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Exploring the macroeconomic fluctuations under different environmental policies in China: A DSGE approach

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ABSTRACT

Due to the uncertain effects on economic growth and economic fluctuations caused by environmental policies, the best means of choosing the most appropriate environmental policy remains controversial. In the face of various uncertain economic factors, economic fluctuation is an important criterion for evaluating different environmental policies. Thus, we established an environmental dynamic stochastic general equilibrium model under New Keynesian framework embodying nominal price rigidities, environmental policies, pollutant emissions and real uncertainties with the aim of comparing the impacts of different environmental policies on the macroeconomic fluctuations. The results are as follows. First, the responses indicate that all kinds of environmental policies are counter-cyclical. Emissions intensity policy has the strongest effect on curbing fluctuations. Second, a positive energy efficiency shock will lead to a corresponding increase in energy inputs, which is referred to as the energy rebound effect, as well as a rise in pollutant emissions. Third, an emissions intensity shock will exert greater impacts than environmental tax rate shock and emissions cap shock. Fourth, the lower is the price dispersion the less intermediate goods are needed, and, consequently, the lower are the pollutant emissions. Taken together, the results highlight the policy implications associated with choosing an environmental policy.

1. Introduction

Over the past decade, notable progress has been made with regards to environmental protection through the cutting of pollutant emissions following years-long campaigns by Chinese government, which can mainly be attributed to a series of laws and environmental policies (Cui et al., 2014; Mo et al., 2018). Currently, there are three kinds of environmental policies based on market mechanisms in China: environmental tax policy, emissions permits policies, and emissions intensity policy. As all three kinds of environmental policies have their own pros and cons, determining the optimal environmental policy has become an unavoidable issue. Indeed, the question of how to choose environmental policies has become a hot topic among many scholars in recent years. Thus, this paper mainly focuses on the different environmental policies in China from the perspective of economic fluctuations.

Why should we consider the relationship between macro-economy and environmental policy? Simply, the implementation of environmental policy will produce some economic costs, which will inevitably restrict the economic development and bring uncertainty to different kinds of economic activities (Mardones and Baeza, 2018). In recent decades, long-term economic growth and short-term economic fluctuation have always been the core issues of macroeconomics. The relationship between economic growth and environmental policy has been intensively investigated in previous researches (Doda, 2014; Abdullah and Morley, 2014). However, there are fewer researches about the economic fluctuations brought by environmental policies. Economic fluctuation is not only one of the main fields of theoretical research, but also a practical problem in macroeconomic decision-making (Ramzi et al., 2017). Several scholars pointed out that economic fluctuations have real effects on environmental policies and vice versa (Heutel and Fischer, 2013). Under different environmental policies, the dynamic responses and short-term fluctuations of economy to uncertain exogenous shocks can be quite different. So, some important feedback effects in the economy will be ignored if we drop the relationship between environmental policies and economic fluctuations (Xu et al., 2016)). Thus, in the face of various uncertain economic factors, economic fluctuation is an important aspect of evaluating the advantages and disadvantages of different environmental policies (Xu et al., 2015).

The aim of this paper is to answer the following questions. How will different environmental policy regimes affect our economy? To what extent do different environmental policies influence the

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macroeconomic fluctuations seen in China? How will different environmental policies respond optimally to the business cycle under nominal rigidities? To answer these questions, we established an environmental dynamic stochastic general equilibrium (DSGE) model under classical New Keynesian framework embodying nominal price rigidities, environmental policy variables and pollutant emission variables which are treated as the by-products of energy inputs. In all, all these analyses have reference meaning for the Chinese government in terms of choosing the optimal policy for cutting air pollutant emissions.

2. Literature review

In the context of cutting and regulating emissions of environmental pollutants, a number of economists have attempted to value market-based climate management tools and environmental policies, thereby striving to minimise the economic costs of realising the given emissions reduction targets (Duan et al., 2018; Tiba and Omri, 2017). All these climate management tools and environmental policies based on market mechanisms can be classified into three categories: price instruments, quantity instruments and intensity-based instruments. For example, environmental tax policies (Rausch and Schwarz, 2016), emissions trading schemes (Fan et al., 2017; Liu and Fan, 2018) and emissions permits policies (Jiang et al., 2016). The former are characterised by price control (Cui et al., 2014), while the latter are characterised by total amount control (Zhang and Wei, 2010). Moreover, some scholars have also analysed intensity-based policies. Weitzman (1974) compared quantitative environmental policy and price based environmental policy by partial equilibrium model. From then on, many previous studies have applied various alternative methods for discussing the performances and effects of alternative environmental policies on emissions controls (Goulder et al., 1999; Quirion, 2005), including the system dynamics model (Liu et al., 2015; Xiao et al., 2016), the computable general equilibrium (CGE) model (Cui et al., 2014; Xiao et al., 2015; Fan et al., 2016), the input-output model (Dong et al., 2018; Su and Ang, 2017; Sun et al., 2017; Wang et al., 2017) and the DSGE model (Heutel, 2012; Xu et al., 2016), all of which mainly focus on the macro impact of environmental policies.

In the branch of the general equilibrium models, the DSGE models stand out due to their theoretical basis in policy simulation and analysis. Structural, micro-founded DSGE model can simulate the response of dynamic behaviours and fluctuations on stochastic shocks in the short term and long term equilibrium, which can move away from reduced-form modelling and towards structural-form modelling by embedding micro-founded principles (Aiyagari, 1995; Kurozumi and Zandweghe, 2011; Leeper and Yang, 2008; Benavides et al., 2015). Thus, an increasing number of scholars have begun to pay attention to the dynamic effects of the environment and the macro-economy, and they have embedded environmental policies into the DSGE model.

To summarize, the DSGE models that include pollution and environmental policies can be divided into two varieties: those adopting an RBC structure with flexible prices; and those adopting a NK framework incorporating some type of nominal rigidities. Examples of the former are Angelopoulos et al. (2010), Fischer and Springborn (2011) and Heutel (2012). Angelopoulos et al. (2010) and Heutel (2012) added pollutant emissions by treating them as a by-product of production, while in the study by Fischer and Springborn (2011), the pollutant emissions were considered to be emitted by energy consumption. Heutel and Fischer (2013) comprehensively reviewed and summarised the research on environmental economics. They focused on two macroeconomic tools, namely real business cycle models and endogenous technological growth models, and their application within environmental economics. From then on, some researchers began to embed environmental policies into the DSGE model. Fried et al. (2013) constructed a typical DSGE model based on the microcosmic basis of environmental feedback, linking carbon dioxide emissions with economic growth. Lintunen and Vilmi (2013) also used a DSGE model to analyse the periodicity of environmental policy, and they found that the optimal emissions tax policy is pro-cyclical. Compared to the previous literatures on prices vs. quantities policies, Annicchiarico and Di Dio (2015) used a DSGE model to compare the dynamic effects of different environmental policy choices under productivity shocks within the NK framework. Following the approach of Annicchiarico and Di Dio (2015), Xu et al. (2016) extended the model and analysed other shocks on different policy regimes. Dissou and Karnizova (2016) analysed alternative environmental policy instruments in the presence of persistent productivity shocks by disaggregating the economy into six sectors. Further, Golosov et al. (2011) established a dynamic public finance model in order to study optimal carbon taxes with endogenous technological change.

Following the contributions of previous literatures, we try to combine macroeconomics and environmental economics by embedding the environmental block into a New Keynesian DSGE model. Different from Annicchiarico and Di Dio (2015), we embedded energy consumption and energy efficiency into our model, and we used it to analyse the three different environmental policy regimes in China. In addition, along with the development of economy, the uncertain factors from economy and environment gradually increased, which will affect the environmental policy effects. Hence, more uncertainties need to be taken into consideration when evaluating and selecting the environmental policies. We not only considered technology uncertainty and energy efficiency uncertainty, which are all real shocks to the economic cycle, fiscal policy uncertainty including government expenditure shock and tax rate shocks are all taken into consideration. More importantly, in order to analyse the uncertainties of environmental policies, we also simulated and compared the macroeconomic fluctuations and emissions controls under an environmental tax rate shock, an emissions cap shock and an emissions intensity shock.

3. Methodology

The structure of this DSGE model is represented by four major economic agents, that is, representative household, intermediate goods producers, final goods producers and government. The framework of this DSGE model is shown in Fig. 1. The dotted arrow represents the money flow, while the solid arrow represents the material flow.

3.1. Households

The representative household is endowed with labour (L_t), capital (K_t) and energy (M_t) dedicated to the different intermediate goods producing firms. Note that the labour capital and energy are homogeneous goods in that the agent does not distinguish between different jobs, capitals and energy. The representative infinitely lived household maximises the following lifetime utility:

$$U = E_t \sum_{t=0}^{\infty} \beta^t \left\{ \ln C_t - \frac{L_t^{1+\theta}}{1+\theta} - \frac{[(1-er_t)\mu M_t]^{1+\upsilon}}{1+\upsilon} \right\} \tag{1}$$

such that the budget constraint in units of goods:

$$P_t C_t + P_t I_t + B_{t+1} = (1-\tau_t^L) W_t L_t + (1-\tau_t^K) R_t K_t + (1-\tau_t^M) P_t^M M_t + \left(1+R_t^B\right) B_t + D_t P_t + Tr_t \tag{2}$$

Households are the owners of firms. The representative household receives profits (D_t) as a dividend from each intermediate goods producing firm. In addition to the dividends, the representative household receives factor payments for labour (W_t), capital (R_t) and energy (P_t^M) supplied to intermediate goods firms as well as a lump-sum transfer (Tr_t) from the government. Meanwhile, the government levies tax on factor incomes with different tax rates. The household uses its income to purchase consumption (C_t), invest (I_t) or acquire assets, for example, government bonds (B_t).

The investment adjustment cost is an essential specification for the modern DSGE (Smets and Wouters, 2007; Christiano et al., 2005). The

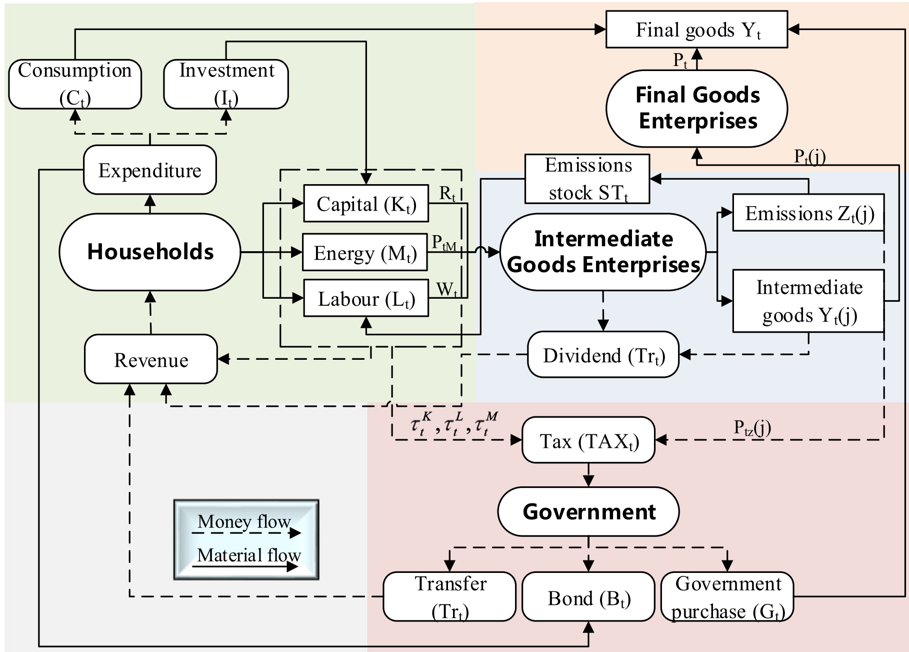

Fig. 1. The framework of the DSGE model.

law of motion of capital is given as Eq. (3), where δ_K is the depreciation rate of capital, ϑ is the parameter of investment adjustment cost.

$$K_t = (1-\delta_K)K_{t-1} + \left[1-\frac{\vartheta}{2}\left(\frac{I_t}{I_{t-1}}-1\right)^2\right]I_t \tag{3}$$

