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# **Australian Emissions Reduction Subsidy Policy under Persistent Productivity Shocks**

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# **Australian Emissions Reduction Subsidy Policy under Persistent Productivity Shocks**

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## **Abstract**

The implementation of emissions reduction 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. One of the critical concerns of policy makers is that the costs of these policies would adversely affect economic activity and result in larger economic volatility. This paper investigates how business cycle fluctuations of the Australian economy, arising from productivity shocks, would be affected under an abatement reduction subsidy policy in which the regulator supports abatement efforts in each period. To answer this question, a real business cycle (RBC) model is applied. The responses of economic and environmental variables to unexpected productivity shocks are presented and compared. The results indicate that the regulator should adjust the abatement subsidy to be pro-cycle, i.e. increase during expansion and decrease during recessions.

*Keywords:* emissions reduction policy, real business cycle, productivity shock, Australia

*JEL Codes:* C61, H23, O56, Q58

## 1. Introduction

The implementation of emissions control policies in Australia has experienced significant volatility over the last decade as the result of policy makers' different attitudes towards the costs and benefits of such policies. The Australian emissions pricing system was introduced under the Clean Energy Programme by the Australian government under the Prime Ministership of Julia Gillard in 2011. The program included two phases: first, a fixed price, or a carbon tax, period commenced from 1 July 2012 and was originally planned to continue until 30 July 2015 when the second phase, with a variable price system under an emissions trading scheme, would begin. However, under the Prime Ministership of Kevin Rudd 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 in which the government funds emissions reduction activities including the improvement of energy efficiency standards (Australian Government, 2014b). Such fluctuations are in contrast to Stern (2006) who discusses that a successful emissions scheme requires that the society, especially consumers and investors, believe that the policy will continue in the future, particularly in regard to high-carbon goods and services.

To investigate the effects of the above mentioned policies on the Australian economy, Computable General Equilibrium (CGE) models have been broadly used (Asafu-Adjaye, 2004; Asafu-Adjaye and Mahadevan, 2013; Meng *et al.*, 2013) and several sophisticated models such as ORANI, GTEM and G-Cubed have been developed to illustrate widespread interactions between economic agents. These models are all deterministic in nature ignoring any environmental and economic uncertainty related to environmental policies. The choice of environmental policy, however, depends on the size and source of uncertainty (Angelopoulos *et al.*, 2010). The literature in environmental economics also highlights the role of uncertainty in environmental policy analysis. This literature, beginning with Weitzman (1974), shows that under asymmetric information conditions when the regulator cannot observe the real firm's abatement costs, price-based (quantity-based) controls, such as a carbon tax (cap), will be an advantage if the marginal cost curve is steeper (flatter) and the marginal benefit curve is flatter (steeper). In order to add other types of uncertainties into environmental policy

analysis, we can use a Dynamic Stochastic General Equilibrium (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 optimization behaviour of agents with different constraints, technology and equilibrium. DSGE models are also compatible with including sources of uncertainty and to be solved for exogenous shocks.

In this paper, we study the transitions effects of abatement subsidy policy, which is similar to the current Australia's emissions reduction policy, under macroeconomic uncertainty conditions. To this end we use a real business cycle (RBC) model to compare the dynamic effects of three different emissions reduction policies when productivity shocks occur.

The literature on DSGE environmental analysis is still in a preliminary stage and mostly focuses on RBC models showing how environmental policies respond to economic fluctuations. These models were first introduced by Fischer and Springborn (2011) who apply an RBC model with total factor productivity (TFP) shocks to provide a comparison between an emissions tax, an emissions cap, and an intensity target. 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, a few other studies have applied DSGE models for environmental policy analysis including Hassler and Krusell (2012), Angelopoulos *et al.* (2013), Dissou and Karnizova (2012) and Annicchiarico and Di Dio (2015). In this paper, we follow the existing literature by analysing emissions reduction policies in an RBC framework; however, we compare the behaviour of an abatement subsidy. We show that with the presence of productivity shocks, the abatement subsidy policy would affect only the level and not the volatility of business cycles. We also show that the subsidy should be implemented to be pro-cyclical, i.e. increase during expansion and decrease during recession.

This paper proceeds as follows. Section 2 presents the model used which is calibrated in Section 3. The model is solved and the results are displayed and discussed in Section 4. Section 5 provides conclusions and discusses the future research direction.

## **2. Model**

In this paper we generally follow Heutel (2012) to obtain the structure of an environmental RBC model. The focus of his research is a centralised economy in which the economy's

agents' optimisation problem is the same as the social planner's problem and there is no externality. He then extended his model to a decentralised economy to study the performance of an emissions tax under asymmetric information regarding total factor productivity shocks. In this paper we use a decentralised economy with an externality from pollution in which polluters are not automatically concerned about the costs of pollution they produce. The model consists of a representative producer and a representative consumer where production  $y_t$  generates emissions  $m_t$ . We outline the main structure of the model in Sections 2.1, 2.2 and 2.3 and we then specify the emissions reduction policy in Section 2.4.

### 2.1. Environment

The emissions aggregate in the atmosphere can be shown by the pollution stock  $x_t$  which imposes negative effects on the economy in terms of damages  $d(x_t)$ . 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. Thus,  $d(x_t)$  is an increasing function 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 jungles and oceans. The stock of pollution is a function of domestic emissions  $m_t$  and emissions from the rest of the world  $m_t^{row}$ :  $x_t = \eta x_{t-1} + m_t + m_t^{row}$ . Emissions arise from production equal to:  $m_t = (1 - \mu_t)h(y_t)$  in which  $h$  shows the relationship of emissions with output for given technology, maintaining constant abatement.  $0 \leq \mu_t \leq 1$  is abatement or the fraction of emissions abated in period  $t$  which can be done by shifting to environmental friendly technologies such as renewable energies and is determined by  $g(\mu_t) = z_t / y_t$ .  $g(\mu_t)$  is the marginal abatement cost which is proportional to output. This implies that total abatement spending  $z_t$  is equal to the marginal abatement cost multiplied by total output:  $z_t = g(\mu_t)y_t$ .

