. Recall that the elasticity of emissions to output is shown by $1 - \gamma$ in the emissions function $m_i = (1 - \mu_i)h(y_i)$ where $h(y_i) = y_i^{1-\gamma}$. This research assumes that $1 - \gamma \leq 1$ which implies that the rate of increase in emissions is less than or equal to the rate of increase in output, but not greater than it (Heutel, 2012). The result of this sensitivity
analysis reveals how progress in developing and applying environmentally friendly technologies, such as shifting to renewable energies which result in lower emissions for the same level of output and abatement, can influence the effectiveness of emissions reduction policies in the presence of shocks.

As explained in Chapter 5 Section 5.2, this thesis calibrated the parameters to the existing literature except for the elasticity of emissions to output which was not calculated in previous studies. Hence, it is the only parameter estimated by the current research. To this end data on Australia’s emissions and output was collected and was estimated to be equal to 0.0975. A lower value of this elasticity indicates moving to cleaner production technology, and producing the same level of production at a lower emissions level. Thus, in this section, this elasticity is reduced to two lower coefficients 0.07 and 0.04 in order to capture the effects of moving to less polluting production technologies.

The sensitivity simulation results of emissions during expansionary and recessionary periods under a variable emissions tax (or abatement subsidy) scenario are displayed in Figure 7.2. Figure 7.3 also shows emissions during expansionary and recessionary periods under a fixed emissions tax scenario. As both figures show, a lower elasticity, which represents lowering the carbon intensity of production, can reduce emissions fluctuations. This is because with a lower carbon intensity, the connection between emissions and output decreases and, thus, an increase in output still results in an increase in emissions but the increase is smaller. The sensitivity of the model to the emissions intensity parameter is nonlinear in a way that the

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27 As was explained in Chapter 5 Section 5.2 and shown by Appendix A.1, this coefficient is calculated as the regression of the log of emissions on the log of output.

28 This implies that a one unit increase in \( \log(y) \) will result in an increase in \( \log(e) \) of 0.0975 units.

29 As discussed in Chapter 6, Section 6.2, based on theory and under a full information situation, both a variable emissions tax and subsidy policy result in the same outcome which was also obtained in the results presented in Chapter 6 Sections 6.1 and 6.2, as well as in the sensitivity analysis here.
effects of moving to green technologies (i.e. a lower emissions intensity parameter) is more when emissions variation is greater.\textsuperscript{30} Therefore, moving to cleaner production technologies can significantly help the government to stabilise emissions.

Figure 7.2: A sensitivity analysis of emissions during output expansion and recession under a variable emissions tax/subsidy policy to the emissions elasticity of output

\textsuperscript{30} This is due to the fact that the emissions intensity parameter is specified as an exponent in the model.
Figure 7.3: A sensitivity analysis of emissions during output expansion and recession under a fixed emissions tax policy to emissions elasticity of output.

A comparison between these policies is also conducted and the results are presented in Figure 7.4. As the figure indicates, although a lower emissions elasticity (i.e. 0.04) reduces the magnitude of variations in emissions it is still the case that under a fixed tax scenario emissions are higher (lower) during output expansion (recession) than they are under a variable emissions tax or subsidy. This implies that the main finding of Chapter 6 is not sensitive to the elasticity of emissions: a variable tax or subsidy program can assist in stabilising emissions, and in order to achieve the lowest emissions the regulator should implement a variable emissions tax or abatement subsidy during periods of output expansion and a fixed tax during recessions.
Figure 7.4: Emissions impulse during output expansion and recession under a fixed emissions tax and a variable emissions tax/abatement subsidy policy when the emissions elasticity of output is reduced to 0.04

The response path of output and consumption, however, is not sensitive to the parameter $1-\gamma$ which means that by moving to cleaner technologies, the Australian economy can maintain business cycles while experiencing smaller fluctuations in emissions. This implies that in order to achieve emissions reduction targets the government should apply not only an emissions pricing program but should also attempt to influence the emissions elasticity of output. To this end, Australian policy makers should pay more attention to structural changes in the production sector by encouraging the adoption of available cleaner technology and supporting innovation and creativity by increasing investment in new technologies. In order to progress technology, Australia can benefit from international collaboration to accelerate
movement towards the adoption of lower carbon intensity technologies (Department of the Environment, 2015a).

Upgrading current technology and implementing structural changes could significantly affect the Australian environment, since current production technology is heavily dependent on burning fossil fuels. Electricity generation technology, for example, is responsible for about one-third of emissions produced in Australia, as shown in Figure 2.1 and represented here in Figure 7.5. This is due to the heavy reliance of electricity generation on fossil fuels. Key sources of electricity generation are displayed in Table 7.2. As the table shows, more than 85 per cent of Australia’s electricity was generated by fossil fuels in 2013-14 while 42.6 per cent was generated from burning black coal (Department of Industry and Science, 2015). These numbers highlight that the Australian production sector, especially electricity, needs more support to improve and accelerate the transformation to renewable energy technologies.

Many other countries, however, are seriously pursuing changes in energy systems towards “zero pollution”, especially in the electricity sector. Denmark is a good example. It has had a carbon tax since 1992 (Sumner et al., 2011) and has been successfully shifting to renewable resources. Breaking a world record for wind power in 2015, Denmark now generates 42 per cent of its electricity requirements from wind turbines (Neslen, 2016). This is a significant step towards achieving the government’s aim of having fossil fuel independent electricity and heating by 2035 and a fossil fuel independent energy system by 2050 (Danish Government, 2011). The industrial park in the Kalundborg district of Denmark is also another example of moving towards zero pollution. Not only developed countries such as Denmark, but also developing countries including China and India have been accelerating their movement towards renewable energy. China and India increased their investment in energy efficiency and renewable energy by 17 and 23 per cent respectively in 2015 (Buckley, 2016).
Note: “LULUCF” and “Fugitive” refer to “land use, land use change and forestry” and “industrial fugitive activities including extraction and production of oil and natural gas” respectively.