3.2. Enterprises

3.2.1. Final goods producers

The representative final goods producer uses $Y_t(j)$ units of each intermediate good $j \in [0,1]$ in order to produce the final good Y_t, according to the constant returns to scale technology suggested by Dixit and Stiglitz (1977), where $\varphi > 1$ is the elasticity of the substitution between the different intermediate goods.

$$Y_t = \left[\int_0^1 Y_t(j)^{\frac{\varphi-1}{\varphi}} dj\right]^{\frac{\varphi}{\varphi-1}} \tag{4}$$

Note that $P_t(j)$ is the price of the intermediate good j. The representative final goods producer's aim is to maximise profits by deciding Y_t and $Y_t(j)$, as given by[1]:

$$\max_{Y_t(j)} P_t \left[\int_0^1 Y_t(j)^{\frac{\varphi-1}{\varphi}} dj\right]^{\frac{\varphi}{\varphi-1}} - \int_0^1 Y_t(j)P_t(j)dj \tag{5}$$

3.2.2. Intermediate goods producers

Intermediate goods producers are monopolistic competitors in their product markets, and they take factor prices as given. For now, we focus on a representative intermediate goods producing firm j. It hires labour $L_t(j)$, expends capital $K_t(j)$ and purchases energy $M_t(j)$ to produce $Y_t(j)$ using the necessary Cobb-Douglas technology.

$$Y_t(j) = A_t K_t^{\alpha}(j)\left[\eta_t^L L_t(j)\right]^{\Delta}\left[\eta_t^M M_t(j)\right]^{(1-\alpha-\Delta)} \tag{6}$$

[1] The FOCs (first order conditions) of Lagrangian function for the household and final goods producers are listed in Appendix A.

where A_t is the total factor productivity (TFP), following an exogenous process:

$$\ln A_t - \ln A = \rho_A \ln A_{t-1} - \rho_A \ln A + \varepsilon_{t,A} \quad \varepsilon_{t,A} \sim i.i.d.N\left(0,\sigma_A^2\right) \tag{7}$$

In the production function, we add efficiency variables into the labour and energy input. Following the "learning by doing" (LBD) approach in the process of capital and labour experience accumulation, we presume that the energy efficiency improvement can be attributed to the use of energy. It is assumed that there exists a relationship between the efficiency of the energy input and the amount of energy used in production. Note that the Cobb-Douglas production function is increasing returns to scale due to the LBD approach of energy efficiency. q_t is a variable for improving the efficiency of the energy use during the process of LBD, and it follows the AR(1) process.

$$\eta_t^M = q_t M_t^{(\gamma-1)} \tag{8}$$

$$\ln q_t - \ln q = \rho_q \ln q_{t-1} - \rho_q \ln q + \varepsilon_{t,q} \quad \varepsilon_{t,q} \sim i.i.d\left(0,\sigma_q^2\right) \tag{9}$$

The energy use will lead to pollutant emissions $Z_t(j)$. The emissions coefficient is written as μ. We assume that representative enterprise can determine its proportion of emission reductions $er_t(j)$.

$$Z_t(j) = (1-er_t(j))\mu M_t(j) \tag{10}$$

Marginal abatement cost $MCE_t(j)$ is a function of proportion of emission reductions. Parameter $\Lambda < 0$ is estimated by Chinese industrial abatement cost.

$$MCE_t(j) = \Lambda \ln(1-er_t(j)) \tag{11}$$

Total emission reduction cost $CE_t(j)$ can be expressed by the integral of $MCE_t(j)$ at the interval $[0, RE_t(j)]$, where emission reduction $RE_t(j) =$

$\mu \cdot er_t(j) M_t(j)$.

$$CE_t(j) = \int_0^{RE_t(j)} \Lambda \ln\left(1 - \frac{RE_t(j)}{\mu M_t(j)}\right) dRE_t(j) = -\Lambda \mu M_t(j) \cdot [\ln(1-er_t(j))(1-er_t(j)) + er_t(j)] \quad (12)$$

We presume that the efficiency of labour will be affected by the pollutant emissions. The law of motion for pollutant stock is shown in Eq. (14), where δ_Z is depreciation rate of pollutant stock.

$$\eta_t^L = 1 - \left(\eta_0 + \eta_1 ST_t + \eta_2 ST_t^2\right) \quad (13)$$

$$ST_t = (1-\delta_Z) ST_{t-1} + Z_t \quad (14)$$

For now, the problem for representative intermediate goods producing firm j can be written as follows.[2] Where P_t^Z is the price for buying each unit emission permit from government.

$$\max\ \Pi = \frac{P_t(j)}{P_t} Y_t(j) - \frac{W_t}{P_t} L_t(j) - \frac{R_t}{P_t} K_t(j) - \frac{P_t^M}{P_t} M_t(j) - \frac{P_t^Z}{P_t}(1-er_t(j))\mu M_t(j) - CE_t(j)$$
$$s.t. \quad Y_t(j) = A_t K_t^{\alpha}(j) \left[\eta_t^L L_t(j)\right]^{\Delta} \left[\eta_t^M M_t(j)\right]^{(1-\alpha-\Delta)} \quad (15)$$

Following the approach of Calvo (1983), we assume that intermediate firms can only change their nominal prices when they receive a random signal to do so. The probability that a firm can change its price during any given period is $1-\omega$. Firms that have the chance to change their prices at t choose their price in order to maximise the expected sum of discounted future real profits**.

$$\max_{P_t(j)} \ \Re = E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{U'(C_{t+i})}{U'(C_t)} Y_{t+i} \left[\frac{P_t(j)}{P_{t+i}} \left(\frac{P_{t+i}}{P_t(j)}\right)^{\varphi} - MC_{t+i} \left(\frac{P_{t+i}}{P_t(j)}\right)^{\varphi}\right] \quad (16)$$

3.3. Government

The government passively adjusts lump-sum transfers so as to clear the budget each period. We assume that the net supply of bonds is zero. Hence, the government budget constraint can be given as:

$$P_t G_t + \left(1 + R_t^B\right) B_t + Tr_t = \tau_t^L W_t L_t + \tau_t^K R_t K_t + \tau_t^M P_t^M M_t + P_t^Z Z_t + B_{t+1} \quad (17)$$

where public consumption Gt is fully financed by the taxes levied from the labour, capital, energy and emissions revenue collected from environmental policies, including an environmental tax, selling emissions permits etc. There are three shocks. We assume that government consumption, the capital tax rate and the labour tax rate all follow the AR(1) stochastic process. $\varepsilon_{t,\ G}$, $\varepsilon_{t,\ K}$, and $\varepsilon_{t,\ L}$ all follow a normal distribution.

$$\ln G_t - \ln G = \rho_G \ln G_{t-1} - \rho_G \ln G + \varepsilon_{t,G} \quad \varepsilon_{t,G} \sim i.i.d.N(0, \sigma_G^2) \quad (18)$$

$$\ln \tau_t^K - \ln \tau^K = \rho_K \ln \tau_{t-1}^K - \rho_K \ln \tau^K + \varepsilon_{t,K} \quad \varepsilon_{t,K} \sim i.i.d.N(0, \sigma_K^2) \quad (19)$$

$$\ln \tau_t^L - \ln \tau^L = \rho_L \ln \tau_{t-1}^L - \rho_L \ln \tau^L + \varepsilon_{t,L} \quad \varepsilon_{t,L} \sim i.i.d.N(0, \sigma_L^2) \quad (20)$$

3.4. Aggregation and market clearing

For the factors and goods markets clearing, the sum of the labour, capital and energy is equal to the total factor used in all of society, that is, $L_t = \int_0^1 L_t(j)dj$, $K_t = \int_0^1 K_t(j)dj$, $M_t = \int_0^1 M_t(j)dj$.

The price dispersion can be defined as Eq. (21). Then, following the approach of Calvo (1983), the price dispersion (and so of total output dispersion) and the production function can be rewritten as Eqs. (22) and (23):

$$V_t = \int_0^1 \left(\frac{P_t(j)}{P_t}\right)^{-\varphi} dj \quad (21)$$

$$V_t = (1-\omega)\left(\frac{P_t^*}{P_t}\right)^{-\varphi} + \omega\left(\frac{P_t}{P_{t-1}}\right)^{\varphi} V_{t-1} \quad (22)$$

$$Y_t = A_t K_t^{\alpha} \left[\eta_t^L L_t\right]^{\Delta} \left[\eta_t^M M_t\right]^{(1-\alpha-\Delta)} (V_t)^{-1} \quad (23)$$

Finally, the resource constraint of the economy can be given as:

$$Y_t = C_t + I_t + G_t + CE_t \quad (24)$$

3.5. Scenario setting

In order to analyse the different policy effects, we set four scenarios in this study, namely scenario 1: BAU (without any policy), scenario 2: TAX (environmental tax policy), scenario 3: EI (emissions intensity policy) and scenario 4 (emissions permits policy). The specific scenarios and key variable settings are presented in Table 1.

4. Parameters and data

4.1. Calibration

Some parameters are determined by Bayesian estimation based on the relevant quarterly data from China, while the rest of the parameters are determined via the calibration method based on both the existing research and related statistical data. The parameters and values, as well as their sources, are listed in Table 2.

4.2. Bayesian estimation

4.2.1. Data source

This paper select China quarterly data from January 1992 to December 2017 to estimate parameters. The total output (Y), government expenditure (G), investment (I), labour (L) and inflation (π) are selected as observable variables. We select GDP to reflect the total output (Y). Quarterly GDP data are collected from National Bureau of Statistics of the People's Republic of China (NBS). Quarterly government expenditure data (G) are collected from Ministry of Finance of the People's Republic of China. We select fixed assets investment to reflect the investment (I). Quarterly fixed assets investment data are collected from NBS. Quantity of employment data are selected to reflect labour (L), which are also collected from CEIC database. Consumer price index, which are collected from NBS, can fully reflect the inflation (π) in China. Thus, we calculated quarterly inflation by monthly consumer price index data.

In order to render the observed variables consistent with the variables in the model, we need to deal with the observed variables. First, we used the Census X12 method to deseasonalise the variables. Then, we established the logarithm for observed variables. Finally, the Hodrick-Prescott (HP) filter was used to detrend the variables and obtain the volatile components.

[2] The derivation of the FOCs for intermediate goods producers and the Calvo pricing optimisation problems are listed in Appendix A.

Table 1
The specific scenarios and key variable settings.

Scenario		Policy measure	Variable setting
Scenario 1: BAU	No policy (Baseline scenario)	In this baseline scenario, we presume that the price of the pollutant emissions is zero. Governments will not levy any tax on emissions or set emission target. Hence, external costs of pollutant emissions are ignored by intermediate goods producers. The emission pollutant price is set to be 0.	$p_t^Z = 0$
Scenario 2: TAX	Environmental tax policy	In this scenario, the governments will levy environmental tax on the firms who emit pollutions to interiorize the external costs of pollutant emissions. It will lead to lower pollutant emissions. Hence, the pollutant emissions price is equal to the tax rate. We presume that the tax rate levied on pollutant emissions is τ_t^Z.	$p_t^Z = \tau_t^Z$ $\ln \frac{\tau_t^Z}{\tau^Z} = \rho_Z \ \ln \frac{\tau_{t-1}^Z}{\tau^Z} + \varepsilon_{t,Z}$[a] $\varepsilon_{t,\ Z}$~$i.\ i.\ d.\ N(0,\sigma_Z^2)$
Scenario 3: EI	Emissions intensity policy	In this scenario, the governments will announce a mandatory emissions intensity target in per unit of output. In the meantime, the governments ask for the emission permits for every unit of pollutant emissions, and sell emission permits to the producers with the emission price. Hence, the proportion of emission and output will be given exogenously.	$_t/Y_t$=$(1\text{-}er_t)\mu M_t/Y_t$= ψ_t $\ln \frac{\psi_t}{\psi} = \rho_\psi \ \ln \frac{\psi_{t-1}}{\psi} + \varepsilon_{t,\psi}$[a] $\varepsilon_{t,\ \psi}$~$i.\ i.\ d.\ N(0,\sigma_\psi^2)$
Scenario 4: EP	Emissions permits policy	In this scenario, the governments will establish a cap and trade system to control pollutant emissions. The governments will announce a mandatory total amount of pollutant emissions (cap), and still sell emission permits to the producers with the emission price in the meantime. Hence, the total pollutant emissions will be given exogenously.	$Z_t = \kappa_t \overline{Z}$ $\ln \frac{\kappa_t}{\kappa} = \rho_\kappa \ \ln \frac{\kappa_{t-1}}{\kappa} + \varepsilon_{t,\kappa}$[a] $\varepsilon_{t,\ \kappa}$~$i.\ i.\ d.\ N(0,\sigma_\kappa^2)$

[a] τ_t^Z is environmental tax rate, ψ_t is emission intensity, and κ_t is emission cap. $\varepsilon_{t,\ Z}$, $\varepsilon_{t,\ \psi}$, $\varepsilon_{t,\ \kappa}$ all follow a normal distribution.