### 2.2. Production Sector

There is a representative agent who produces a commodity using capital from the last period  $k_{t-1}$ . Like many other emissions reduction policy analyses (Kelly, 2005; Schumacher and Zou, 2008; Heutel, 2012; Angelopoulos *et al.*, 2013), labour is not included here for simplicity since employment fluctuation is not the interest of this study. The production function is  $y_t = (1 - d(x_t))a_t f(k_{t-1})$  in which  $a_t$  is total factor productivity (TFP) and is the main source of economic fluctuations with an expected value of 1.  $a_t$  evolves according to a stationary,

first order autoregressive process:  $\ln a_t = \rho \ln a_{t-1} + \varepsilon_t$  where  $\rho$  is the persistence parameter and  $\varepsilon_t$  is an i.i.d. normal random variable, known as the innovation shock to the productivity, with a mean of zero and standard deviation  $\sigma$ . This random variable can occur once each period and can be observed by agents at the beginning of that period. Here, the externality of pollution arises as the firm does not consider the effects of emissions it produces although it receives damage from the stock of pollution. This assumption is plausible in a competitive market in which there are many identical small firms, each chooses the optimal level of abatement (and thus, emissions) while they receive damages from the aggregate of pollution from domestic emissions and emissions from the rest of the world. In such a market the firm is sufficiently small that it ignores the impact of 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:  $\pi_t = y_t - r_t k_{t-1} - z_t$  where  $\pi_t$  is profit and  $r_t$  is the rate of return on capital.

### 2.3. 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  $a_t$  at the beginning of each period and expect future values of  $a_{t+1}$  and thus, maximises *expected* total discounted utility:  $E_t \sum_{t=0}^{\infty} \beta^t u(c_t)$ . The operator  $E_t$  is the expectation of future values of  $a_{t+1}$  at period  $t$  and  $\beta$  is the discount factor. The household is the owner of the firm and receives the 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  $\delta$ :  $k_t = (1 - \delta)k_{t-1} + i_t$  and the budget constraint is:  $\pi_t + r_t k_{t-1} = c_t + i_t$ .

### 2.4. Emissions Reduction Scenarios

In this section, we specify four scenarios including Business-as-usual (BAU), fixed emissions tax, variable emissions tax and abatement subsidy. Under a BAU scenario the government does not make any environmental policy. Thus, there is no price on emissions and the firm can produce emissions at any desired level. Without any emissions policy the profit maximising firm is not motivated to engage in abatement activity and, consequently, it does not take into account the effects of emissions it produces. The firm sets the costs of

abatement equal to zero, i.e.  $z_t=0$ , by refusing any abatement activities, i.e.  $\mu_t=0$ . Optimising the profit over capital, the marginal value product of capital is set equal to the rate of return:  $r_t = y_t f'(k_{t-1}) / f(k_{t-1})$ . On the other hand, the consumer chooses between consumption and investment by maximising expected discounted utility which results in the Euler equation  $-u'(c_t) + \beta E_t u'(c_{t+1}) [r_{t+1} + (1 - \delta)] = 0$ . The household's optimisation behaviour results in the same Euler equation under other scenarios as well. Using these equations we can display the economy under a BAU scenario as:

$$r_t = y_t f'(k_{t-1}) / f(k_{t-1}) \quad (1)$$

$$m_t = h(y_t) \quad (2)$$

$$\pi_t + r_t k_{t-1} = c_t + i_t \quad (3)$$

$$\pi_t = y_t - r_t k_{t-1} \quad (4)$$

$$-u'(c_t) + \beta E_t u'(c_{t+1}) [r_{t+1} + (1 - \delta)] = 0 \quad (5)$$

$$x_t = \eta x_{t-1} + m_t + m_t^{row} \quad (6)$$

$$y_t = (1 - d(x_t)) a_t f(k_{t-1}) \quad (7)$$

$$k_t = (1 - \delta) k_{t-1} + i_t \quad (8)$$

$$\ln a_t = \rho \ln a_{t-1} + \varepsilon_t \quad (9)$$

In an abatement subsidy regime, the regulator supports abatement by allocating the subsidy of  $s_t$  to the firm for any abatement effort made in each period:  $\mu_t$  is the percentage of emissions abated in each period, holding output constant. We assume that the regulator is neutral as they levy a lump-sum tax on consumers and allocates the revenues to subsidise the abatement efforts. Thus, the resource constraints are:

$$\pi_t + r_t k_{t-1} - s_t \mu_t = c_t + i_t \quad (10)$$

$$\pi_t = y_t - r_t k_{t-1} + s_t \mu_t \quad (11)$$

The subsidy motivates the firm to decrease emissions by decreasing production or making abatement efforts since emissions is a function of output and abatement, equation (12). The cost of abatement is shown by equation (13).

$$m_t = (1 - \mu_t) h(y_t) \quad (12)$$

$$z_t = g(\mu_t) y_t \quad (13)$$

Under this policy the firm chooses the optimal level of abatement which maximises profit, equation (10), subject to equations (7), (12) and (13) which results in  $g'(\mu_t) y_t = s_t$ . Maximising revenue with respect to capital also leads to the optimal level of capital in each



period as  $r_t = y_t f'(k_{t-1}) / f(k_{t-1}) [1 - g(\mu_t)]$ . 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:

$$\max_{s_t, k_t, y_t, x_t} \sum_{t=0}^{\infty} \beta^t E u(c_t) \quad (14)$$

subject to equations (5) to (13) and

$$g'(\mu_t) y_t = s_t \quad (15)$$

$$r_t = y_t f'(k_{t-1}) / f(k_{t-1}) [1 - g(\mu_t)] \quad (16)$$

We can write this optimisation problem in the Lagrangian equation below:

$$\begin{aligned} L_t = & \sum_{t=0}^{\infty} \beta^t E_t u(y_t - k_t + (1 - \delta)k_{t-1} - z(s_t, y_t)) + \lambda_t \{-u'(y_t - k_t + (1 - \delta)k_{t-1} - z(s_t, y_t)) \\ & + \beta u'(y_{t+1} - k_{t+1} + (1 - \delta)k_t - z(s_{t+1}, y_{t+1})) \times (r(y_{t+1}, k_t) + 1 - \delta)\} \\ & + \varsigma_t \{x_t - \eta x_{t-1} + m_t^{row} + m(s_t, y_t)\} + \omega_t \{y_t - [1 - d(x_t)]f(k_{t-1})\} \end{aligned} \quad (17)$$