Table 7.2: Australian electricity generation by fuel type

<table>
<thead>
<tr>
<th></th>
<th>2013–14</th>
<th>Average annual growth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GWh</td>
<td>Share (per cent)</td>
</tr>
<tr>
<td>Fossil fuels a</td>
<td>211 254.8</td>
<td>85.1</td>
</tr>
<tr>
<td>Black coal</td>
<td>105 772.4</td>
<td>42.6</td>
</tr>
<tr>
<td>Brown coal</td>
<td>46 076.2</td>
<td>18.6</td>
</tr>
<tr>
<td>Gas</td>
<td>54 393.9</td>
<td>21.9</td>
</tr>
<tr>
<td>Oil</td>
<td>5 012.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Renewables</td>
<td>37 042.2</td>
<td>14.9</td>
</tr>
<tr>
<td>Hydro</td>
<td>18 421.0</td>
<td>7.4</td>
</tr>
<tr>
<td>Wind</td>
<td>10 252.0</td>
<td>4.1</td>
</tr>
<tr>
<td>Solar PV</td>
<td>4 857.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Bioenergy</td>
<td>3 511.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Geothermal</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>248 297.1</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Source: Department of Industry and Science (2015), Australian Energy Update, p.21
To sum up, the policy implications of the sensitivity analysis is that the government needs to influence the elasticity of emissions to output to decrease emissions fluctuations. Encouragement of greener technology can help the government to achieve emissions reduction targets without adversely impacting output and jobs. By stabilising emissions the government can avoid undesired variations in emissions as a result of economic fluctuations. This requires both national and international collaboration strategies to decrease the dependence of production technologies on fossil fuels, and it also requires finding new, cleaner technologies. This finding is in line with Stern (2007) who suggests that the government must consider three elements, which should be applied simultaneously, when designing such policies: a carbon price, a technology policy and the removal of barriers to behavioural change, as explained in Section 2.2. In the next section the main policy implications of the findings of this thesis, which were presented in Chapter 6 and summarised in Section 7.1, are discussed.

7.3. Policy Implications

This research has provided a policy analysis of Australian emissions reduction programs. To this end three policies were specified in a way that resembles the programs designed/implemented in Australia, including a carbon tax and Emissions Reduction Fund. However, there are several differences between the scenarios in this research and the Australian programs. These differences make it difficult to ascribe the results from an abatement subsidy scenario to the Emissions Reduction Fund program. Therefore, before discussing the policy implications from the findings of the current research, these differences are clarified first. The discussions of the differences, as well as the policy implication of the thesis are backed up by related studies.
One of the biggest differences relates to the time frame of this policy, which is currently designed to continue for only five years starting from 2015. Its aim is to reduce Australia’s emissions by 5 per cent below the 2000 level by 2020 (Roson, 2013). This implies that even if the program achieves the 2020 emissions reduction goal it will not be able to address the long-term global warming problems of Australia. Chapter 2 Section 2.6.1 pointed to such problems including droughts, floods, tropical cyclones, heatwaves, bleaching of the Great Barrier Reef and bushfires across Australia. Moreover, this would be contrary to the claim made by Stern (2007) that a successful emissions scheme requires that society believe that the government reflects its wishes when setting a policy, and that the policy will continue into the long run and not be reversed with a change of government or policymakers.

Not only is the long-term impact of the Emissions Reduction Program questionable, but its short-term effectiveness is also uncertain. For instance, Roson and van der Mensbrugghe (2012) applied a Computable General Equilibrium model and showed that the budget allocated to the Emissions Reduction Fund scheme is half the amount required to meet the target of reducing emissions by 5 per cent below the 2000 level by 2020. Moreover, there are several criticisms relating to the adoption of a subsidy policy, including the fact that the cost of the program is directly imposed on tax payers while polluters receive the benefits (Maddison and Rehdanz, 2011).

Comparing the carbon tax and Emissions Reduction Fund programs Roson and van der Mensbrugghe (2012) argue that the emissions tax system is straightforward to implement as polluters pay for the actual emissions they produce while with an abatement system the government may pay for abatements some of which will occur anyway. For instance, a decrease in electricity demand can result in a reduction in emissions from coal fired electricity generators while the firm makes no abatement effort.
Not only the distribution cost of the program but also the motivation that the program is supposed to provide to polluters can be questioned, as the outcome of the second auction in 4-5 November 2015 showed. About 129 contracts were signed to reduce emissions by about 45.5 million tonnes of CO₂ equivalents. Figure 7.6 shows the outcomes. The figure classifies the emissions reduction projects based on the method of abatement into seven categories as explained below (Australian Government, 2015b).

The first is the vegetation category which includes reforestation, revegetation and the protection of native forest or vegetation that is at imminent risk of clearing. The second is programs which reduce savannah burning in fire management across savannah regions in the north of Australia. The third is the agriculture category which includes management to reduce methane emissions from agricultural products including cattle, pigs, fertilising irrigated cotton and soil carbon. The fourth category is energy efficiency. This covers projects that reduce the consumption of electricity and natural gas. The fifth category is landfill and waste management. This refers to projects that decrease emissions through the operation of landfill and/or alternative waste treatment facilities. The sixth category is transport measures and it includes schemes which reduce emissions from air, land and sea transport. The seventh category consists of projects that reduce fugitive emissions from industrial activities including extraction and the production of oil and natural gas.

Figure 7.6 reveals that 25.6 million tonnes of CO₂ equivalent emissions reduction, equal to more than 56 per cent of abatement which is committed under contracts, is going to be obtained by means of the vegetation category including reforestation, revegetation and the protection of native forest or vegetation that is at imminent risk of clearing (Australian Government, 2015c). These activities are classified as “land use, land use change and
forestry” (LULUCF) in the classification of the sources of emissions and is responsible for only three per cent of Australian emissions as shown in Figure 7.5.

Figure 7.6: Outcomes of the second auction of the Emissions Reduction Fund held in November 2015, by method

![Volume of abatement by method](image)

Source: Clean Energy Regulator website, Australian Government (2015a)

Comparing other abatement contracts signed under the second auction in November 2015 also reveals that more than 87 per cent of abatement will be achieved in the vegetation, savannah burning, agriculture, and landfill and waste categories. These activities are categorised into three sources of emissions including agriculture, LULUCF and waste in Figure 7.5 and produce only 20 per cent of Australian emissions. This means that the contributions of major Australian polluters, including electricity, transport and industrial processes to the Emissions Reduction Fund program is only 13 per cent while they together produce 80 per cent of emissions. This implies that the motivation provided by the Australian
Emissions Reduction Fund program may not be strong enough for major polluters to be involved in emissions reduction activities.

After discussing the basic differences between the Australian Emissions Reduction Fund program and the abatement subsidy scenario applied in the current research, the implications of the results of this study are then reviewed. This thesis has addressed how Australia’s emissions reduction policy should be adjusted to the country’s business cycle in order to achieve lower levels of emissions, and to stabilise emissions. This question has not been previously addressed in the literature, and it is the main focus and contribution of the current study.