4.2.2. Prior distribution & diagnostic check

We used Bayesian estimation method to estimate the persistence of the AR(1) processes. Learning from Smets and Wouters (2007), and Traum and Yang (2010), prior distributions of parameters of the AR (1) processes are assumed to be beta distribution. As shown in Table 3, persistence of the AR(1) processes of technology shock is beta distributed with standard deviation 0.1 and mean 0.8. Similar distributions are assumed for parameters of the AR(1) processes of energy efficiency shock, government expenditure shock, capital tax rate shock and labour tax rate shock, all of which are beta distributed with standard deviation 0.1 and mean 0.49, 0.8, 0.8 and 0.8 respectively.

After setting the prior distributions of AR(1) parameters, Bayesian estimation method are applied. Bayesian estimation of our DSGE model is achieved by software package DYNARE in Matlab 2014 (Boucekkine, 1995; Juillard, 1996; Collard et al., 1999). Posterior density function and posterior mode can be obtained by prior distribution of structural parameters and the likelihood function value of data. Then, random walk Metropolis-Hastings (MH) algorithm is adopted to sample from the posterior distribution (the sampling number in this paper is 100,000).

Table 2
The parameters and values.

No.	Parameters	Value	Description
1	β	0.99	Discount factor
2	θ	1.97	Elasticity of labour supply
3	φ	6	Price elasticity of intermediate products
4	α	0.33	C-D parameter of capital
5	Δ	0.58	C-D parameter of labour
6	γ	2.136	Elasticity of energy use efficiency
7	μ	0.6	Emissions per unit of energy
8	ω	0.75	Calvo's price parameter for nominal rigidities
9	δ_k	0.025	Depreciation rate of capital
10	δ_z	0.005	Depreciation rate of pollutant stock

1. Çebi (2011):0.99; Lintunen and Vilmi (2013):0.995; Fischer and Springborn (2011):0.95. Angelopoulos et al. (2010):0.97; Leeper and Yang (2008):0.96.
2. Çebi (2011):2; Lintunen and Vilmi (2013):2; Brzezina et al. (2013):2; Pop (2017):2;
3. Annicchiarico and Di Dio (2015):6; Xu et al. (2016):6;
4. Kydl and Prescott (1982): 0.36; Angelopoulos et al. (2010): 0.33; Fischer and Springborn (2011):0.33; Leeper and Yang (2008): 0.36; Chang and Kim (2007):0.36; Nalban (2018):0.33.
5. Fischer and Springborn (2011):0.58; Pop (2017):0.55;
6. Yang et al. (2014): 2.136; Shao et al. (2013): 2.136
7. Xu et al. (2016): 0.601; Guidelines for National Greenhouse Gas Inventories (IPCC)
8. Annicchiarico and Di Dio (2015): 0.75; Nalban (2018):0.75; Brzezina et al. (2013):0.66.
9. Kydl and Prescott (1982):0.025; Lintunen and Vilmi (2013):0.025; Annicchiarico and Di Dio (2015):0.025; Heutel (2012):0.025; Chang and Kim (2007):0.025.
10. According to Nordhaus (1991), the conventional estimate for decay rate of CO_2 in the atmosphere is 0.005 (representing a residence time of 200 years); IPCC (2001): 0.003–0.129.

The diagnostic results of convergence are shown in Appendix B. Multivariate potential scale reduction factors (MPSRF) of Brooks and Gelman (1998) are used for the univariate and multivariate diagnostic check in Figs. B.2 and B.3. When the blue line and red line close to each other, it means MPSRF is close to 1 for the evidence of no divergence. It is note that convergence conditions for all estimated parameters are satisfied in Figs. B.2 and B.3. Specific technical details of convergence can be referred to Brooks and Gelman (1998), and An and Schorfheide (2007).

4.2.3. Estimation results

Table 3 reports the post mean values and confidence intervals of Bayesian estimation based on MH algorithm. The results of the Bayesian estimation tell us that the capital tax rate shock is the most persistent, while the labour tax rate shock is the shortest of all shocks. Technology shock and public expenditure shock are relatively persistent. As expected, capital tax rate shock can directly impact investment, thereby affecting the capital accumulation. However, depreciation and accumulation of capital stock is a slow process, which indicates that capital tax rate shock can influence the capital in a long time period. That explains why capital tax rate shock is the most persistent. The wage level in China is lower than that in developed countries. Therefore, workers with rational expectations will work harder to offset the negative effects caused by high tax rate. Moreover, in a labour-surplus economy such as China, effects of labour tax rate shock will not last a long time. The surplus labour force can partially smooth the labour tax rate shock.

5. Results and discussion

5.1. Results for the steady state values

The results for the steady state values of the main variables are represented in Table 4. In order to compare the effects of the three different policies, we try to fix the exogenous variables so as to achieve the same emissions reductions under three different scenarios. Additionally, the changes in the steady state values relative to the BAU are also shown in Table 4.

Due to the use of the same emissions reduction level, the steady state values of the variables in the three different environmental policy regimes are basically the same. Lots of macroeconomic indicators will be negatively impacted by all kinds of environmental policies. For example, GDP (Y) will decrease by 1.76%, capital stock will decrease by 1.75%, and investment will also decrease by 1.75%.

Obviously, the environmental policies can promote environmental quality improvements. Pollutant emissions, the emissions intensity and the stock of pollutant emissions all decrease under the three different environmental policy regimes. The pollutant

Table 3
The Bayesian estimation results in the BAU.

Parameters	Prior	Prior mean	Post mean	Confidence interval		Standard deviation
ρ_A(rhoa)	Beta distribution	0.800	0.8372	0.7457	0.9295	0.1
ρ_q(rhoe)	Beta distribution	0.490	0.3621	0.1626	0.5466	0.1
ρ_G(rhoG)	Beta distribution	0.800	0.7506	0.6206	0.8755	0.1
ρ_K(rhoK)	Beta distribution	0.800	0.9143	0.8918	0.9347	0.1
ρ_L(rhoL)	Beta distribution	0.800	0.2014	0.1414	0.2545	0.1

emissions will decrease by 9.94%. The emissions intensity (Z/Y) is 0.244 in the BAU scenario and 0.223 in the three different environmental policy regimes, which indicates a decrease of 8.6%. When there is a 1% decline in pollutant emissions, the GDP in the steady state will decrease by 0.18% in the three different environmental policy regimes.

When the government levies an environmental tax, it will restrain the production activities of enterprises due to pushing up production costs. The environmental tax is an indirect tax, in accordance with the tax shifting and price conduction mechanism, and a tax imposed upstream will transfer downstream through the cost-push process. The real wage will decline by 1.83%, which will lead to a decline in household revenue. The lower disposable income will limit consumption and investment decisions. As a result, it will reduce household consumption by 1.97% and investment by 1.75%. Although the capital interest rates will remain unchanged, the falling level of investment will lead to a reduction in the capital stock (−1.75%). Enterprises will cut their energy inputs because of rising production costs, which could result in a decline in energy efficiency according to our LBD setting in the relation between energy input and efficiency. Thus, there is no doubt that the pollutant emissions will decrease, as will the stock of pollutant emissions. Although the lower stock of pollutant emissions will push up the labour efficiency, the increase in the marginal output of labour cannot make up for the GDP loss caused by the negative effects of the environmental tax.

Similarly, when there is an emissions intensity target, the government will control pollutant emissions by implementing mandatory pollutant emissions per unit of output. Undoubtedly, the pollutant emissions will decrease, as will the stock of pollutant emissions. The sharp rise in the price of pollutant emissions will greatly cut the energy input, which will in turn further cut energy efficiency. Thus, the sharp decline in GDP is mainly attributed to the substantial decline in the capital stock and energy input. Meanwhile, household consumption and investment will suffer a significant impact, which is mainly caused by the great decline in both the real wage and household revenue. When the government announces a mandatory emissions cap, which is a command and control method, it will also restrain the production activities of enterprises. Different from the environmental tax, this policy mainly affects the economy via the control of pollutant emissions or energy inputs. The decline in the GDP is also due to the decline in the capital stock and energy input. Moreover, household consumption and investment will suffer a great impact, which is mainly caused by the great decline in the real wage and household revenue.

Table 4
Long term steady state values of the main variables.

Variables	BAU	TAX	EI	EP	Change
p^Z	0	0.2	0.2	0.2	/
er	0	0.0392	0.0392	0.0392	/
L	0.8892	0.8899	0.8899	0.8899	0.08%
w	1.4992	1.4718	1.4718	1.4718	−1.83%
C	1.7948	1.7594	1.7594	1.7594	−1.97%
r	0.0473	0.0473	0.0473	0.0473	0.00%
π	1.0058	1.0058	1.0058	1.0058	0.00%
I	0.4005	0.3935	0.3935	0.3935	−1.75%
K	16.0211	15.7401	15.7398	15.7399	−1.75%
Y	2.2953	2.255	2.255	2.255	−1.76%
M	0.9321	0.8736	0.8736	0.8736	−6.28%
η_L	0.9974	0.9976	0.9976	0.9976	0.02%
η_M	0.9232	0.8577	0.8577	0.8577	−7.10%
V	1.0014	1.0014	1.0014	1.0014	0.00%
Z	0.5592	0.5036	0.5036	0.5036	−9.94%
ST	111.8485	100.7261	100.7261	100.7261	−9.94%
tax	0.2905	0.3811	0.3812	0.3811	31.19%

5.2. Results for exogenous shocks

The analyses above are concerned with the steady state values for the main variables, ignoring the potential effects of different sources of uncertainties, whereas exogenous uncertain factors from the different sources may influence the choice of environmental policy. In order to analyse the response of the macro-economy, we introduce technology uncertainty (technology shock), fiscal policy uncertainty (government consumption expenditure shock, labour tax rate shock and capital tax rate shock) and energy efficiency uncertainty (energy efficiency shock) into our model. Then, we analyse the different effects of the exogenous shocks of emissions intensity targets, the emissions cap and the emissions tax rate in three different environmental policy regimes.

5.2.1. Technology uncertainty

We simulate the effect of a technology shock by exerting one unit positive impact of variable A ($\varepsilon_{t,\,A} = 1$). Fig. 2 represents the results of technology uncertainty in four scenarios: BAU, EI, EP and TAX. All the impulse responses are reported as percentage deviations from the steady state of variables over a 100-quarter period.

When the economy is affected by a positive technology shock, most variables will positively deviate from the steady state values. According to Bayesian estimation, the coefficient of the AR(1) technology shock is 0.8372, which means that the positive technology shock will last for nearly the 40th period.

Investment will rise to 1.52% in the BAU scenario and gradually converge with the steady state value, which will lead to an increase in the capital stock. Note that the capital stock will follow a “hump-shaped” dynamic in response to the technology shock. Prior to the 15th period, the sharp increase in investment will gradually help society to accumulate capital. As time goes by, the increment of investment will slow down and capital will gradually accumulate. When the depreciation of the capital stock is larger than the increment of investment, the “turning point” will be reached and the capital stock will gradually decrease and converge with its steady state.