Optimising this Lagrangian with respect to abatement subsidy leads to:

$$\begin{aligned} & -u'(c_t) z'_s(s_t, y_t) + \lambda_t \{u''(c_t) z'_s(s_t, y_t)\} \\ & + \lambda_{t-1} \{u''(c_t) (-z'_s(s_t, y_t)) (r_t + 1 - \delta)\} + \varsigma_t \{-m'_s(s_t, y_t)\} = 0 \end{aligned} \quad (18)$$

In order to solve such a Ramsay model the regulator optimises social welfare over  $k_t$ ,  $y_t$  and  $x_t$  as below:

$$\begin{aligned} & -u'(c_t) + \beta u'(c_t) (1 - \delta) + \beta \lambda_{t+1} \{-u''(c_{t+1}) (1 - \delta)\} \\ & + \lambda_t \{u''(c_t) + \beta u''(c_{t+1}) (1 - \delta) (r_{t+1} + 1 - \delta) + \beta u'(c_{t+1}) r'_k(y_{t+1}, k_t)\} \\ & + \lambda_{t-1} \{-u'(c_t) (r_{t+1} + 1 - \delta)\} - \beta \omega_{t+1} [1 - d(x_{t+1})] a_{t+1} f'(k_t) = 0 \end{aligned} \quad (19)$$

$$\begin{aligned} & u'(c_t) (1 - z'_y(s_t, y_t)) + \lambda_t \{-u''(c_t) z'_y(s_t, y_t)\} + \omega_t \\ & + \lambda_{t-1} \{u''(c_t) (1 - z'_y(s_t, y_t)) (r_t + 1 - \delta) + u'(c_t) r'_y(y_t, k_{t-1})\} + \varsigma_t \{-m'_y(s_t, y_t)\} = 0 \end{aligned} \quad (20)$$

$$\varsigma_t - \beta \varsigma_{t+1} \eta + \omega_t a_t f'(k_{t-1}) d'(x_t) = 0 \quad (21)$$

Equations (5) to (16) and (18) to (20) represent the economy under the abatement subsidy regime. These equations, plus those from BAU scenario, are calibrated in the next section.

### 3. Calibration

In order to calibrate the model we first specify the general relationships of the model, such as the utility function and production function. Like Heutel (2012), the current research utilizes 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, emissions from the rest of the world. Calibrating his research to the US economy, Heutel (2012) assumes that emissions from the rest of the world is 3 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 provides a channel to transfer the effects of domestic emissions reduction policies to the rest of the world emissions. In other words, if a policy affects domestic emissions its effect would transfer to the emissions produced by the rest of the world, which is not necessarily true. To avoid this we calculate the rest of the world emissions under a business-as-usual (BAU) scenario and will keep it constant under the abatement subsidy policy. This assumption is consistent with the aim of this study, which is to analyse the performance of emissions reduction policies on Australia and not on the world economy. We collect the global and Australian carbon dioxide emissions data from the Carbon Dioxide Information Analysis Centre (CDIAC) over the period 1950-2010 (CDIAC, 2013). The data reveals that emissions from the rest of the world are about 30 times greater than that of Australia's. Therefore, the rest of the world's emissions are set at 30 times the steady state value of domestic emissions  $m$  under a BAU scenario:  $\bar{g}m$  where  $\bar{g}$  is equal to 30.

After specifying the functions the model is parameterised to the Australian economy. To parameterise our RBC model we use Australian RBC literature, such as Rees (2013), Gomez-Gonzalez and Rees (2013), Jaaskela and Nimark (2011). The coefficient of output over emissions is not available in the literature and we estimate it using Australian databases including the Australian National Accounts (Australian Bureau of Statistics, 2014) and Australia's National Greenhouse Accounts (Australian Government, 2014c). We also use the Regional Integrated model of Climate and the Economy (RICE) model to calibrate abatement cost and damage functions. In the latest model, RICE (2010), 198 countries of the global economy are divided into 12 regions in which Australia is in the Other High Income (OHI) group. Thus, we use the parameters of the OHI group.

The consumption sector is calibrated first. Each period of time is set equal to a quarter. We use Jaaskela and Nimark (2011), Gomez-Gonzalez and Rees (2013) and Rees (2013) to

calibrate the utility discount factor  $\beta$ , i.e. the rate at which the consumer discounts the utility gained from future consumption. They all estimated  $\beta$  to be equal to 0.99. The capital depreciation rate  $\delta$  is set equal to 0.02 (Rees, 2013). The consumer utility function is

$$u(c_t) = \frac{c_t^{1-\zeta}}{1-\zeta} \text{ where } \zeta \text{ represents the constant coefficient of relative risk aversion and is set}$$

to 1.66<sup>1</sup> based on Hodge *et al.* (2008).

To calibrate  $g(\mu_t)$  we use the RICE model. Nordhaus (2010) assumes that  $g(\mu_t)$  is highly convex and the marginal costs of emissions abatement rises more than linearly with the abatement rate. 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 an initial value of 0.07 for the OHI countries which decreases by 5 percent each decade to be 0.029 in 50 years. Such a little change in  $\theta_1$  makes us able to assume that it is constant at its initial value since incorporating changes in backstop technologies is not the aim of this paper. For calibrating  $\eta$ , which represents the persistence of pollution in the atmosphere, we follow Heutel (2012), who uses the Reilly and Anderson (1992) estimation of the half-life of atmospheric carbon dioxide which is 83 years and is equivalent to 0.9979 quarterly. We can specify the relationship between output and emissions  $h(y_t)$  as  $h(y_t) = y_t^{1-\gamma}$ . We estimate  $1-\gamma$  as the regression coefficient of the log of emissions on the log of output. To find this coefficient we collect the seasonally adjusted quarterly data of emissions for Australia from September 2001 to December 2013 from Australia's National Greenhouse Accounts (Australian Government, 2014c) as well as the seasonally adjusted quarterly data on Australian GDP for September 2001-December 2013 from the Australian National Accounts (Australian Bureau of Statistics, 2014). We estimated the coefficient,  $1-\gamma$ , to be equal to 0.0975. The regression results are presented in Appendix A.1.