The results of adopting an emissions pricing policy to business cycles showed that an abatement subsidy, or a variable emissions tax, can assist in stabilising emissions. However, in order to achieve a lower overall emissions outcome, the regulator should choose a variable emissions tax or abatement subsidy policy during the expansionary phase of the business cycle and a fixed emissions tax during the recessionary phase of the business cycle. But how can this be applied in practice by policy makers? To answer this question the difference between policy ‘rules’ and ‘discretion’ must first be clarified. These concepts can play a critical role in the implementation of environmental policies, so this thesis devotes a subsection to a discussion of them.

7.3.1. Rules and Discretion in Emissions Reduction Policies

The difference between policy rules and discretion was first discussed by Kydland and Prescott (1977). They pioneered the discussion of differences between policy rules and discretion and how government should implement both of them to obtain its targets. Focusing on monetary policy they discuss how government should evaluate alternative policies and
select the one which matches its targets the best. There are inherent imperfections in the ability of governments to implement desirable economic policies since different sectors of the economy make optimisation decisions based on both current policies and expected future policies, but their expectations about future policies may be different from the government’s plans, or they may be affected by uncertainties. This can be due to the fact that even a benevolent government may have an incentive to diverge from its stated intentions.

To obtain credibility and influence the private sector’s expectations, policy makers must be committed to their policies to ensure that the private sector firms believe that the policies will continue into the future, and that they will therefore take the policies into account when shaping their expectations. In other words, an optimal policy rule should be time-consistent to be credible. But even with consistent policies the perceptions of the private sector may not be the same as the government’s, since the private sector sets its expectations based on the government’s incentives and policies but may not believe that the government will implement policies and retain them over a significant period of time (a situation of relevance in the context of Australia).

A policy maker can also use discretion. Tabellini (2005) defines discretion as making policies sequentially over time. Goulder et al. (1999) provides another definition for it as being when a monetary authority is free to act based on its own judgments. Discretionary behaviour would suffer from inconsistency and thus a lack of credibility. To obtain credibility policy makers should be committed to policy rules and avoid inconsistency. Following simple fixed rules, however, may not always be useful. In the case of monetary policy, for example, Tabellini (2005) argues that an international agreement made in regard to monetary policy, such as fixing the exchange rate, could increase the credibility of such a policy. On the other hand, non-contingent rules, such as a fixed exchange rate or inflation rate, would not be
desirable since such rules would result in larger fluctuations in output (Bouman et al., 2000). Additionally, and in reality, policy makers have an incentive to deviate from the rule, or they may learn new information which necessitates updating policy rules. Thus, policy rules should be flexible. But how can governments convince the private sector to believe in its policies if they are flexible?

Clean Energy Regulator (2016) provides a possible answer to this question by showing that monetary policy should be delegated to a conservative and independent institution (i.e. a central bank) that would make it possible to obtain both credibility and flexibility. This idea became the fundamental motivation for a number of countries to implement institutional reform of monetary policy frameworks including Sweden, New Zealand and the United Kingdom. The reforms have focused mostly on increasing the independence of central banks in implementing policies in order to achieve objectives including desired inflation rates. These objectives were also specified more clearly and in more detail by these countries (Bouman et al., 2000). Another solution is provided by Kydland and Prescott (1977) who suggest that the policy maker should clearly specify its policy rules, but also take into account the circumstances that may result in a modification in policies and specify possible deviations from policy rules under defined circumstances.

In the case of environmental policies a flexible and credible policy system is also required. One of the main reasons for this are the different types of uncertainty related to the cost and benefits of environmental policies which were discussed in detail in Chapter 2 Section 2.5. A similar issue is also highlighted by Dissou (2005). Providing a policy analysis regarding rules and discretion, they discuss policy rules that may not even result in the best solution in environmental policies due to uncertainty relating to the actual costs and benefits of abatement. If the government sets the policy and remains committed to it in future even when
it gains new information on abatement costs and benefits, then the policy may not reflect the actual costs and benefits and thus, it may lose its effectiveness.

Tarui and Polasky (2005) also show that when uncertainty about climate change damage is large, discretion is preferred to rules. The idea of having flexible environmental policies which change over time has come to be of significant interest to researchers. Several studies have analysed emissions reduction policies which change when new technologies are adopted (Kennedy and Laplante, 2000; Tarui and Polasky, 2005). Others bring uncertainty into account and develop systems in which policy makers change their policies when they learn about abatement costs and damages (Dwyer Jr, 1993; Thampapillai and Sinden, 2013; Fusion Media Limited, 2016; Thampapillai, 2016).

Incorporating these concepts into the findings of the current research requires that the difference between a ‘policy’ and an ‘instrument’ be clarified first. Goulder et al. (1999) argues that a “policy means a plan of action or a strategy. A policy may either be the outcome of some process or it may be a plan designed specifically to further some goals.” To implement a policy, an instrument is required. Dwyer also defines policy instruments as “the tools manipulated to produce the desired outcomes.” Applying these definitions to environmental policies, reducing emissions is a policy while a tax or subsidy is an instrument. In the environmental literature, similar definitions have also been used. For instance, both emissions taxes and abatement subsidies are classified as market-based instruments (Perman et al., 2003; Bouzaher et al., 2015). Therefore, a key finding of this research is to show which instruments should be applied during different stages of a business cycle in order to obtain the best outcome in terms of lower emissions.

This research suggests that governments should develop emissions reduction programs based on where the economy is on the current business cycle, so if the government sets an
emissions reduction policy during a boom (recession), it should implement a subsidy policy or a variable emissions tax (fixed tax). In order to observe the current position in the business cycle the government needs to review recent and current fluctuations in economic variables and concurrent or leading indicators such as employment.

This conclusion might raise the question of how the government, in the real world, can change abatement policies instantly due to changes in business cycles. There are three points to answer this question: 1. as the impulse responses in Figure 6.1 and Figure 6.2 show, the effect of a shock remains in the economy for a long period and it takes about 50 years for the effect of a TFP shock to completely disappear. 2. Some variables, such as output, change and reach their peak as soon as the shock happens while for the others it takes several periods to reach their peak. For example, it takes about 15 years after the shock happens for abatement under a variable tax or subsidy policy to reach their maximum. 3. In the real world, the government can learn about a TFP shock by observing the changes in output which implies that the time of learning about the shock might be a few periods after it has happened. But the government can still have enough time to make the right decision since the effect of the shock remains in the economy for several years and, based on the impulse response function of the key variable of abatement, polluters will be motivated to do abatement for more than a decade after a shock occurs. Therefore, the government should make the right policy as soon as it observes the shock, and not as soon as the shock happens, and keep the policy for about 15 years, or until it learns about another shock.