The intermediate goods producing firms will slightly increase their labour demand during the 0th period. Then, labour will sharply increase and reach the peak value in nearly the 5th period. Why will the labour demand increase sharply and then drop? At the beginning, enterprises want to rent more capitals and labours to expand production. However, due to the lag of capital accumulation, rational enterprises will hire more labours to replace the capitals. As time goes by (nearly 5 quarters), the capital stock will gradually increase. Rational enterprises will rent more capitals to meet their production requirements, which will cause a sharp decrease in labour demand.

The figure also reveals some results of the environmental policies. We found that the trends of the impulse response curves are basically the same in all four scenarios. For some macroeconomic variables, the

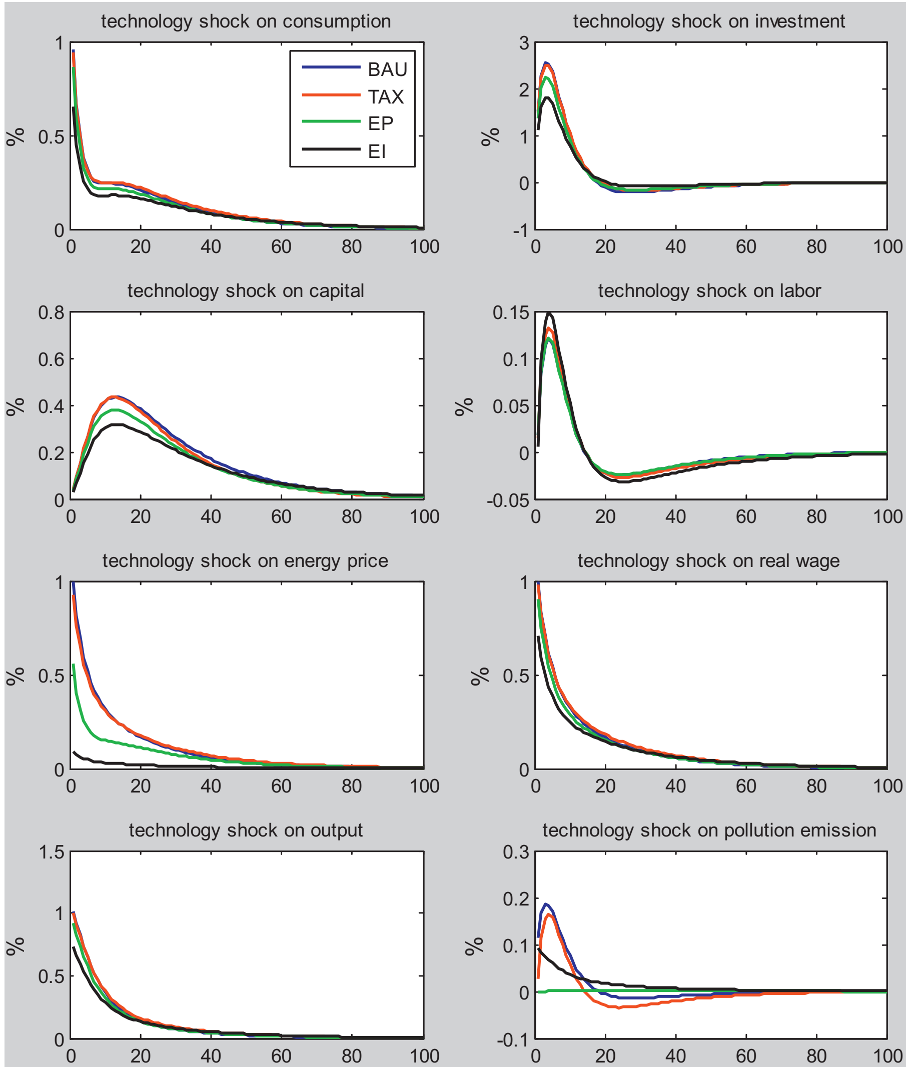

Fig. 2. Impulse response to a technology shock.

effects of a technology shock in the EI, EP and TAX scenarios are lower than in the BAU scenario, for example, Y, I, C and L. In the BAU scenario, increases in TFP will affect positively all real economic variables because of the productivity increase. The implementation of environmental policies will reduce the economic expansion with respect to the BAU scenario although the differences are quite small. This conclusion may seem to a certain extent obvious since, though in a different degree, all the environmental policies raise the cost of production, and thus affect negatively the real economic variables.

There are significantly different effects on pollutant emissions in the four scenarios. In the EP scenario, the pollutant emissions will remain at the steady state and will not respond to the technology shock, which is mainly due to the fixed pollutant emissions target announced by the government. Intuitively, the positive technology shock will lead to a corresponding increase in pollutant emissions in the EI, TAX and BAU scenarios, since we assume a proportional relationship between energy input and pollutant emissions. The positive percentage deviation from the steady state of pollutant emissions in the BAU scenario is the largest, which is mainly because the economic expansion effect caused by the technology shock is the largest in all the scenarios. The pollutant emissions will increase more with an environmental tax and less with a cap rule while the intensity target produces an intermediate result.

According to our equation, the pollutant emissions are emitted by energy inputs. In the BAU scenario, the economic expansion effect can increase the energy demand. Without any environmental policies, enterprises can use energy without restrictions. Therefore, the energy price will jump up. In the TAX scenario, the environmental tax will, in turn, lead to a lower energy demand, which implies a milder rise in the energy price. The energy prices in the EI and EP scenarios are relatively low due to the mandatory emissions targets.

5.2.2. Fiscal policy uncertainty

5.2.2.1. Government expenditure shock. For fiscal policy uncertainty, we now consider the environmental policy and macroeconomic dynamics in relation to a government expenditure shock. In particular, we simulate the effect of a government expenditure shock by exerting one unit positive impact of variable G ($\varepsilon_{t,G} = 1$). The results of a government expenditure shock are displayed in Fig. 3.

According to Bayesian estimation, the coefficient of the AR(1) government shock is 0.7506, which means that the government expenditure shock will converge with the steady state at a relatively fast speed (by nearly the 30th period). Consequently, the variables will rapidly return to the steady state. When compared to a technology shock, the effect of a government expenditure shock is significantly weaker. The total output

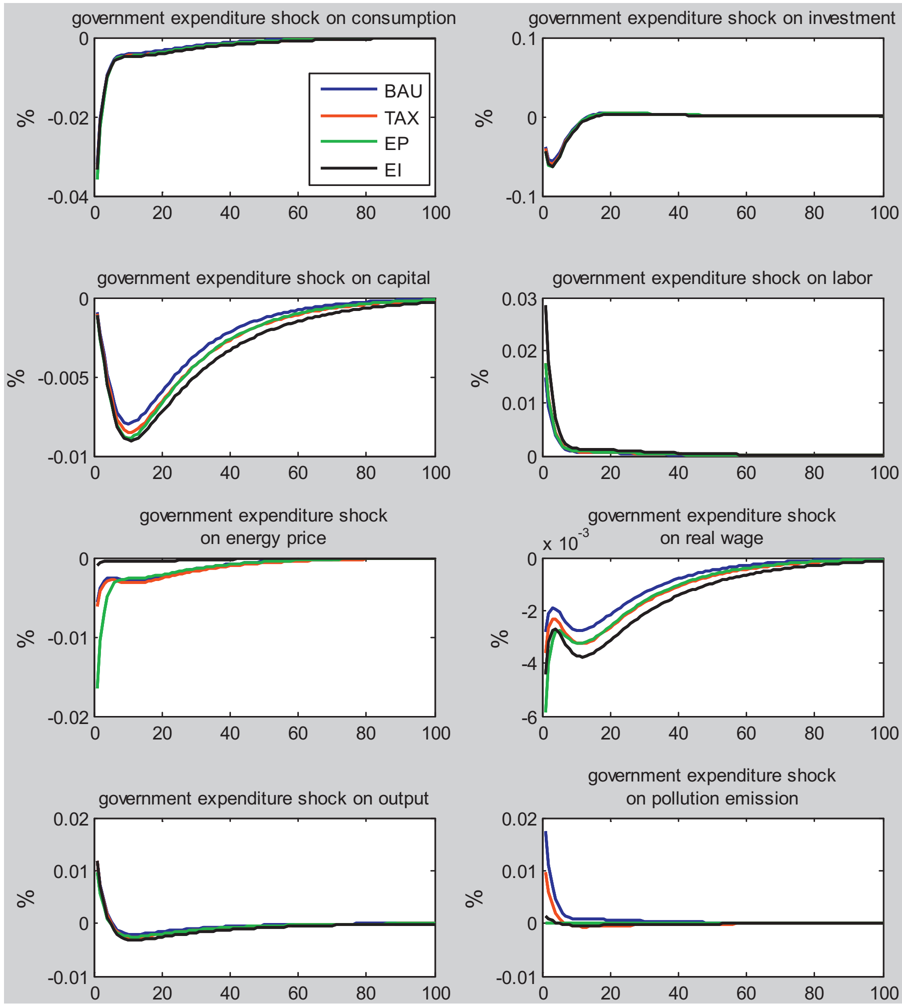

Fig. 3. Impulse response to a government expenditure shock.

will increase to 0.012% at 0th period, and then gradually converge to steady state after nearly the 40th period in the BAU scenario.

The expansion of government expenditure will exert a positive shock on the total output, the labour supply and the pollutant emissions. As expected, lower energy price will boost the energy inputs, which can increase pollutant emissions. Although the expansion of government expenditure can bring economic expansion effects, it will trigger a decrease of investment which is crowded out by the higher public expenditure. Therefore, capital accumulation will be affected negatively.

Wealth effects determine the behaviour of household labour supply. Due to the lower real wage, households will supply more labour to offset the lower wealth, which will increase in hours, in turn, gives a boost to total output. Previous researches pointed out that the public expenditure will influence the private consumption. In response to this shock, household consumption will be crowded out by the higher government expenditure. Investment and consumption will drop to −0.04% and −0.032% respectively and converge with the steady state at a relatively high speed in all the scenarios.

5.2.2.2. Capital & labour tax rate shock. In order to analyse the effects of increasing the capital and labour tax levy, we simulate the effect of a capital tax rate shock and a labour tax rate shock by exerting one unit positive impact of variable $\tau_t^L$and $\tau_t^K(\varepsilon_{t,\,L}, \varepsilon_{t,\,K} = 1)$.

Fig. 4 illustrates the impulse responses of the economy to capital tax rate shock. The positive capital tax rate shock means that the government will increase the capital tax levy. According to Keynesian economics, governments should boost the total demand through quantitative easing monetary policy and fiscal stimulus. Without doubt, the temporary tight fiscal policy can keep economics growth muted. If the government increases the capital tax rate in order to dampen economic growth, capital and investment will experience the impact first. The higher capital tax rate can cool the enthusiasm for investment, which will cause the capital stock to be pulled down. Along with the decreasing capital stock, there will be lower demand for labour and energy.

It is noteworthy that the negative effects of increasing the capital tax in the BAU scenario are larger than in the other scenarios with environmental policies. Therefore, environmental policies are counter-cyclical in terms of smoothing economic fluctuations of the macro-economy (Annicchiarico & Di Dio, 2015; Sim, 2006; Xu et al., 2016). But different from Annicchiarico & Di Dio (2015), energy intensity policy has the strongest effect on curbing economic fluctuations.

The capital tax rate shock have a positive impact on consumption at 0th period while the impacts on most of other variables are negative, which is mainly due to the fact that the households prefer short-term consumption rather than low-return investment caused by high capital tax levy. We found that the impact of a capital tax shock on investment, in terms of deviation from steady state, is larger than that on consumption. These results can be verified by Leeper et al. (2010). Empirically, investment should be more sensitive than consumption.