We set the damage function  $d(x_t)$  to a linear 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 Appendix A.2. The production function is calibrated to  $f(k) = k^\alpha$  where  $0 < \alpha < 1$  shows the output elasticity of capital. Calibrating to Rees (2013) and Gomez-Gonzalez and Rees (2013)  $\alpha$  equals 0.33. Finally, we use Rees (2013) to calibrate the persistence of TFP shocks,  $\rho$ , to be 0.98 while  $\varepsilon_t$  is a normally distributed IID shock with a mean of 0 and standard deviation,  $\sigma$ , of 0.0069. Table 1 summarises all the parameters explained above.

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<sup>1</sup> This can be interpreted as the elasticity of the marginal utility of consumption and is equal to 1.66.

**Table 1:** Summary of the model parameters

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

Source: compiled by the authors.

We substitute these equations and parameters into the model described in Section 2 to obtain the numerical results in the next section.

#### 4. Simulation Result

The model does not have an analytical solution, thus we present the numerical solution here. We start with the steady state solutions where  $a_t$  is equal to the expected value of 1. The BAU results are used as a benchmark case to compare with the effects of abatement subsidy policy. The steady state of a variable  $\bar{b}$  is the value that does not change over time, i.e.  $b_t = b_{t+1}$ . A stability test has also been conducted to assure that the dynamics of the model is stable. Table 2 shows the steady state levels of the economic and environmental variables when TFP is equal to one. The table also represents the percentage changes of variables under an abatement subsidy policy relative to the BAU. The simulation results indicate that an abatement subsidy policy can lead to emissions reductions of 6.45 percent under the subsidy policy. This indicates that the subsidy policy can provide motivations for a producer to undertake emissions abatement but this outcome comes at an economic cost. The steady state outcomes reveal that under the subsidy policy capital has a reduction of 4.68 relative to the BAU scenario percent under the abatement subsidy policy. The drop in capital, as an input, in the subsidy policy results in a reduction in output which can be taken into account as GDP. As the table shows, output decreases by 1.52 percent relative to the BAU scenario under the subsidy policy.

The GDP reduction in the subsidy regime results in the lower income for households, and so the lower consumption as it decreases to 0.60 percent lower than BAU compared. We are also interested to find the welfare costs of the subsidy policy. To this end we follow 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 of the reduction in consumption which is needed under a policy to make the consumer indifferent between a BAU scenario and the 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 welfare costs of 0.60 percent in the abatement subsidy policy.

**Table 2:** Steady-State Levels with TFP Equal to 1

<b>Variable</b>	<b>BAU</b>	<b>Emissions Reduction Subsidy (% change from BAU)</b>
Emissions ( $m$ )	1.1075	1.0361 (-6.45%)
Abatement ( $\mu$ )	0	0.0625
Output ( $y$ )	2.8335	2.7904 (-1.52%)
Capital ( $k$ )	32.0936	30.5901 (-4.68%)
Consumption ( $c$ )	2.1917	2.1785 (-0.60%)
Welfare Cost	0	0.60%

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Source: Authors' calculations.

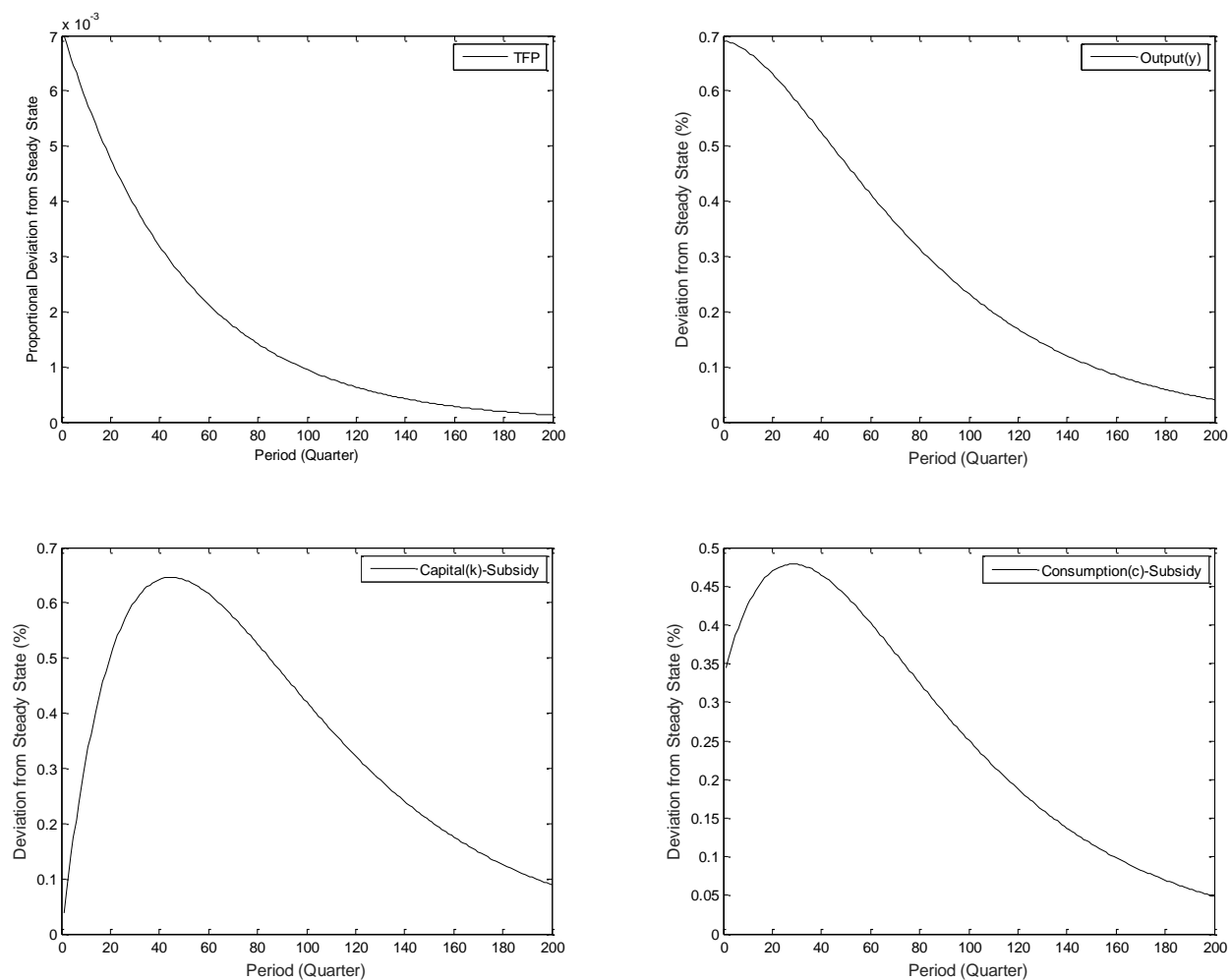
The above results represent the economy when TFP is equal to 1 and no shock occurs. In order to obtain a solution in the presence of TFP shocks, we log-linearize the model around the steady state values. The log-linearized model will be a good approximation of the original model which facilitates showing small fluctuations around steady state caused by a shock. To solve the log-linearized model we use the Anderson-Moore Algorithm (AMA)<sup>2</sup> which is a method for solving complex problems including perfect-foresight models and for asymptotic constraints on non-linear models, which contain the main features of the model used in the current study. Then the model is coded to Matlab. The solution results can be shown graphically via two approaches: first, impulse response functions (IRFs) which are the response path of the economic and environmental variables over a period of time when a TFP