These sources can also be used to predict, roughly, the future position of the economy in the business cycle, and, consequently, the changes that may need to be made to emissions reduction policies. Then the government should clearly state the current program as well as the potential changes that may happen to the program in the future due to variations in the
business cycle. Such an announcement can form the basis of the private sector’s expectations based on the current program, situations which would result in modifications of the program, and, consequently, continuation of the current program if those specified situations do not occur. In other words, in order to gain credibility, policy makers need to convince the private sector that they are committed to obtaining their policy targets and make their policies a part of an international agreement such as the Kyoto Protocol to lock the government into an international agreement that cannot be changed unilaterally.

While sticking to one instrument may increase the chance of convincing the private sector, it does not necessarily mean that using different instruments will undermine credibility of a policy. The government only needs to reassure the private sector, by being committed to the current program and announcing changes in advance, that it is committed to reducing emissions with the current program, for example a fixed tax policy, or a planned future program. The prior announcement of future changes to programs can provide the private sector with the opportunity to modify their expectations about emissions policies and make abatement decisions.

Australian policy makers can learn more from the rules and discretion concepts as explained in this section regarding the credibility of emissions reduction policies. To gain credibility, there needs to be cross-party consensus on the issue, otherwise a new government could change direction completely. As reviewed in Chapter 2 Section 2.7 the implemented emissions reduction programs in Australia have fluctuated significantly over the last four years. These changes are due to the different attitudes of policy makers regarding the importance, costs and benefits of emissions control policies in Australia. This lack of consensus between the major political parties has exerted a negative effect on the credibility of emissions reduction policies in such a way that the Australian people cannot readily
anticipate the future impact of such policies, and many do not even believe in the current programs. This is due to the fact that the arguments for emissions policies have not been well articulated in Australia. For instance, Jotzo et al. (2012) conducted a survey in 2012 when the carbon tax program was in operation and found that 40% of Australian-based carbon pricing experts working for large emitters, the finance industry and other organisations expected that the tax program would be repealed and 80% of respondents expected that the tax system would be re-introduced in 2020.

Such disbelief is due to the diverse and conflicting information that has been broadcast to Australians by the major Parties, which has resulted in uncertainty as there appears to be no consensus on this issue between them. In fact, environmental issues in Australia seem to have become a politically-driven rather than a science-driven issue. For example, the Gillard Labor government introduced a carbon tax in 2012 but the subsequent Tony Abbott-led Liberal-National Coalition government severely criticised it, referring to it as “toxic” to the Australian economy (Australian Academy of Technological Sciences and Engineering, 2014). The Liberal Party also argued that Australia could enjoy a better economy by repealing the carbon tax and replacing it with the Emissions Reduction Fund program which can provide “a better way to reduce emissions than by imposing a tax that increases energy costs for businesses and households” (Roson, 2013).

As Jotzo et al. (2012) also explained, such uncertainty is likely to negatively affect the private sector’s behaviour, including their investment decisions. This highlights the necessity of reducing uncertainty and, consequently, increasing the credibility of emissions reduction policies. To this end a meeting should be held in which all parties discuss their points of view, review Australia’s emissions structure and commitment, set the targets, choose the programs and make themselves committed to them regardless of their position in each
election. This consensus does not look possible right now in Australia. Perhaps it is important to convince voters of this need and then, through the electoral system, force the parties to respond. This can reduce consistency problems, convincing the private sector that government is committed to its policies and this will increase the credibility of emissions reduction policy.

A similar idea has been recently highlighted by the Business Council Chief Executive Jennifer Westacott, who called for consensus on emissions reduction programs. She believes that Australia needs national and bipartisan energy and climate change policies, whenever possible, and stated that “Australia needs durable, national, integrated climate change and energy policies capable of delivering Australia’s 2030 emissions reduction target, at lowest possible cost, while maintaining competitiveness and growing Australia’s future economy” (Business Council of Australia, 2016). Recently, as explained in Chapter 1 Section 1.1, the Australian government specified new emissions reduction goals and pledged itself to reduce per capita emissions by 50 to 52 per cent and by 54–56 per cent in terms of emissions intensity between 2005 and 2030 (Department of the Environment, 2015a).

7.4. Summary

This chapter has complemented the results presented in Chapter 6 by conducting a sensitivity analysis and elaborating upon policy implications. The sensitivity analysis indicated that the elasticity of emissions to output can affect emissions and a reduction in this parameter, which captures moving to cleaner technologies, decreases emissions fluctuations without a loss of output. This implies that the government can target this parameter by lowering the dependence of Australian production technology on fossil fuels, as has been done by Denmark through its programs and achievements which were explained in Section 7.2, and also by supporting innovation and creativity in terms of financial support of projects with the
aim of improving accessibility to green technologies and reducing their price. These changes require international collaboration. They are likely to be more successful when Australia commits itself to an international agreement which exerts more pressure to conform. If Australia acts unilaterally it is more likely to change its policy later on.

Furthermore, the policy implications of the results presented in Chapter 6 imply that a flexible emissions pricing system such as a variable tax or an abatement subsidy program can help the government to stabilise emissions. Moreover, in order to achieve the lowest emissions the government can get the benefit of a fixed tax during periods of recession and a variable emissions tax or abatement subsidy policy should be implemented during periods of expansion. To investigate the credibility of such findings, the differences between a policy rule and discretion, as discussed by Kydland and Prescott (1977), were clarified here. It was explained that credibility means that the private sector believes in the policy maker’s program and takes the current and future impact of such programs into account when making decisions.

Setting consistent policies can increase credibility but, in reality, policy makers may need to deviate from them especially in uncertain economic environments. This issue is highlighted in the literature, as several studies suggest that environmental policies should be modified when cleaner technologies arrive, or when the government learns new information about the costs and benefits of emissions reduction policies and uncertainties decrease.

Additionally, the difference between a policy and an instrument should be clarified when it comes to environmental policies. Reducing emissions is a policy while a tax or subsidy is an instrument. Adopting these concepts in this research implies that the government should set an emissions reduction policy, apply a tax or subsidy as an instrument to achieve the policy targets and announce any potential changes that may happen to the program under specified
situations. This will make the private sector more likely to believe the government and take the program and possible future changes into account when making economic and environmental decisions.