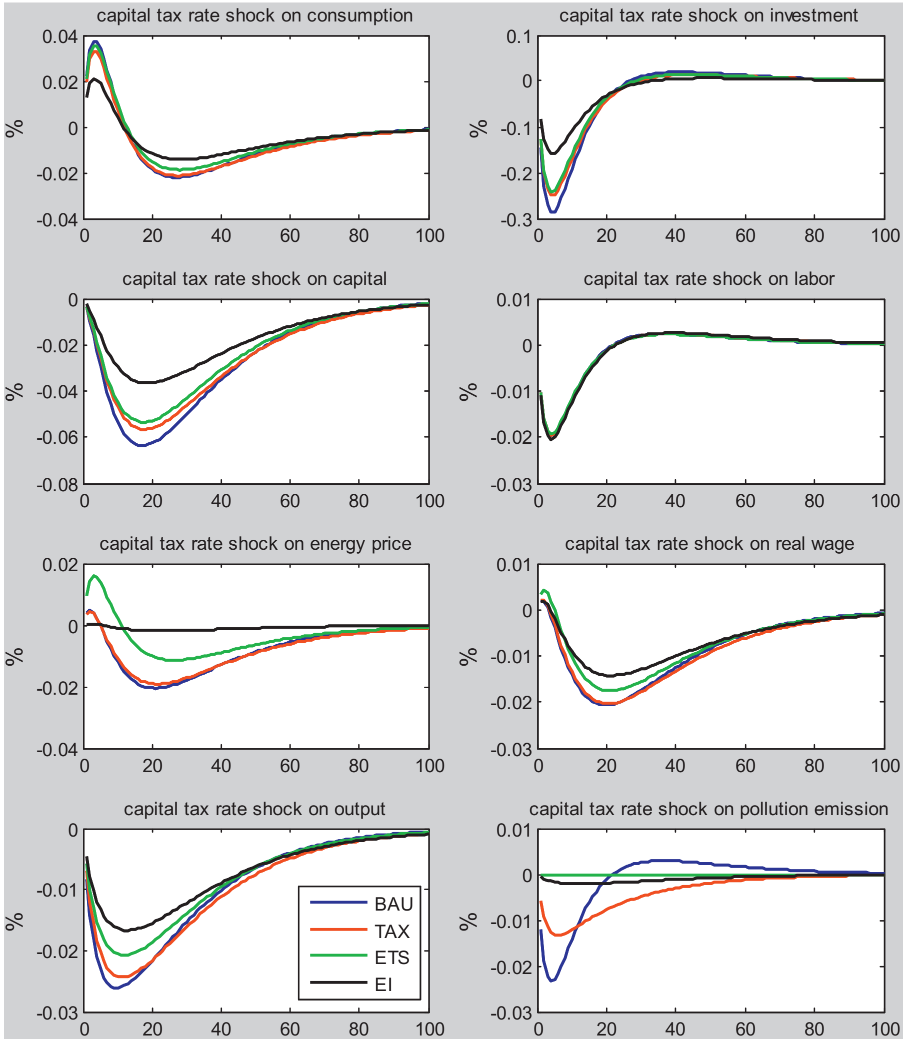

Fig. 4. Impulse response to a capital tax rate shock.

The results of a labour tax rate shock in the four scenarios are displayed in Fig. 5. When the economy is affected by a positive labour tax rate shock, most variables will negatively deviate from the steady state values. The coefficient of the AR(1) technology shock is 0.2014, which means that the labour tax rate shock will maintain for a short time. If the government increases the labour tax rate in order to restrain surplus labour, labour and the real wage will experience the impact first. Then, economic development will be curtailed. From Fig. 5, labour, capital, investment, consumption and output will all suffer negative impacts. Now, turning to the dynamic implications of the environmental policy regimes, the results suggest that the EI, EP and TAX scenarios all slightly diminish the responses of the macroeconomic variables, including capital, output, investment, labour and consumption. With the falling labour demand, there will be falling demand for both investment and energy. These decreases in demand will, in turn, diminish the levels of capital stock.

Finally, looking at the impulse response of pollutant emissions under the four scenarios, we found that, except for the emissions permits policy whose pollutant emissions remain constant, the levels of pollutant emissions in the other scenarios will be reduced by the falling demand for energy inputs, although the associated emissions reduction is quite small in size.

5.2.3. Energy efficiency uncertainty

The results of the impulse responses of the main macroeconomic variables to an energy efficiency shock in the four scenarios are displayed in Fig. 6. More specifically, we simulate the effect of an energy efficiency shock by exerting one unit positive impact of variable q ($\varepsilon_{t,\,q} = 1$).

Following the LBD approach, we presume that the energy efficiency improvement can be attributed to the use of energy and, further, that it follows the AR(1) process. Intuitively, energy efficiency enhancement implies a rising marginal output of energy input. As expected, just like the positive technology shock, the improvement in energy efficiency also generates an economic expansion effect. Following the shock, the total output, consumption, investment, capital stock and real wage all react positively, which stimulates the pollutant emissions. Why does the efficiency shock have a negative impact on labour at 0th period while the impacts on other variables are positive? Looking back to Eq. (13), the growing pollutant emission stock will exert negative effect on labour efficiency and cut the marginal output of labour. Therefore, rational enterprises will hire less labour at 0th period.

As previously explained in the case of a technology shock, a positive energy efficiency shock will lead to a corresponding increase in energy inputs (known as the energy rebound effect), which can lead to the growing pollutant emissions in the EI, TAX and BAU scenarios. Under an emissions permits policy, the pollutant emissions remain constant due

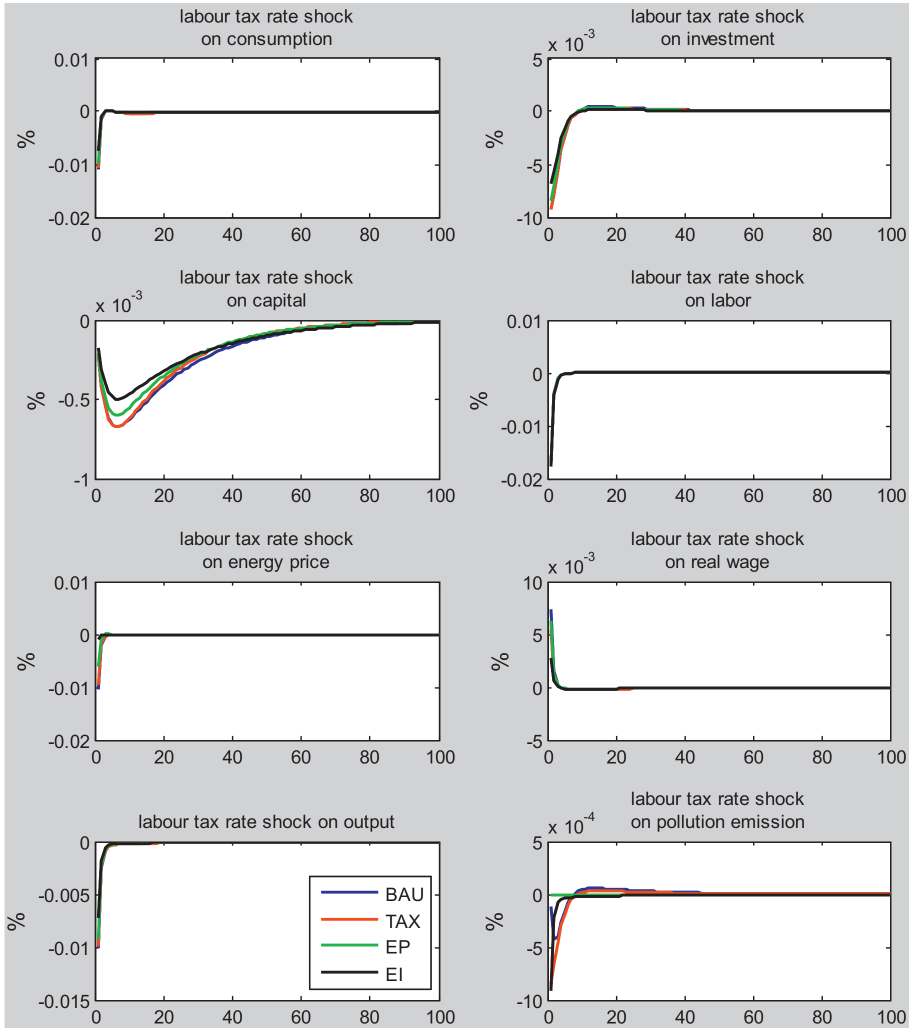

Fig. 5. Impulse response to a labour tax rate shock.

to the fixed pollutant emissions target announced by the government. Since the exogenous shock will push up energy efficiency, enterprises can produce more outputs with the same energy inputs. As a result, these producers will expand their outputs and spur on economic growth.

5.3. Shocks of policy intensity

In order to analyse the effects of policy intensity, we simulate the effects of an environmental tax rate shock, an emissions cap shock and an emissions intensity shock. We also use the Bayesian parameter estimation method to estimate the first-order autoregressive coefficients of the three shocks. The results of the Bayesian estimation and the diagnostic results are shown in Appendix B (Figs. B.4, B.5).

The results of an environmental tax rate shock, an emissions cap shock and an emissions intensity shock are displayed in Fig. 7. We simulate the effects of an emissions cap shock and an emissions intensity shock and an environmental tax rate shock by exerting one unit impact of variables, ψ_t, $\kappa_t$and τ_t^Z ($\varepsilon_{t,\ \psi}$, $\varepsilon_{t,\ \kappa} = 1\varepsilon_{t,\ Z} = -1$), which means that the government will loosen both the emissions cap and the emissions intensity target, and decrease environmental tax rate by one unit.

The results of the Bayesian estimation tell us that the coefficient of the AR(1) of environmental tax rate shock is 0.7705 and emissions cap shock is 0.8301, while that of the emissions intensity shock is 0.8652, which means that the emissions intensity shock will last longer than other two shocks. As expected, if the government loosens the tax levy, the emissions cap and the emissions intensity target, the price of pollutant emissions will decrease and all the macroeconomic variables will positively react to these shocks. Meanwhile, pollutant emissions will increase due to the lower environmental standards.

Accompanied by increasing pollutant emissions, the stock of pollutant will follow a "hump-shaped" dynamic in response to these three shocks. As already explained in the case of a technology shock, the stock of capital will follow a "hump-shaped" dynamic in response to the technology shock. The reason why the "hump-shaped" dynamic will appear in the case of the stock of pollutant emissions is basically the same as for the stock of capital.

Note that the responses of the variables to the emissions intensity shock are larger than the responses to the environmental tax rate shock and the emissions cap shock. According to our previous results, the emissions intensity policy (EI) will exert greater impacts on the economy than the environmental tax policy (TAX) and the emissions permits policy (EP). Therefore, when compared to the emissions intensity policy, if the government loosens the emissions cap or tax rate, the fluctuations of the variables will be milder.