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<sup>2</sup> AMA was developed at the Federal Reserve Board by Anderson and Moore (1985) and evaluated by Anderson (2008) and Anderson (2010) and is verified as an accurate, fast available method.

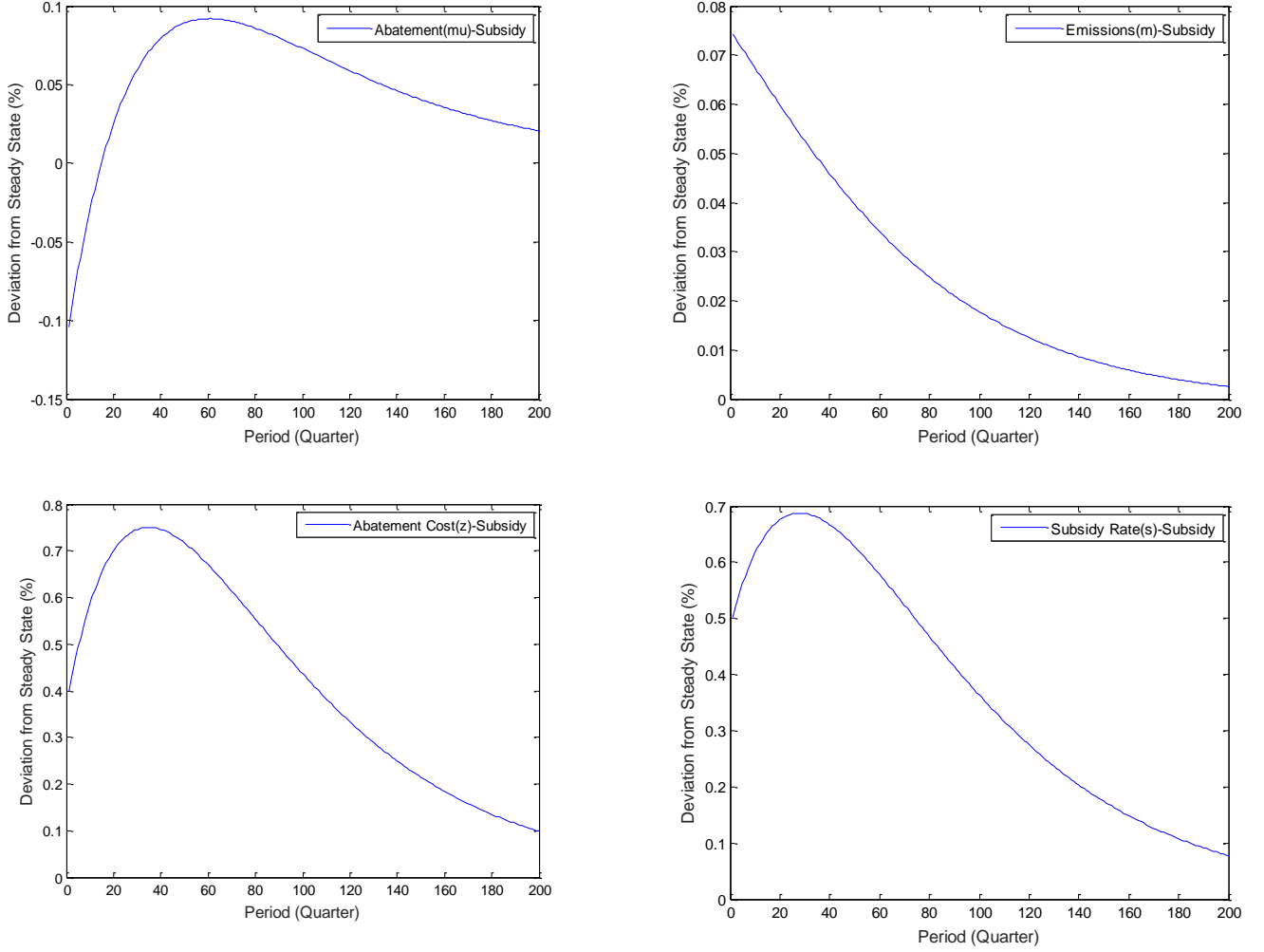
shock occurs in the first period; second, via simulating business cycles in the economy by introducing a series of TFP shocks over a period of time and analysing the responses of variables to those shocks. We present both approaches here.