Finally, there is a significant fundamental difference between the abatement subsidy scenario specified in this research and current Australian policy, the Emissions Reduction Fund. The scenario specified here assumes that the policy will continue indefinitely, while the actual emissions subsidy policy is set to run only for five years and no program has been announced for the period afterwards. This can influence the effectiveness of the policy by introducing uncertainty and thus reducing its credibility. To achieve Australia’s environmental targets, policy makers should clearly specify their policies and continue with them. This requires political consensus. Instead of climate change being seen as a political issue it needs to be seen in economic, and also perhaps survival terms, and it needs to be understood that the cost of not addressing it increases all the time.
Chapter 8
Summary and Conclusions

8.1. Introduction

This research has presented the first application of a dynamic stochastic general equilibrium (DSGE) model to emissions reduction policy analysis in Australia. The focus of the research was on policies designed and/or implemented in Australia. As explained in Chapter 1 Section 1.1, climate change issues have become of significant concern to scientists and governments. For instance, World Meteorological Organisation statistics show that the years 2011–2015 were the warmest years on record (World Meteorological Organization, 2015). This issue has encouraged researchers to estimate the effects of global warming. For instance, Nordhaus (2010) estimated that a 3.4°C increase in average global temperatures would cause global damage equal to US$12 trillion, and a 2.8 per cent decrease in global output if GHG emissions are not controlled (Nordhaus, 2010).

In Australia the evidence of an increase in average temperatures and of the associated environmental and economic costs if no emissions reduction program is adopted are significant (IPCC, 2014). The costs can include damage to ecosystems, problematic changes in rainfall, and increases in the frequency and intensity of extreme events such as heatwaves, droughts and floods. Climate change can also directly affect the Australian agriculture sector and this sector has already been adversely affected by extreme climate events. For instance, during the 2005–2007 drought food prices increased at more than twice the rate of the increase to the Consumer Price Index (CPI), with the price of fresh fruit and vegetables increasing by 43% and 33% respectively (Climate Council of Australia Limited, 2015).
The role of human activities, especially the burning of fossil fuels, in global warming is significant. The Intergovernmental Panel on Climate Change (IPCC) has been studying climate change since 1990 through investigating climate systems, global warming, atmospheric GHGs concentrations, and radioactive forcing and it has found that it is extremely likely (i.e. there is a 95-100 per cent probability) that humans are responsible for more than half of global warming (IPCC, 2013, p. TS-25). The estimated threats of climate change and the contribution of human activity in accelerating it require policies and programs to control human-caused global warming to avoid future problems (IPCC, 2014). To this end, several international meetings and conferences including the meetings in Kyoto in 1997, in Copenhagen in 2009 and most recently in Paris from 30 November to 12 December 2015 have been held. Countries debated programs to control global warming and set agreed and binding emissions targets.

The Paris meeting presented a historic opportunity for the 196 attending countries to agree to keep the average global temperature increase to within 2°C of the pre-industrial level. The agreement is designed to come into force when at least 55 countries, which together are responsible for 55 per cent of global greenhouse gas emissions, ratify it between April 2016 and 2017 (Taylor, 2016). The agreement was signed by 170 countries including Australia on 22 April 2016.

Before the meeting countries including Australia submitted their emissions targets, or their intended nationally determined contributions (INDCs). Australia submitted its INDC which aimed to decrease emissions economy-wide by 26 to 28 per cent below the 2005 level by 2030 (Center for Climate and Energy Solution, 2015). Additionally, the Australian government set new targets of reducing emissions by 50-52 per cent in terms of per capita and by 54-56 per cent in terms of emissions intensity between 2005 and 2030 (Department of
The current target of Australia is to meet its Copenhagen Accord pledges of reducing its emissions by 5 per cent relative to 2000 by the year 2020 unconditionally (Borrello, 2016). To achieve this target several programs have been designed. The programs have experienced several changes due to different policy makers’ attitudes about the economic costs and environmental outcomes of such policies. The first program was the Clean Energy Program introduced in 2011 which included two phases: first, a fixed price, or a carbon tax, which commenced on 1 July 2012 and was originally planned to continue until 30 July 2015 when the second phase, with a flexible price system under an emissions trading scheme, would begin. The tax phase began in July 2012 as planned. However, it was abolished with effect from 1 July 2014 (Australian Government, 2014a). As an alternative an Emissions Reduction Fund program was introduced which came into effect on 13 December 2014 in which the government funded emissions reduction projects (Department of the Environment, 2014a).

This thesis attempted to provide an analysis of the abovementioned emissions reduction policies. To this end, four scenarios were specified: first, business-as-usual (BAU) or no policy which was used as the benchmark case; second, a fixed emissions tax scenario resembling a carbon tax program; third, a variable emissions tax system as a proxy to the emissions trading scheme and fourth, an abatement subsidy scenario similar to the Emissions Reduction program. Additionally, since Australia’s carbon tax program was designed to increase by 2.5 per cent per year, the economic and environmental impacts of such an increase in a fixed tax emissions program when all sectors of the economy are aware of such changes beforehand was studied. The model was specified under these four scenarios in Chapter 4 and was calibrated to the Australian economy in Chapter 5.
The results were presented in Chapter 6. The simulation results showed that the variable emissions tax or subsidy should be set to be pro-cyclical to business cycles so as to be able to provide motivation for firms to make abatement efforts in situations where a fixed emissions tax system would lose its power to motivate. This is due to the fact that the marginal cost of emissions does not change over time. The simulation results also indicate that a variable tax or an abatement subsidy policy can help the government to stabilise emissions.

Additionally, a numerical derivation of the steady state solution of the model showed that a fixed emissions tax policy results in the highest emissions reduction but it does so at a greater output reduction and welfare cost, followed by a flexible emissions tax and abatement subsidy. Under conditions of uncertainty, however, there is an adjustment process in which economic sectors adjust their decisions to the uncertainty and the cumulative impact of such an adjustment cannot be captured by just comparing the steady states. Finding the cumulative impact of various emissions reduction policies over the entire adjustment period revealed that the cumulative effects are significantly different from their impacts under steady state conditions as the fixed tax program has the lowest cumulative effects on emissions and output. This finding is a significant contribution of the current research from which the following implications can be derived:

- The policy choice depends on the regulator’s perspective and priorities. If the regulator’s priority is emissions reduction during a boom period a flexible system, such as a variable emissions tax which is the proxy for a cap-and-trade scheme, is the appropriate solution while if the regulator’s main concern is to minimise the impact on output, a fixed emissions tax is best.
- This finding confirms that for the real business cycle simulation a variable emissions tax or abatement subsidy program can help to decrease the effects of economic
fluctuations on emissions and reduce variations to emissions. However, in order to achieve the lowest emissions the government can get the benefit of a fixed tax during periods of recession and a variable emissions tax or abatement subsidy policy should be implemented during periods of expansion.

- This shows the significance of taking uncertainties into account when analysing emissions reduction policies. Ignoring the correlation between economic fluctuations and emissions, and only focusing on the deterministic situation in which the firm’s decision over production and reducing emissions does not change over time and is not affected by exogenous factors, such as changes in productivity, can result in a misunderstanding of the costs and benefits of policies and, thus, may increase the risk of encountering undesired changes in emissions over a period of time.