5.4. Price rigidities

Nominal rigidities under NK framework, such as sticky prices in this paper, have become important components of models used in modern

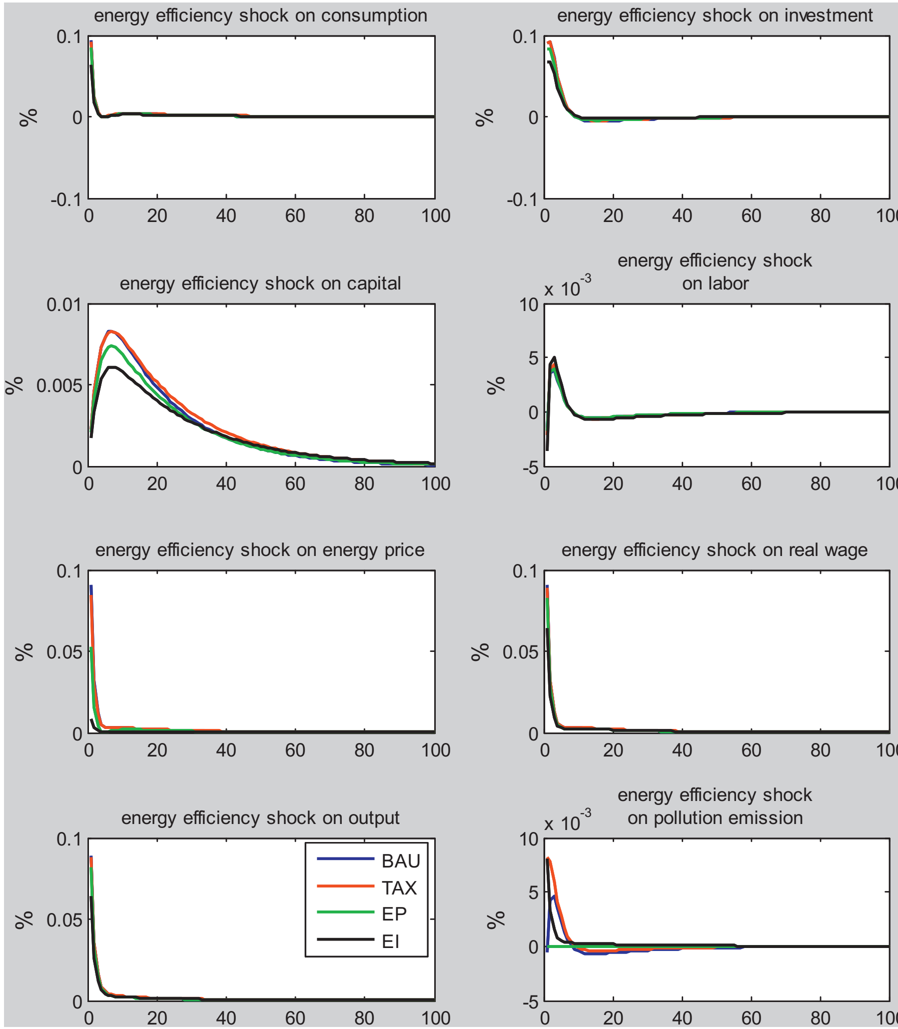

Fig. 6. Impulse response to an energy efficiency shock.

economics today. It is important to investigate the role of nominal rigidities. We try to find out the link between the NK setting and the empirical results. Calvo's price parameter for price rigidities are set to be 0.3, 0.5, 0.75 and 0.9. Table 5 displays the long term steady state values of the main variables under different price rigidities. The smaller the ω value, the lower the price rigidity, and vice versa. When $\omega = 0.9$, 90% of the intermediate goods producers cannot change their prices, which corresponds to an extremely high price rigidity.

With the nominal rigidity going up, the lower price dispersion will cut the demands for labour, capital stock, investment and energy by intermediate goods producers and push up total output and consumption. In our model, pollutant emissions derive from the use of energy inputs by the intermediate good producer firms. Hence, we can expect that the lower is the price dispersion the less intermediate goods are needed to produce a final output, and consequently, the lower are the pollutant emissions.

The nominal rigidity can not only influence the long term steady state value, but also can influence impulse response of variables. As shown in Fig. 8, we select the impulse response of technology shock on investment and pollutant emissions to see how price rigidity influence the empirical results.

It is noteworthy that the external shocks on the investment and pollutant emission under different price rigidities are similar. However, the larger the ω value, the lower the impulse responses of investment and pollutant emissions, and vice versa. High price rigidity means high proportion of intermediate goods producers cannot change their prices. Consequently, faced with economic uncertainties, high price rigidity can reduce macroeconomic fluctuations. This result can be also verified by the standard deviations of the variables in Table 5. Standard deviations of most variables under high price rigidity, such as Z, M, I, K and L, are lower than them under low price rigidity. Hence, we would expect that the higher is the price dispersion, the variables are more insensitive to exogenous shocks.

6. Conclusions

In this paper, we established an environmental DSGE model under classical New Keynesian framework embodying environmental policy variables and pollutant emission variables that aimed to compare the impacts of different environmental policies on the macroeconomic fluctuations and emissions controls under conditions of technology uncertainty, fiscal policy uncertainty and energy efficiency uncertainty. In addition, in order to analyse the environmental policy uncertainty, we simulated the effect of an environmental tax rate shock, an emissions cap shock and an emissions intensity shock. The results of this paper indicate the following.

(1) We analysed the technology uncertainty by exerting one unit positive impact of the TFP. In the BAU scenario, increases in TFP will affect positively all real economic variables because of the productivity increase. The implementation of environmental

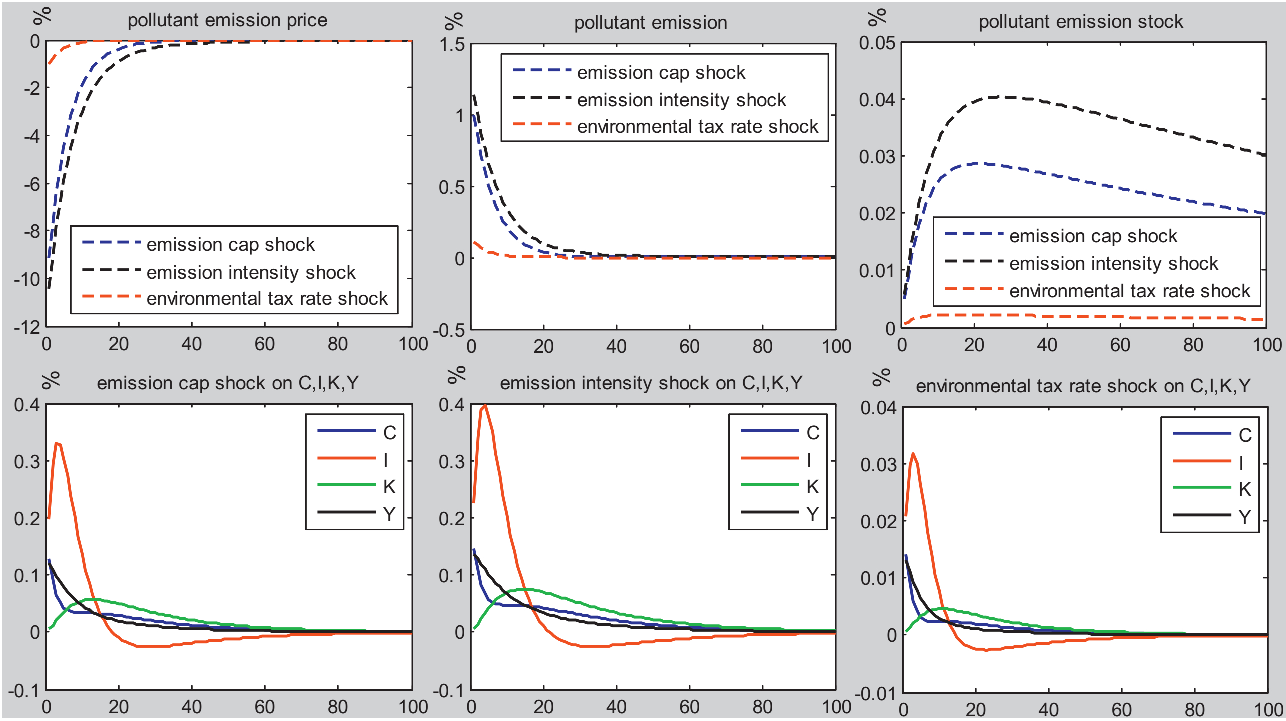

Fig. 7. Impulse response to an environmental tax rate shock, an emissions cap shock and an emissions intensity shock.

policies will reduce the economic expansion with respect to the BAU scenario, which is mainly due to the fact that environmental policies can push up the production cost. The only significant differences concern the energy price and pollution emissions. They will increase more with an environmental tax and less with a cap rule while the intensity target produces an intermediate result.

(2) For fiscal policy uncertainty, we considered the macroeconomic dynamics of a government expenditure shock, a capital tax shock and a labour tax shock. Intuitively, a proactive fiscal policy, for example, cutting the tax levy and increasing public expenditure, can contribute to the overall flourishing of the economy (and vice versa). However, the higher public consumption can crowd out investment and private consumption. The responses of the macroeconomic variables further reveal that all kinds of environmental policies are counter-cyclical, just as the previous literatures stated. But different from Annicchiarico & Di Dio (2015), energy intensity policy has the strongest effect on curbing economic fluctuations.

(3) Following the LBD approach, we presumed that the energy efficiency improvement can be attributed to the use of energy, which follows the AR(1) process. Intuitively, energy efficiency enhancement implies the rising marginal output of the energy input, which can generate an economic expansion effect in the same way as a positive technology shock. A positive energy efficiency shock will lead to a corresponding increase in energy inputs (known as the energy rebound effect), which can lead to growing pollutant emissions.

(4) If the government loosens the environment standards, the price of pollutant emissions will decrease and all the macroeconomic variables will react positively, which will be accompanied by increasing pollutant emissions. The dynamic responses of variables show that the emissions intensity shock will exert greater impacts on the economy than the environmental tax rate shock

Table 5
Long term steady state values of the main variables under different price rigidities.

Variables	$\omega = 0.3$		$\omega = 0.5$		$\omega = 0.75$		$\omega = 0.9$	
	Value	Std.de	Value	Std.de	Value	Std.de	Value	Std.de
L	0.89	0.2742	0.8895	0.2739	0.8892	0.2737	0.8891	0.2736
w	1.4994	3.1599	1.4992	3.1599	1.4992	3.1599	1.4991	3.1599
C	1.7921	3.2132	1.7938	3.2173	1.7948	3.2194	1.7951	3.2202
r	0.0473	0.0982	0.0473	0.0982	0.0473	0.0982	0.0473	0.0982
π	1.0383	0.0012	1.017	0.0006	1.0058	0.0002	1.0019	0.0001
p^M	0.4741	0.9822	0.4741	0.9823	0.4741	0.9824	0.4741	0.9824
I	0.4009	2.5834	0.4007	2.5831	0.4005	2.5829	0.4005	2.5828
K	16.0376	32.7181	16.0267	32.7128	16.0211	32.7102	16.0192	32.7091
Y	2.293	5.3012	2.2945	5.3048	2.2953	5.3067	2.2956	5.3073
M	0.933	0.341	0.9324	0.3405	0.9321	0.3402	0.932	0.3401
V	1.0034	0.0002	1.0021	0.0001	1.0014	0.0001	1.0011	0.0001
Z	0.5598	0.2046	0.5594	0.2043	0.5592	0.2041	0.5592	0.2041
ST	111.9619	2.7083	111.887	2.7043	111.8485	2.7021	111.835	2.7013

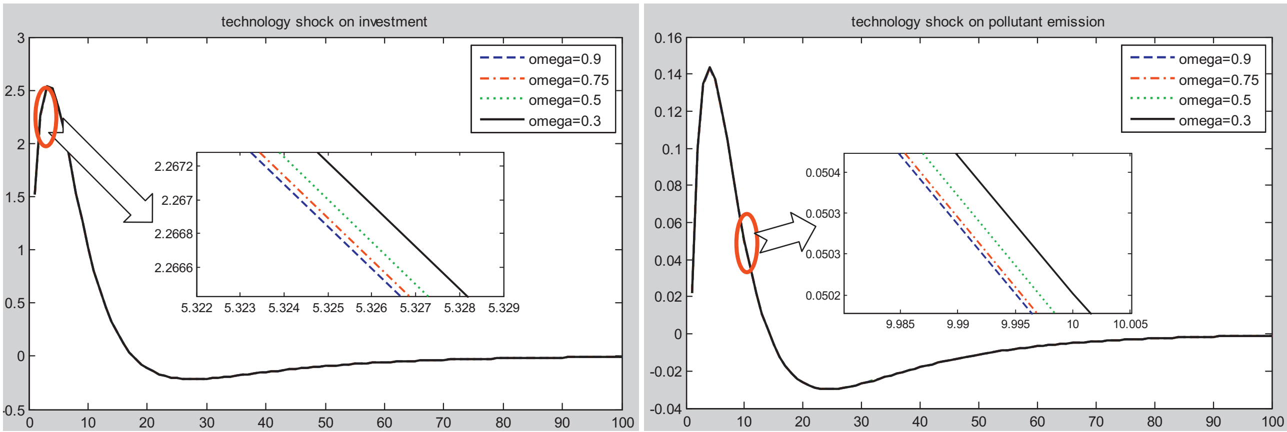

Fig. 8. The impulse responses of technology shock under different price rigidities.

and the emissions cap shock. When compared to the emissions intensity policy, if the government loosens the emissions cap or tax rate, the fluctuations of the variables will be milder.