Figure 1 displays the response path of four economic variables including TFP, capital, output and consumption to a one-time, transitory shock to TFP under the abatement policy. The shock occurs exogenously in period one at the size of one standard deviation of the innovation, 0.0069, and decays at the rate of 0.98. As shown by the figure 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 innovation shock occurs exogenously. The simulation is run for 200 periods, equal to 50 years. The result shows that the responses of economic variables to a one period shock are pro-cyclical, i.e. follow the same direction of 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 of TFP, i.e. the first period. The increase of productivity of capital raises the firm's demand for capital. However, the peak of capital does not occur at the first period since TFP is a flow variable while capital is stock and, thus, it takes more time, about 45 periods, equal to 11 years, to reach its peak. Consumption is highly affected by output, capital and abatement costs:  $c_t = y_t - k_t + (1 - \delta)k_{t-1} - z_t$ . As shown by the figure a positive TFP shock leads to an increase in consumption which highlights the key role of income in consumption: an increase in income will increase consumption regardless of the direction of changes in investment and abatement costs. The dynamic of the consumption response, however, is affected by the path of capital and it does not peak in the first period, but by around period 30 equivalent to year 7.



**Figure 1:** Impulse Responses of Economic Variables to a TFP Shock under an Abatement Subsidy Scenario





**Figure 2:** Impulse Responses of Environmental Variables to a TFP Shock under an Abatement Subsidy Scenario

The effects of a positive TFP shock on environmental variables are also presented here, in Figure 2. The figure displays the response path of abatement, emissions, abatement costs, variable emissions tax rate and subsidy rate when the same TFP shock occurs. As the figure shows, the impulse response function of abatement is pro-cyclical under the subsidy system, i.e. follows the same direction of the shock. This is due to the fact that under a subsidy scenario the firm's choice of abatement is affected by not output as well as the subsidy rate. The first relationship, i.e. with output is affected by the sign of  $\gamma$ ,  $\theta_1$  and  $\theta_2$ . As explained in Section 3,  $1-\gamma$  represents the emissions elasticity of output and, thus, it is strongly positive, calculated as 0.0975. Also,  $\theta_1$  and  $\theta_2$  determine the relationship between abatement and abatement cost which are positive, and calibrated to be 0.007 and 2.8 respectively. These

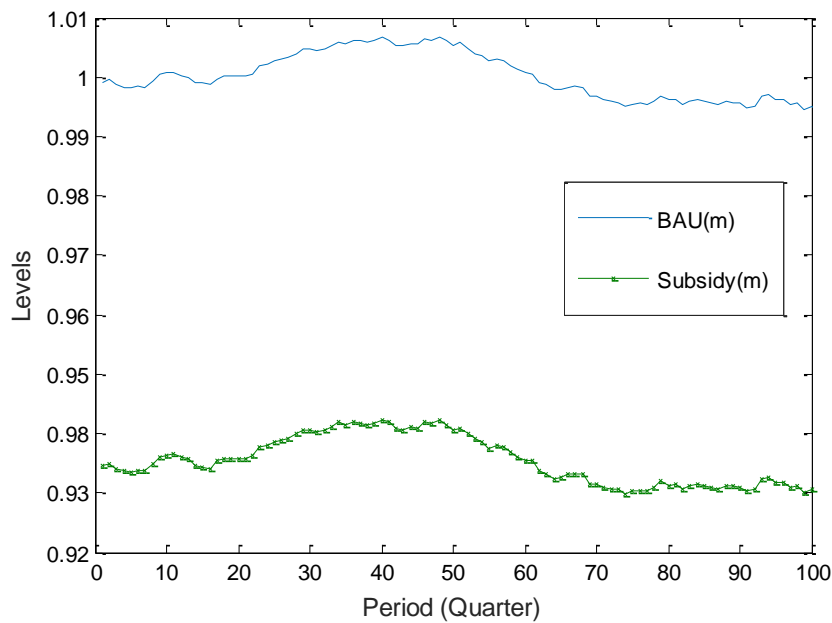
positive parameters result in a negative relationship between abatement and output which means that a positive TFP shock which increases output leads to a decrease in abatement.

To investigate how the subsidy would be affected by a shock the IRF of subsidy is simulated and displayed in Figure 2. As shown by the figure the response path of subsidy is procyclical. Also, since the subsidy is a function of current and expected future consumptions, it follows the consumption path and peaks in period 30, year 7. Therefore, an increase in TFP leads to an increase in output and subsidy. The subsidy increase motivates the firm to decrease emissions by increasing abatement while the increase in productivity, and consequently output, signals the firm 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, however, the motivation of subsidy dominates and abatement increases to a positive deviation from steady state and peaks in period 60, year 15.