The simulation results for a fixed emissions tax policy which increased by 2.5 per cent per year indicated that such an increase in the tax rate leads to an increase in abatement, and a decrease in output and emissions. However, the reduction in output is almost negligible, while the increase in abatement is significant. These findings provided the answers to the research questions specified in Chapter 1 Section 1.3. These questions and their answers are explained in the next section.

### 8.2. Answers to Research Questions

The following research questions were specified in Chapter 1 Section 1.3. This section provides the answer to them.

1. What would be the effect of emissions reduction programs, including a fixed emissions tax, a variable emissions tax and an abatement subsidy, on Australian emissions and welfare?
In a deterministic situation, a fixed emissions tax policy results in the lowest level of emissions and the highest output and welfare costs. During a boom period, however, the variable emissions tax or subsidy can lead to a better emissions outcome in terms of the highest cumulative emissions reduction.

2. Which one of these emissions reduction programs is likely to be the most efficient in terms of having less negative impacts on Australian GDP and welfare?

The impacts of a variable emissions tax and a subsidy policy are the same. The fixed emissions tax system results in the lowest output and welfare lost and, thus, can have less negative impacts on Australian GDP and welfare under deterministic situations.

3. What would be the effect of TFP shocks on the Australian economy under each of these emissions reduction programs?

When a positive transitory TFP shock happens, output, capital, consumption and emissions increase under all programs while the increase in emissions under a fixed emissions tax program is higher than it is under a variable tax or subsidy program.

4. What would be the effect of these programs on Australia’s business cycles?

These programs can only affect the level of the fluctuations but not their frequency and direction of Australia’s business cycles. They decrease the steady state of output.

1. How can these emissions pricing programs be adjusted to business cycles in order to stabilise emissions?

A variable emissions tax or subsidy can help the Australian government to decrease the influence of output fluctuations on emissions and, thus, stabilise emissions. To this end the
variable tax or subsidy should be adjusted pro-cyclically; that is, the subsidy should increase during booms and decrease during recessions.

The policy implications of these findings are summarised in the next section.

8.3. Summary of Policy Implications

As explained in Chapter 7, Section 7.3, in order to interpret the policy implications of the steady state and stochastic results, the differences between policy ‘rules’ and ‘discretion’ must be clarified first. These two concepts were highlighted by Kydland and Prescott (1977) who argued that the government must set long-term policy rules by evaluating alternative policies and selecting the one with the best opportunity characteristics. However, the government should be aware that there are inherent imperfections in its ability to implement desirable economic policies. This is because different sectors of the economy make optimisation decisions based on current and expected future policies, but their expectations of future policies may be different to the government’s plans and they can be affected by uncertainties. Thus, the government can get benefits from discretionary action; that is, from changes to the rules in an uncertain environment and under defined circumstances.

The implication of such concepts for the findings of the current research is that the government should develop its emissions reduction programs based on the current business cycle. That is, if the government is formulating an emissions reduction policy during a boom, a subsidy or a variable emissions tax policy should be implemented and if it is doing so in a recession, a fixed tax policy should be applied. However, the government should clearly announce ahead of time the changes that may happen to the program due to variations in the business cycle. This can provide different sectors with the opportunity to modify their expectations regarding future policies and avoid potential policy uncertainty.
Additionally, there is a difference between the subsidy policy tested in this thesis and the Australian Emissions Reduction Fund program. The scenario developed here assumes that the policy continues into the future while the Australian program is designed to continue for only five years in order to reduce Australia’s emissions by 5 per cent below the 2000 level by 2020 (Roson, 2013). This implies that even if the program succeeds in achieving the 2020 emissions reduction goal, it would not be able to address the long-term global warming problems of Australia such as predicted droughts, floods, tropical cyclones, heatwaves and bushfires that Australia is likely to face as discussed in Chapter 2 Section 2.6.1. To avoid such problems the government should develop a long-term program by choosing a policy or even a group of policies, assure the economy that such programs will continue into the future, and be committed to following the programs unconditionally regardless of political changes.

Based on these concerns relating to the Emissions Reduction Fund program and the findings of this thesis, the current research provides several suggestions to policy makers which are summarised in Table 8.1.

### Table 8.1: Adjustments that can improve Australia’s emissions reduction programs

<table>
<thead>
<tr>
<th>Implemented emissions reduction programs</th>
<th>Improvement in the implemented emissions reduction programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>The current Emissions Reduction Fund program has been designed to continue for only five years and no program to replace it after that time has as yet been announced.</td>
<td>Australia needs a long-term program to be able to obtain the desired environmental outcomes including meeting international commitments and reducing the environmental consequences of human-caused emissions.</td>
</tr>
<tr>
<td>The number of major polluters, such as</td>
<td>The program should target the main sources of</td>
</tr>
<tr>
<td>Implemented emissions reduction programs</td>
<td>Improvement in the implemented emissions reduction programs</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>----------------------------------------------------------</td>
</tr>
<tr>
<td>electricity and transportation firms, that are involved in the current Emissions Reduction Fund program is low.</td>
<td>emissions and through legislation is should be able to motivate firms to make abatement efforts and shift to cleaner technologies.</td>
</tr>
<tr>
<td>Different programs have been developed by various governments and have been changed several times due to a lack of political consensus on the issue. Climate change has become a political rather than an economic and social issue with many important aspects not adequately discussed.</td>
<td>The major political parties need to come to a consensus through discussing their opinions, setting targets, choosing programs and remaining committed to programs regardless of changes in government. Policies need to be consistent in order to be effective.</td>
</tr>
<tr>
<td>The credibility of emissions reduction policies has been adversely affected by uncertainty caused by changes of programs. A lack of credibility can reduce the environmental efforts of the private sector in the Australian economy.</td>
<td>Policy makers should set and commit to consistent policy rules, should be prepared to change them to meet changing situations. These situations should be pre-announced to the private sector.</td>
</tr>
<tr>
<td>The Australian production sectors, especially the electricity sector, are very carbon intensive since they rely heavily on fossil fuels which are the main sources of emissions.</td>
<td>The government should support a move to less polluting green technology which can help the economy to address emissions reduction without adversely impacting output and jobs.</td>
</tr>
</tbody>
</table>
### Table 1: Implemented emissions reduction programs

<table>
<thead>
<tr>
<th>Implemented emissions reduction programs</th>
<th>Improvement in the implemented emissions reduction programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>International emissions agreements.</td>
<td>The Australian government should take a leading and exemplary role in the implementation of international climate change agreements. Participating in international agreements is likely to be more effective than individual country action. By signing up to international agreements domestic policy on the issue is likely to have greater credibility and to impact economic agents’ expectations in the desired direction.</td>
</tr>
<tr>
<td>Australia is a signatory to the Paris agreement.</td>
<td></td>
</tr>
</tbody>
</table>

Source: Compiled by the author.