(5) With the nominal rigidity going up, the lower price dispersion will cut the demands for labour, capital stock, investment and energy by intermediate goods producers and push up total output and consumption. Hence, we can expect that the lower is the price dispersion the less intermediate goods are needed to produce a final output, and, consequently, the lower are the pollutant emissions. High price rigidity means high proportion of intermediate goods producers cannot change their prices. Consequently, our results pointed out that high price rigidity can reduce macroeconomic fluctuations.

Environmental policies have been continually issued in an attempt to solve the environmental problems facing China. However, arguments persist regarding how to choose the most appropriate environmental policy to solve the increasingly serious environmental problems. Taken together, all these analyses are of relevance to the Chinese government in relation to choosing the optimal policy for reducing air pollutant emissions. Future studies should consider the financial behaviour in different environmental policy regimes, for example, tradable permits. Additionally, monetary policy also could be included.

Acknowledgments

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Appendix A. The model derivation

A.1. Households

In order to solve the household problem, form the Lagrangian function:

$$\ell = E_t \sum_{t=0}^{\infty} \beta^t \Bigg\{ \left(\ln C_t - \frac{L_t^{1+\theta}}{1+\theta} - \frac{Z_t^{1+\upsilon}}{1+\upsilon} \right) + \xi_t \begin{bmatrix} (1-\tau_t^L) W_t L_t + (1-\tau_t^K) R_t K_{t-1} + \dots \\ (1-\tau_t^M) P_{tM} M_t + R_{t-1}^B B_{t-1} + D_t P_t + Tr_t - P_t C_t - P_t I_t - B_t \end{bmatrix} + \nu_t \left[K_t - (1-\delta_K) K_{t-1} - \left[1 - \frac{\vartheta}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \right] I_t \right] \Bigg\} \tag{A.1}$$

where ξ_t and ν_t are Lagrange multipliers. The FOCs for the household's problem:

$$\frac{\partial \ell}{\partial C_t}: \quad \frac{1}{C_t} = \xi_t P_t \tag{A.2}$$

$$\frac{\partial \ell}{\partial L_t}: \quad L_t^{\theta} = \xi_t (1-\tau_t^L) W_t \tag{A.3}$$

$$\frac{\partial \ell}{\partial K_t}: \nu_t + \beta E_t \left[\xi_{t+1} (1-\tau_{t+1}^K) R_{t+1} - (1-\delta_K) \nu_{t+1} \right] = 0 \tag{A.4}$$

$$\frac{\partial \ell}{\partial I_t}: \quad \xi_t P_t = -\nu_t \left[1 - \frac{\vartheta}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \right] + \nu_t \vartheta I_t \left(\frac{I_t}{I_{t-1}^2} - \frac{1}{I_{t-1}} \right) - \beta E_t \left[\vartheta \nu_{t+1} \frac{I_{t+1}^2}{I_t^2} \left(\frac{I_{t+1}}{I_t} - 1 \right) \right] \tag{A.5}$$

$$\frac{\partial \ell}{\partial B_t}: \quad \xi_t = \beta E_t \left[R_t^B \xi_{t+1} \right] \tag{A.6}$$

$$\frac{\partial \ell}{\partial M_t}: \quad (1-er_t)^{1+\upsilon} \mu^{1+\upsilon} M^{\upsilon} = \xi_t (1-\tau_t^M) P_t^M \tag{A.7}$$

A.2. Enterprises

A.2.1. Final goods producers

The representative final goods producer's aim is to maximise profits by deciding Y_t and $Y_t(j)$, which are given by

$$\max_{Y_t(j)} P_t \left[\int_0^1 Y_t(j)^{\frac{\varphi-1}{\varphi}} dj \right]^{\frac{\varphi}{\varphi-1}} - \int_0^1 Y_t(j) P_t(j) dj \tag{A.8}$$

The FOC for the final goods producer's problem:

$$Y_t(j) P_t^{\varphi}(j) = Y_t P_t^{\varphi} \tag{A.9}$$

We presume that the final goods are in a perfect competitive and free entry market, which implies the zero profit of the final goods producer, that is, $\int_0^1 Y_t(j) P_t(j) dj = Y_t P_t$. The general price level in the product market is obtained by the zero profit condition $P_t^{1-\varphi} = \int_0^1 P_t(j)^{1-\varphi} dj$.

A.2.2. Intermediate goods producers

In order to solve the household problem, form the Lagrangian function and the FOC:

$$\zeta = \frac{P_t(j)}{P_t} Y_t(j) - \frac{W_t}{P_t} L_t(j) - \frac{R_t}{P_t} K_t(j) - \frac{P_t^M}{P_t} M_t(j) - \frac{P_t^Z}{P_t}(1-er_t(j))\mu M_t(j) - CE_t(j) - \ldots$$
$$\lambda_t \left\{ Y_t(j) - A_t K_t^{\alpha}(j) \left[\eta_t^L L_t(j)\right]^{\Delta} \left[\eta_t^M M_t(j)\right]^{(1-\alpha-\Delta)} \right\} \tag{A.10}$$

where λ_t is lagrange multiplier. The FOCs for the Intermediate goods producers' problem:

$$\frac{\partial \zeta}{\partial L_t(j)} : \quad -\frac{W_t}{P_t} = \lambda_t \Delta A_t K_t^{\alpha}(j) \left(\eta_t^L\right)^{\Delta} L_t(j)^{\Delta-1} \left[\eta_t^M M_t(j)\right]^{(1-\alpha-\Delta)} \tag{A.11}$$

$$\frac{\partial \zeta}{\partial K_t(j)} : \quad -\frac{R_t}{P_t} = \lambda_t \alpha A_t K_t^{\alpha-1}(j) \left[\eta_t^L L_t(j)\right]^{\Delta} \left[\eta_t^M M_t(j)\right]^{(1-\alpha-\Delta)} \tag{A.12}$$

$$\frac{\partial \zeta}{\partial M_t(j)} : \quad -\frac{P_t^Z}{P_t}\mu(1-er_t(j)) - \frac{P_t^M}{P_t}$$
$$= \lambda_t (1-\alpha-\Delta) A_t K_t^{\alpha}(j) \left[\eta_t^L L_t(j)\right]^{\Delta} \frac{\left(\eta_t^M M_t(j)\right)^{(1-\alpha-\Delta)}}{M_t(j)} \tag{A.13}$$

$$\frac{\partial \zeta}{\partial er_t(j)} : \quad \frac{P_t^Z}{P_t} = \Lambda \ln(1-er_t(j)) \tag{A.14}$$

$$MC_t = -\lambda_t$$
$$= \frac{W_t/P_t}{\Delta A_t \left(\eta_t^L\right)^{\Delta} \left(\frac{\alpha}{\Delta}\right)^{\alpha} \left(\frac{W_t}{R_t}\right)^{\alpha} \left[\frac{\gamma(1-\alpha-\Delta)}{\Delta}\right]^{(1-\alpha-\Delta)} \left[\frac{W_t}{P_t^Z \mu(1-er_t)+P_t^M}\right]^{(1-\alpha-\Delta)} \left(\eta_t^M\right)^{(1-\alpha-\Delta)}} \tag{A.15}$$

Following the approach of Calvo (1983), firms that have the chance to change their prices at t choose their price in order to maximise the expected sum of discounted future real profits.

$$\max_{P_t(j)} \quad \mathfrak{R} = E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{U'(C_{t+i})}{U'(C_t)} Y_{t+i} \left[\frac{P_t(j)}{P_{t+i}} \left(\frac{P_{t+i}}{P_t(j)}\right)^{\varphi} - MC_{t+i} \left(\frac{P_{t+i}}{P_t(j)}\right)^{\varphi} \right] \tag{A.16}$$

F.O.C for Calvo pricing:

$$\frac{\partial \mathfrak{R}}{\partial P_t(j)} : \quad E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{U'(C_{t+i})}{U'(C_t)} Y_{t+i} \left[(1-\varphi) P_t^{*-\varphi}(j) P_{t+i}^{\varphi-1} + \varphi MC_{t+i} P_{t+i}^{\varphi} P_t^{*-\varphi-1}(j) \right] = 0 \tag{A.17}$$

$$P_t^* = P_t^*(j) = \frac{\varphi}{\varphi-1} \cdot \frac{E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{U'(C_{t+i})}{U'(C_t)} Y_{t+i} MC_{t+i} P_{t+i}^{\varphi}}{E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{U'(C_{t+i})}{U'(C_t)} Y_{t+i} P_{t+i}^{\varphi-1}} \tag{A.18}$$

$$(\varphi-1) E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{U'(C_{t+i})}{U'(C_t)} Y_{t+i} \left(\frac{P_t^*}{P_{t+i}}\right)^{1-\varphi}$$
$$= \varphi \cdot E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{U'(C_{t+i})}{U'(C_t)} Y_{t+i} MC_{t+i} \left(\frac{P_t^*}{P_{t+i}}\right)^{-\varphi} \tag{A.19}$$

A.3. Competitive equilibrium

Define: $\pi_{t+1} = \frac{P_{t+1}}{P_t}$; $w_t = \frac{W_t}{P_t}$; $r_t = \frac{R_t}{P_t}$; $p_t^M = \frac{P_t^M}{P_t}$; $p_t^Z = \frac{P_t^Z}{P_t}$; $p_t^* = \frac{P_t^*}{P_t}$; $b_t = \frac{B_t}{P_t}$; $tax_t = \frac{TAX_t}{P_t}$

Variables: A_t, G_t, τ_t^K, τ_t^L, p_t^Z, p_t^M, q_t, L_t, w_t, C_t, r_t, π_t, er_t, CE_t, I_t, K_t, Y_t, M_t, η_t^L, η_t^M

V_t, Z_t, ST_t, λ_t, MC_t, $X_{1,\,t}$, $X_{2,\,t}$, p_t^*, tax_t, Tr_t, R_t^B, $\varepsilon_{t,\,A}$, $\varepsilon_{t,\,G}$, $\varepsilon_{t,\,q}$, $\varepsilon_{t,\,K}$, $\varepsilon_{t,\,L}$

Equations:

$$C_t L_t^{\theta} = (1-\tau_t^L) w_t \tag{A.20}$$

$$\nu_t + \beta E_t \left[\frac{1}{C_{t+1}} (1-\tau_{t+1}^K) r_{t+1} - (1-\delta_K) \nu_{t+1} \right] = 0 \tag{A.21}$$

$$\frac{1}{C_t} = -\nu_t \left[1 - \frac{\vartheta}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \right]$$
$$+ \nu_t \vartheta I_t \left(\frac{I_t}{I_{t-1}^2} - \frac{1}{I_{t-1}} \right) - \beta E_t \left[\vartheta \nu_{t+1} \frac{I_{t+1}^2}{I_t^2} \left(\frac{I_{t+1}}{I_t} - 1 \right) \right] \tag{A.22}$$

$$\frac{1}{C_t} = \beta E_t \frac{R_t^B}{\pi_{t+1} C_{t+1}} \tag{A.23}$$

$$C_t \mu^{1+\upsilon} M_t^{\upsilon} = (1-\tau_t^M) p_t^M \tag{A.24}$$

$$K_t = (1-\delta_K) K_{t-1} + \left[1 - \frac{\vartheta}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \right] I_t \tag{A.25}$$

$$Y_t = C_t + I_t + G_t + CE_t \tag{A.26}$$

$$Y_t = A_t K_t^{\alpha} \left[\eta_t^L L_t\right]^{\Delta} \left[\eta_t^M M_t\right]^{(1-\alpha-\Delta)} (V_t)^{-1} \tag{A.27}$$

$$CE_t = -\Lambda \mu M_t \left[\ln(1-er_t)(1-er_t) + er_t \right] \tag{A.28}$$

$$p_t^Z = \Lambda \ln(1-er_t) \tag{A.29}$$

$$MC_t = \frac{W_t/P_t}{\Delta A_t \left(\eta_t^L\right)^{\Delta} \left(\frac{\alpha}{\Delta}\right)^{\alpha} \left(\frac{W_t}{R_t}\right)^{\alpha} \left[\frac{\gamma(1-\alpha-\Delta)}{\Delta}\right]^{(1-\alpha-\Delta)} \left[\frac{W_t}{P_t^Z \mu(1-er_t)+P_t^M}\right]^{(1-\alpha-\Delta)} \left(\eta_t^M\right)^{(1-\alpha-\Delta)}} \tag{A.30}$$