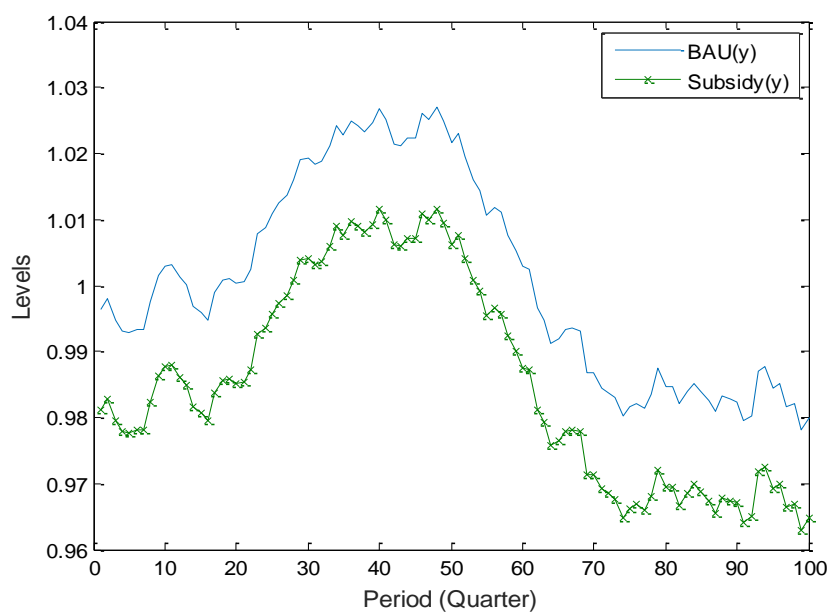
The response paths of abatement costs the positive shock will simulate the subsidy to increase and the higher subsidy rate motivates the firm to increase the subsidy revenue by reducing emissions which can be done via increasing abatement at the same level of output, equation (12). Also, the abatement response path follows the subsidy path peaks in period 30, year 7. The simulation results also show that emissions increase when a positive shock occurs despite the changes in abatement. This finding points to the important role of output in emissions which results in emissions to increase to more than 0.07 percent deviation from steady state.

After having discussed the IRFs of variables, we now present real business cycles here in which a series of exogenous shocks happen to TFP that produces business cycles, i.e. output expansions and recessions. Figure 3 represents the simulation time paths of output to a series of TFP shocks. The simulation results include an expansion from period 20 to 50 followed by a recession from period 50 to 80. In this figure the levels are normalised to the BAU steady state level of output in order to facilitate comparison. As the figure displays, making an abatement subsidy policy affects the steady state level of output but not the path of its

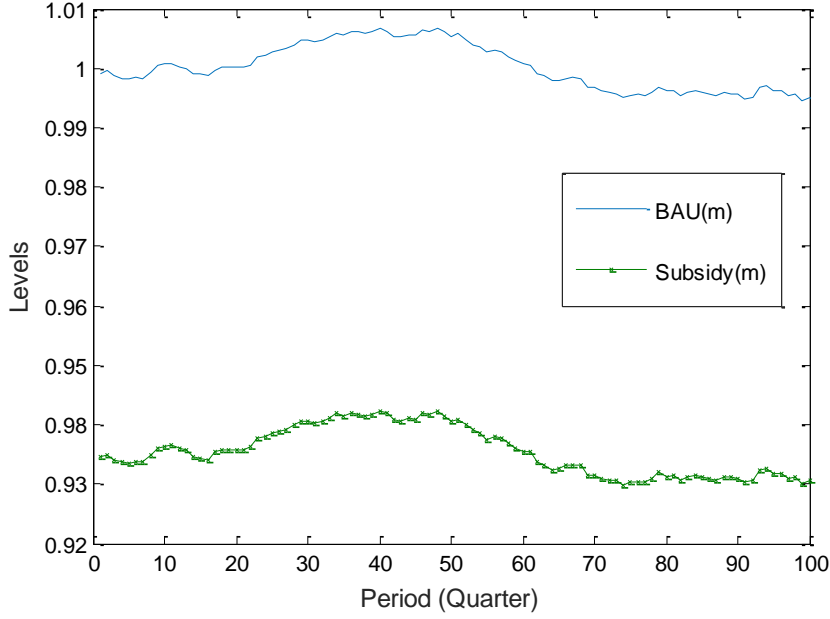
fluctuation. The cyclical simulation result of emissions is displays in



**Figure 4.** Again, the levels are normalised using the BAU steady state level of emissions. As we expected from a one-period IRFs, the emissions path follows output under the abatement scenario, i.e. emissions increase during expansion and decrease during recession. Also, the abatement policy results in lower levels of emissions than the BAU. These findings highly depend on the subsidy rate fluctuations as the government should adjust it to be pro-cyclically to business cycles: the subsidy rate increases during expansions and decreases during recessions.



**Figure 3:** Business Cycle Simulation of Output under Business-as-usual (BAU) Abatement Subsidy (Subsidy) Scenarios when levels are normalised by BAU steady state level of output



**Figure 4:** Business Cycle Simulation of Emissions under Business-as-usual (BAU) and Abatement Subsidy (Sub) Scenarios when levels are normalised by BAU steady state level of emissions

## 5. Conclusion

Australian emissions reduction policies have experienced several changes due to different policy makers' attitudes about the economic costs and environmental outcomes of such policies. In this paper we simulated the economic and environmental effects of an abatement subsidy policies which is the current policy implemented in Australia. The results showed that such a policy results in an emissions reduction but at an output decrease and welfare cost compared with a BAU scenario. In a stochastic situation and in the presence of a TFP shock an emissions subsidy can encourage polluters to move to cleaner technologies such as renewable energies when a positive TFP shock occurs. The real business cycle results also showed that implementing an abatement subsidy policy only affects the steady state level of output and emissions not the path of its fluctuation. The policy implication of this finding is that the regulator should set the subsidy to be pro-cyclical to business cycles: they increase during expansion and decrease during recessions. Note that the abatement subsidy findings are for the scenario specified here in which the firm receives a subsidy for its abatement effort in each period and the policy is run for a long period, which may be different from the Emissions Reduction Fund program which is planned to continue only for 5 years.

In this paper, we explored how the Australian economy under an emissions reduction policy would response to TFP shocks. As a small open economy Australian business cycles are affected not only by domestic shocks such as that of TFP but also by foreign shocks. In future work, we intend to tailor the model to the Australian economy even more by extending our analysis to the performance of emissions reduction policies in the presence of foreign shocks. Finally, we will conduct a sensitivity analysis to investigate the dependence of our findings to parameter values. The sensitivity analysis is necessary here especially for environmental parameters such as the damage function and abatement costs which still remain unknown and a change in any of them could significantly change the results.