#### 8.4. Contributions of the Study

This research has involved the first application of DSGE models in environmental policy analysis in Australia. As explained in Chapter 2, Section 2.6.2, there is a correlation between the fluctuations of emissions and business cycles and this has motivated the current research to investigate the impacts of emissions reduction policies on the responses of emissions to real business cycles. To this end a real business cycle (RBC) model was applied. The main structure of the model benefitted from the work of Heutel (2012). However, the model applied in this study is different to his model in three ways: the scenarios tested, the parameterisation used and the analysis techniques.
The first difference is related to the scenarios. Heutel (2012) tested a variable emissions pricing scenario in which the policy is not constant over time and can be chosen at the beginning of each period. He starts with a centralised decision-making economy in which the sectors’ optimisation behaviours match those of a social planner, which implies that polluters face the costs of pollution they produce and all externalities from pollution are internalised. Then he extended the model to a decentralised economy with asymmetric information about total factor productivity shocks. The present study, however, began with a decentralised economy where polluters do not internalise the costs of the emissions they produce unless the government sets policies which force them to do so. Moreover, while Heutel (2012) tests only a variable emissions pricing system the current research has extended this to include fixed tax and abatement subsidy scenarios which were specified in line with programs that have been implemented in Australia.

The second deviation of this research from Heutel (2012) was in calibrating one of the environmental variables, emissions from the rest of the world. Heutel (2012) calibrated his research to the US economy and assumed that emissions from the rest of the world were three times greater than domestic emissions produced by the US. This assumption, however, would provide a channel to transfer the effects of domestic emissions pricing policy to the rest of the world emissions. That is, it assumes that any changes in domestic emissions due to the implementation of a policy would result in a change in emissions produced by the rest of the world which is not necessarily true for a small economy such as Australia’s. To avoid this, the current research calculated the rest of the world’s emissions under a BAU scenario and kept this figure constant under the various emissions pricing policies. This approach is consistent with the aim of this study which is to analyse the economic effects of emissions pricing policies on Australia, not on the world economy. Therefore, this study delivered
theoretical contributions by extending the scenarios and presenting a different calibration approach, in addition to a practical contribution in terms of applying the model to Australia.

The third contribution of the current research is about the technique used for analysis. Heutel (2012) presented and discussed the outcomes of his model graphically through IRFs which is a common approach in DSGE modelling. Besides this some researchers, such as Fischer and Springborn (2011), present their results not only via IRFs but also by numerically calculating and comparing steady state solution levels. This thesis has provided a new technique by combining these two approaches in order to find the effects of each policy when a shock happens. To this end this thesis calculated the area under the IRFs which shows the cumulative changes in a variable over the adjustment period (i.e. the time period over which the effects of shock are observed). Multiplying the figure for the area under the IRF by the steady state value of that variable can numerically show the total changes in a variable. Comparing the total changes of variables under the different scenarios makes it possible to compare the entire effects of the programs, not only in regard to steady state values, but also in regard to the cumulative gain or loss that each program can cause on a variable for the entire adjustment process.

This research, however, has several limitations which need to be addressed in future studies. These limitations and the potential extension of this thesis are explained in the next section.

8.5. Limitations and Future Study Directions

Despite the progress made in DSGE modelling since Kydland and Prescott (1982), developing and applying these models still requires strenuous effort due to their complexity. This research, in particular, involved up to 14 equations under each scenario, including several complex and nonlinear equations. This made the model too complicated to derive an
analytical solution. To obtain a numerical solution, a DSGE modeller also needs to have strong mathematical and programming skills.

Another limitation of the study is in regard to data availability and accuracy. This limitation occurred in estimating the elasticity of emissions to output in Chapter 5. As explained in Section 5.2, this research used quarterly data of emissions for Australia collected from September 2001 to December 2013 from Australia’s National Greenhouse Accounts (Department of the Environment, 2014b). This is currently the longest time span for which data on Australia’s emissions is available. Accessing emissions data over a longer period in future would increase the accuracy of the coefficients estimated.

Future studies could also discard some of the assumptions made in this research for the sake of simplicity. One of the assumptions made in the model was that there was only one integrated producer. Relaxing this assumption will enable researchers to address the distributional costs of policies for different sectors with different carbon intensities, or answer the question of which sector will be more motivated to make abatement effort and shift to cleaner technologies under a particular policy. Another assumption was about the allocation of tax revenue. This research assumed that the government recycles the revenue to households in the form of a lump sum, since the aim of this research was not to investigate the effectiveness of revenue allocation approaches. Future studies, however, can address this issue by specifying different transfer approaches and investigating the efficiency of each one in a real business model. For instance, the government can use the revenue from the tax to reduce the distorting effect of taxes on other factors such as labour and capital, or to reduce the budget deficit. The government can also allocate the tax revenue directly towards a less polluting economy by updating current technologies, or even moving to zero pollution by investing in R&D.
The specification of the economic and environmental relationships in the literature is broad and future studies can use alternative specifications and functions. For instance, Thampapillai and Sinden (2013) consider nature as capital and hence their distinct equilibrium is \( Y = \text{GDP} - D_{KN} \) where \( D_{KN} \) is the depreciation of natural capital. In another study, Thampapillai (2016) estimates the size of the air shed utilized in Australia. These studies can be used to extend the estimation results of the current research. Another factor that can be investigated in future research is the role of science in determining the level and relevance of intervention since scientific information can, and should, guide the regulator’s preferences.

Additionally, this research abstracted from productivity growth and focused on business cycle implementation of emissions reduction policies. Future studies could extend the model to turn it into a growth model which includes productivity growth, population growth and abatement technology growth. Furthermore, as a small open economy, Australia’s real business cycles are affected not only by domestic shocks such as TFP, but also by foreign shocks. In future research the model used could be tailored to the Australian economy even more by extending the analysis to the performance of emissions reduction policies in the presence of foreign shocks.