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## Appendix

### A.1. Estimation of Output in the Emission Equation

The emissions at each period  $m_t = (1 - \mu_t)h(y_t)$  is 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 Australia's emissions and GDP are used here, from Australia's National Greenhouse Accounts (Australian Government, 2014c) and the Australian National Accounts (Australian Bureau of Statistics, 2014) respectively, for the period of September 2001-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 shown in the table, the coefficient,  $1-\gamma$ , is equal to 0.0975.

**Table A.1:** Regression of Log CO<sub>2</sub> Emissions on Log Output

<i>Regression Statistics</i>								
Multiple R	0.8789							
R Square	0.7725							
Adjusted R Square	0.7678							
Standard Error	0.0056							
Observations	50							

<b>ANOVA</b>						<i>Significance</i>		
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>		<i>F</i>		
Regression	1	0.0051	0.0051	163.0349		0.0000		
Residual	48	0.0015	0.0000					
Total	49	0.0066						

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95%</i>	<i>Upper 95%</i>
Intercept	1.5923	0.0416	38.2942	0.0000	1.5087	1.6759	1.5087	1.67592
LOG(GDP)	0.0975	0.0076	12.7685	0.0000	0.0821	0.1128	0.0821	0.11282

### A.2. Damage Function Calibration

In order to calibrate the environmental damage function due to pollution, we follow Heutel (2012) and the benefits from the 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, we simplify its damage function to a quadratic function. To



this end, we briefly explain the DICE model and then present the simplification process. The DICE model represents the global economic and environmental aspects of climate change. The model is extended to a regionally disaggregated version in RICE. 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:

$$M_{AT}(t) = E(t) + \phi_{11}M_{AT}(t-1) + \phi_{21}M_{UP}(t-1) \quad (22)$$

$$M_{UP}(t) = \phi_{12}M_{AT}(t-1) + \phi_{22}M_{UP}(t-1) + \phi_{32}M_{LO}(t-1) \quad (23)$$

$$M_{LO}(t) = \phi_{23}M_{UP}(t-1) + \phi_{33}M_{LO}(t-1) \quad (24)$$

$E(t)$  represents the emissions produced in period  $t$  and  $\phi_{ij}$  are the flow parameters between the reservoirs. Then the relationship between the reservoirs, or the accumulation of carbon, and climate change is specified. The accumulation of GHGs increases radiative forcing<sup>3</sup> which leads to the warming of the earth's surface.

$$F(t) = \eta \{ \log_2 [M_{AT}(t) / M_{AT}(1750)] \} + F_{EX}(t) \quad (25)$$

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

$$T_{AT}(t) = T_{AT}(t-1) + \xi_1 \{ F(t) - \xi_2 T_{AT}(t-1) - \xi_3 [T_{AT}(t-1) - T_{LO}(t-1)] \} \quad (26)$$

$$T_{LO}(t) = T_{LO}(t-1) + \xi_4 \{ T_{AT}(t-1) - T_{LO}(t-1) \} \quad (27)$$

$T_{AT}(t)$  and  $T_{LO}(t)$  are respectively the mean surface temperature and the temperature of deep oceans. Finally, the economic impact of climate change, or the damages  $\Omega$ , arises from the mean surface temperature.

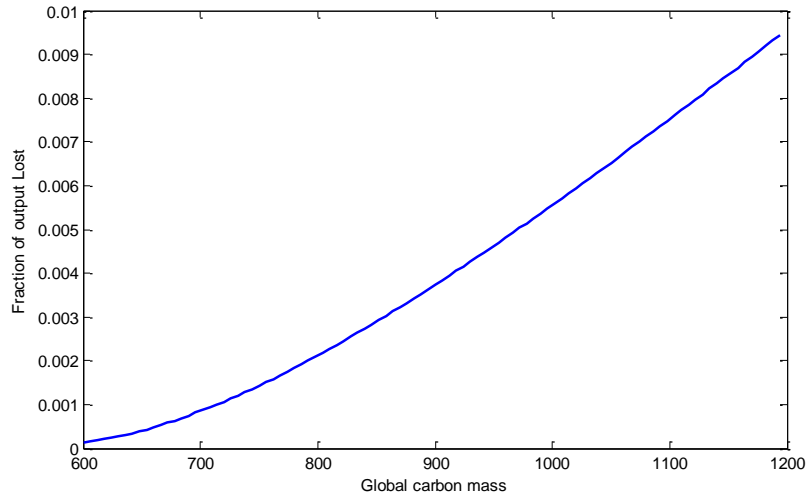
$$\Omega(t) = \psi_1 T_{AT}(t) + [\psi_2 T_{AT}(t)]^2 \quad (28)$$

As Nordhaus (2008) explains this damage function is estimated for the temperature increase in the range of 0-3°C and the damage function is not virtually existent for warming above 3°C as the evidence of such temperature raising is highly limited.

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<sup>3</sup> 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).

Equations (22) to (28) represent carbon dioxide contributions to global warming damage. We summarise the above relationships by modelling the damage as a direct function of the stock of pollution. To this end the DICE (2008) equations of radiative forcing, the atmospheric, ocean temperatures and the damage, equations (25) to (28), are used to find the damages for 100 values of the pollution stock, ranging from 600 Giga tons of carbon (GtC) to 1200 GtC. This helps us to find the damage function for the pollution stock in the atmosphere, or the carbon mass, of 600-1200 GtC. In order to obtain the damage function for Australia in this research, RICE (2010) is used to calibrate the damage coefficients where  $\psi_1=0$  and  $\psi_2=0.1564$ . Plotting such a damage function over the carbon mass of 600-1200 GtC leads to obtaining the relationship between the damage function and the carbon mass as presented in Figure A. 1. As the figure shows there is a quadratic relationship between the carbon mass and output such as that given by  $d(x_t) = d_0 + d_1x_t + d_2x_t^2$ . This leads us to obtain  $d_0=-0.0011$ ,  $d_1=-5.6629*10^{-6}$  and  $d_2=1.2261*10^{-8}$ . 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 A. 1:** The Economic Damages from the Stock of Pollution in Australia