Finally, as explained in Chapter 4, Section 4.2 the existing literature on environmental DSGE modelling has four limitations which need to be overcome in future studies: first, their emphasis on real shocks rather than other types of economic and environmental uncertainties; second, the application of calibration for parameterisation rather than estimation; third, as a result of calibration, the models in these studies focus on forecasting deviations from the steady state of macroeconomic variables rather than the level of such variables; and fourth, environmental DSGE models are usually simplified to one integrated sector. Overcoming
these four limitations in future studies can improve the application of these models for environmental analysis and provide more straightforward conclusions for policy makers.
Appendix

A.1. Estimation of output in the emission equation

The emissions for each period are a function of output, $h(y_t)$, which is specified as $h(y_t) = y_t^{1-\gamma}$. In order to obtain the exponential coefficient $1-\gamma$, quarterly data for Australian emissions and GDP are used from Australia’s National Greenhouse Accounts (Department of the Environment, 2014b) and the Australian National Accounts (Australian Bureau of Statistics, 2014) respectively, for the period of September 2001 to December 2013. Using this data, the exponential coefficient can be found by regressing the log of emissions on the log of output. The regression result is presented in Table A.1. As the table shows the coefficient $1-\gamma$, is equal to 0.0975.

Table A.1: Regression of log CO₂e emissions on log output

<table>
<thead>
<tr>
<th>Regression Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple R</td>
</tr>
<tr>
<td>R Square</td>
</tr>
<tr>
<td>Adjusted R Square</td>
</tr>
<tr>
<td>Standard Error</td>
</tr>
<tr>
<td>Observations</td>
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</table>

<table>
<thead>
<tr>
<th>ANOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>df</td>
</tr>
<tr>
<td>-----</td>
</tr>
<tr>
<td>Regression</td>
</tr>
<tr>
<td>Residual</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Standard Error</th>
<th>t Stat</th>
<th>P-value</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
<th>Lower 95%</th>
<th>Upper 95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.5923</td>
<td>0.0416</td>
<td>38.2942</td>
<td>0.0000</td>
<td>1.5087</td>
<td>1.6759</td>
<td>1.5087</td>
</tr>
<tr>
<td>LOG(GDP)</td>
<td>0.0975</td>
<td>0.0076</td>
<td>12.7685</td>
<td>0.0000</td>
<td>0.0821</td>
<td>0.1128</td>
<td>0.0821</td>
</tr>
</tbody>
</table>
A.2. Log-Linearisation

A nonlinear system of equations does not usually have a closed-form solution. Instead, a numerical solution can be found. To this end the model needs to be log-linearised around the steady state values of variables. The log-linearised model will be used to show fluctuations occurring for variables arising from exogenous shocks. The main idea behind such an approximation is that a nonlinear system of equations, including optimal conditions and resource constraints, can be converted to a linear system if the linear approximation happens in the neighbourhood of a non-stochastic steady state. Thus, the solution near stationary points is a good approximation to the solution for a derived linear system which helps in understanding the behaviour of the underlying nonlinear system. This approximation is called a linear approximation which is a standard approach and can be done through log-linearisation (King et al., 2002). In this method the approximation is a Taylor expansion around a steady state. To be clear, consider a nonlinear model which can be shown by a set of equations such as these:

\[ F(x_t) = \frac{G(x_t)}{H(x_t)} \quad (A-1) \]

where \( x_t \) is a vector of variables which can include expectational variables, lag or lead variables. To conduct log-linearisation, first the logarithm of the functions \( F, G \) and \( H \) must be found and then a first-order Taylor expansion is conducted. Taking the logarithms leads to:

\[ \ln(F(x_t)) = \ln(G(x_t)) - \ln(H(x_t)) \quad (A-2) \]

Taking the first-order Taylor series approximation around the steady state, \( \bar{x} \), gives:
\[
\ln(F(\bar{x})) + \frac{F'(\bar{x})}{F(\bar{x})}(x_i - \bar{x}) \approx \ln(G(\bar{x})) + \frac{G'(\bar{x})}{G(\bar{x})}(x_i - \bar{x})
\]

\[
- \ln(H(\bar{x})) - \frac{H'(\bar{x})}{H(\bar{x})}(x_i - \bar{x})
\]

where the notation \(X'(\bar{x})\) shows the derivative of \(X\) at the steady state of \(x\). The model presented by equation (A-3) is now linear in \(x\) since \(\ln(G(\bar{x})), \frac{G'(\bar{x})}{G(\bar{x})}, \ln(H(\bar{x}))\) and \(\frac{H'(\bar{x})}{H(\bar{x})}\) are all constants. Given the steady state of equation (A-2)

\[
\ln(F(\bar{x})) = \ln(G(\bar{x})) - \ln(H(\bar{x}))
\]

Now, the three \(\ln(X(\bar{x}))\) can be excluded and equation (14) can be simplified to:

\[
\frac{F'(\bar{x})}{F(\bar{x})}(x_i - \bar{x}) \approx \frac{G'(\bar{x})}{G(\bar{x})}(x_i - \bar{x}) - \frac{H'(\bar{x})}{H(\bar{x})}(x_i - \bar{x})
\]

The implicit assumption is that conditions stay in the neighbourhood of the steady state, so that second-order or higher terms of the Taylor expansion are small enough to be irrelevant and can thus be left out.

(Uhlig (1999)) provides a simpler method, called Uhlig's toolkit, for finding a log-linear approximation of a function. His method does not require taking derivatives, yet leads to the same result as the Taylor expansion method. The only difference is that in Uhlig’s method, the linear model is expressed in terms of log differences of variables. Below, Uhlig’s method is explained.

Consider an equation of a set of variables \(X_i\). Define \(\tilde{X}_i = \ln(X_i) - \ln(\bar{X})\). The tilde variable is the log difference of the original variable from the steady state value \(\bar{X}\). Thus, the original variable can be written as
\[ \tilde{X} e^{\tilde{X}_t} = \tilde{X} e^{\ln(X_t) - \ln(\tilde{X})} = \tilde{X} e^{\ln(X_t) / \ln(\tilde{X})} = \tilde{X} X_t / \tilde{X} = X_t \]  

(A-6)

Thus, Uhlig’s definitions are

\[ \tilde{X}_t = \ln(X_t) - \ln(\tilde{X}) \]  

(A-7)

\[ X_t = \tilde{X} e^{\tilde{X}_t} \]  

(A-8)

Also, Uhlig’s rules are

\[ e^{\tilde{X}_t + a\tilde{Y}_t} \approx 1 + \tilde{X}_t + a\tilde{Y}_t \]  

(A-9)

\[ \tilde{X}_t \tilde{Y}_t \approx 0 \]  

(A-10)

\[ E_t[a e^{\tilde{X}_t}] \approx a + aE_t[\tilde{X}_t] \]  

(A-11)

Using the abovementioned rules and definition simplifies the process of log-linearisation which has been applied in this study.
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