$$Z_t = (1-er_t) \mu M_t \tag{A.31}$$

$$\eta_t^M = q_t M_t^{(\gamma-1)} \tag{A.32}$$

$$\eta_t^L = 1 - \left(\eta_0 + \eta_1 ST_t + \eta_2 ST_t^2 \right) \tag{A.33}$$

$$ST_t = (1-\delta_Z) ST_{t-1} + Z_t \tag{A.34}$$

$$-w_t = \lambda_t \Delta A_t K_t^{\alpha} \left(\eta_t^L\right)^{\Delta} L_t^{\Delta-1} \left[\eta_t^M M_t\right]^{(1-\alpha-\Delta)} \tag{A.35}$$

$$-r_t = \lambda_t \alpha A_t K_t^{\alpha-1} \left[\eta_t^L L_t\right]^{\Delta} \left[\eta_t^M M_t\right]^{(1-\alpha-\Delta)} \tag{A.36}$$

$$-p_t^Z\mu(1-er_t)-p_t^M = \lambda_t(1-\alpha-\Delta)A_tK_t^{\alpha}\left[\eta_t^L L_t\right]^{\Delta}\left(\eta_t^M M_t\right)^{(1-\alpha-\Delta)}/M_t \qquad (A.37)$$

$$MC_t = -\lambda_t \qquad (A.38)$$

$$(\varphi-1)X_{1,t} = \varphi X_{2,t} \qquad (A.39)$$

$$X_{1,t} = U'(C_t)Y_t\left(p_t^*\right)^{\varphi-1}+\beta\omega E_t\left[X_{1,t+1}\left(p_t^*\right)^{1-\varphi}\left(p_{t+1}^*\right)^{\varphi-1}\pi_{t+1}^{\varphi-1}\right] \qquad (A.40)$$

$$X_{2,t} = U'(C_t)Y_tMC_t\left(p_t^*\right)^{-\varphi}+\beta\omega E_t\left[X_{2,t+1}\left(p_t^*\right)^{-\varphi}\left(p_{t+1}^*\right)^{-\varphi}\pi_{t+1}^{\varphi}\right] \qquad (A.41)$$

$$V_t = (1-\omega)\left(p_t^*\right)^{-\varphi}+\omega\pi_t^{\varphi}V_{t-1} \qquad (A.42)$$

$$1 = (1-\omega)\left(p_t^*\right)^{1-\varphi}+\omega\pi_t^{\varphi-1} \qquad (A.43)$$

$$G_t+\frac{R_{t-1}^B b_{t-1}}{\pi_t}+Tr_t = tax_t+b_t \qquad (A.44)$$

$$tax_t = \tau_t^L w_t L_t+\tau_t^K r_t K_t+\tau_t^M p_{tM}M_t+p_{tZ}Z_t \qquad (A.45)$$

$$\ln A_t-\ln A = \rho_A \ln A_{t-1}-\rho_A \ln A+\varepsilon_{t,A} \qquad (A.46)$$

$$\ln G_t-\ln G = \rho_G \ln G_{t-1}-\rho_G \ln G+\varepsilon_{t,G} \qquad (A.47)$$

$$\ln q_t-\ln q = \rho_q \ln q_{t-1}-\rho_q \ln q+\varepsilon_{t,q} \qquad (A.48)$$

$$\ln \tau_t^K-\ln \tau^K = \rho_K \ln \tau_{t-1}^K-\rho_K \ln \tau^K+\varepsilon_{t,K} \qquad (A.49)$$

$$\ln \tau_t^L-\ln \tau^L = \rho_L \ln \tau_{t-1}^L-\rho_L \ln \tau^L+\varepsilon_{t,L} \qquad (A.50)$$

Appendix B. The results of Bayesian estimation

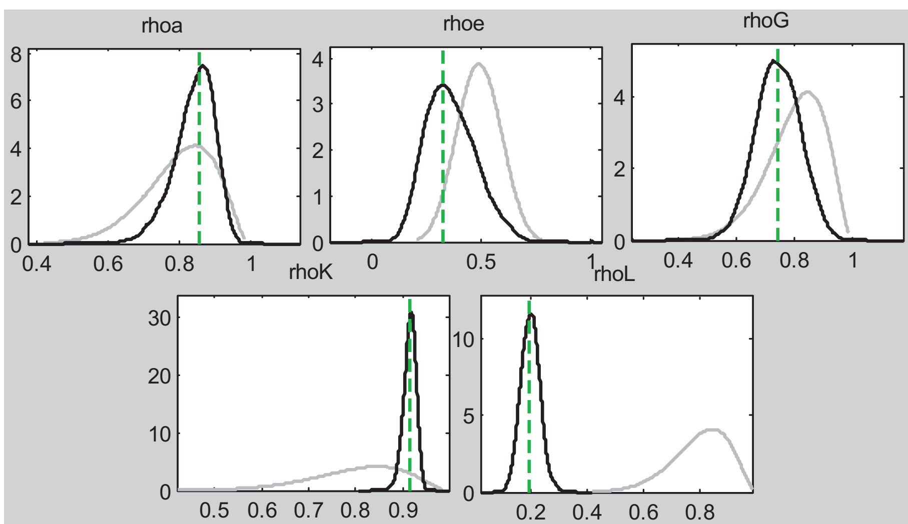

Fig. B.1. The Bayesian estimation results of first order autoregressive coefficients of 5 shocks

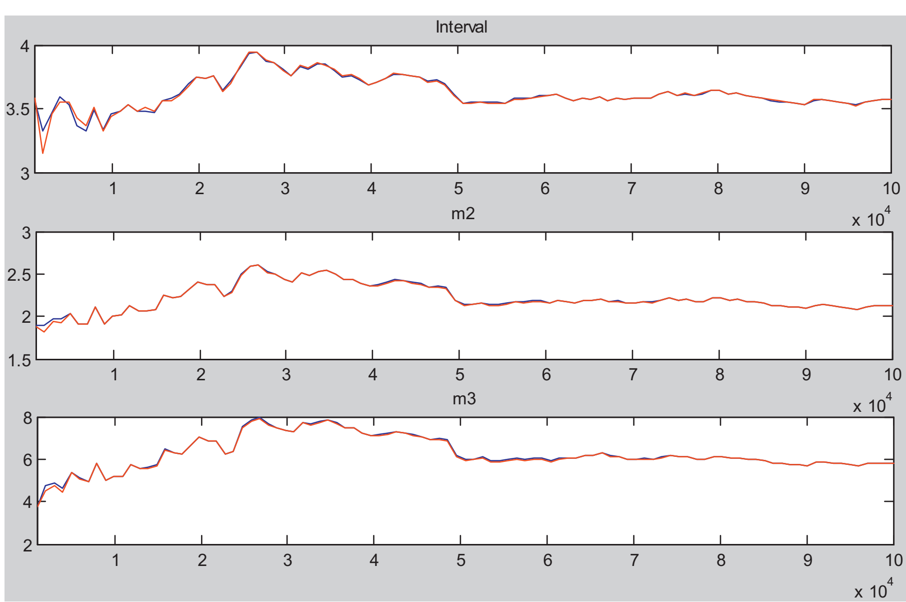

Fig. B.2. Multivariate diagnostic

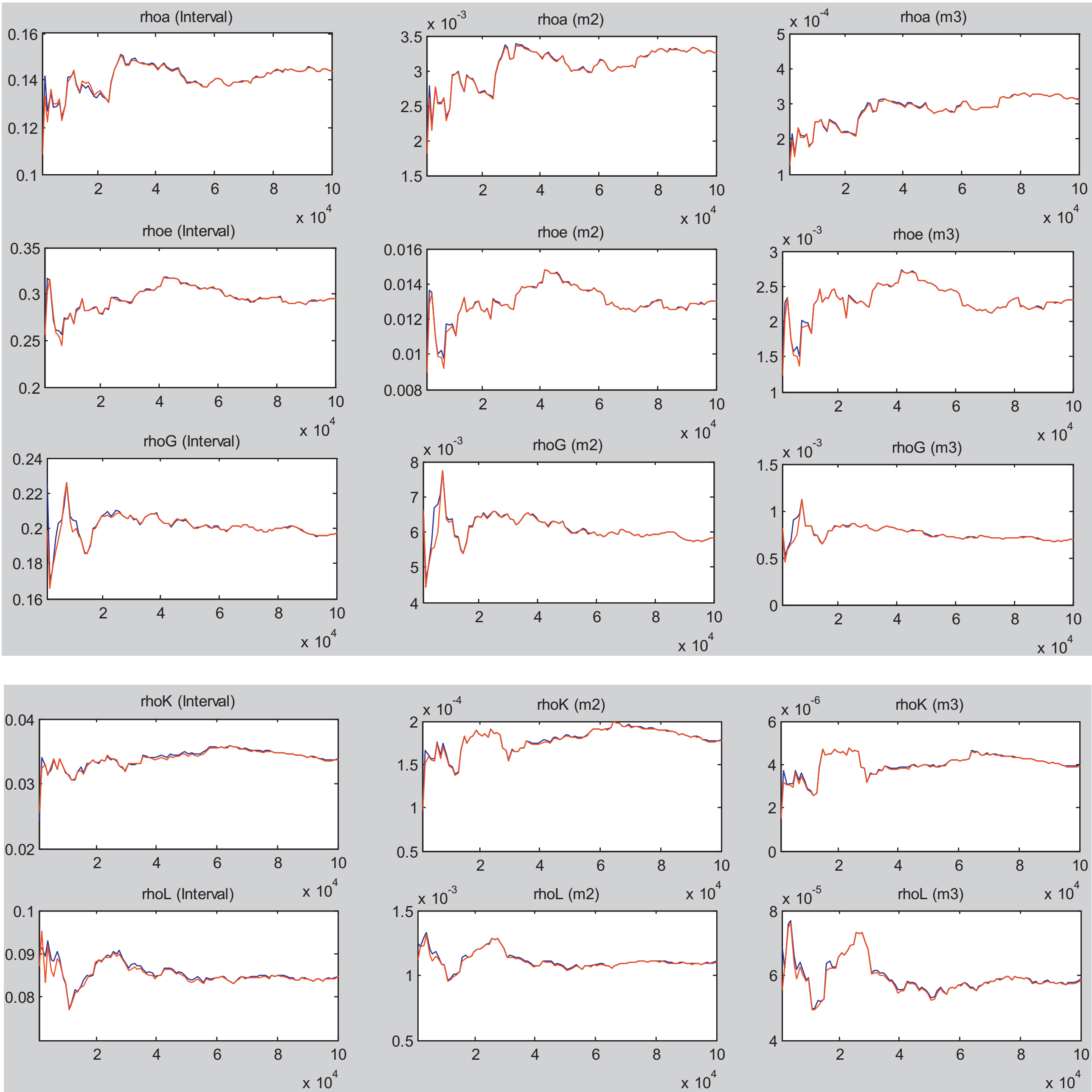

Fig. B.3. Univariate diagnostic

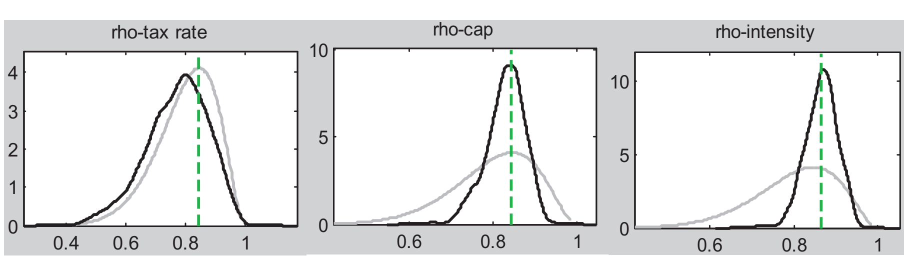

Fig. B.4. The Bayesian estimation results of first order autoregressive coefficients of policy intensity

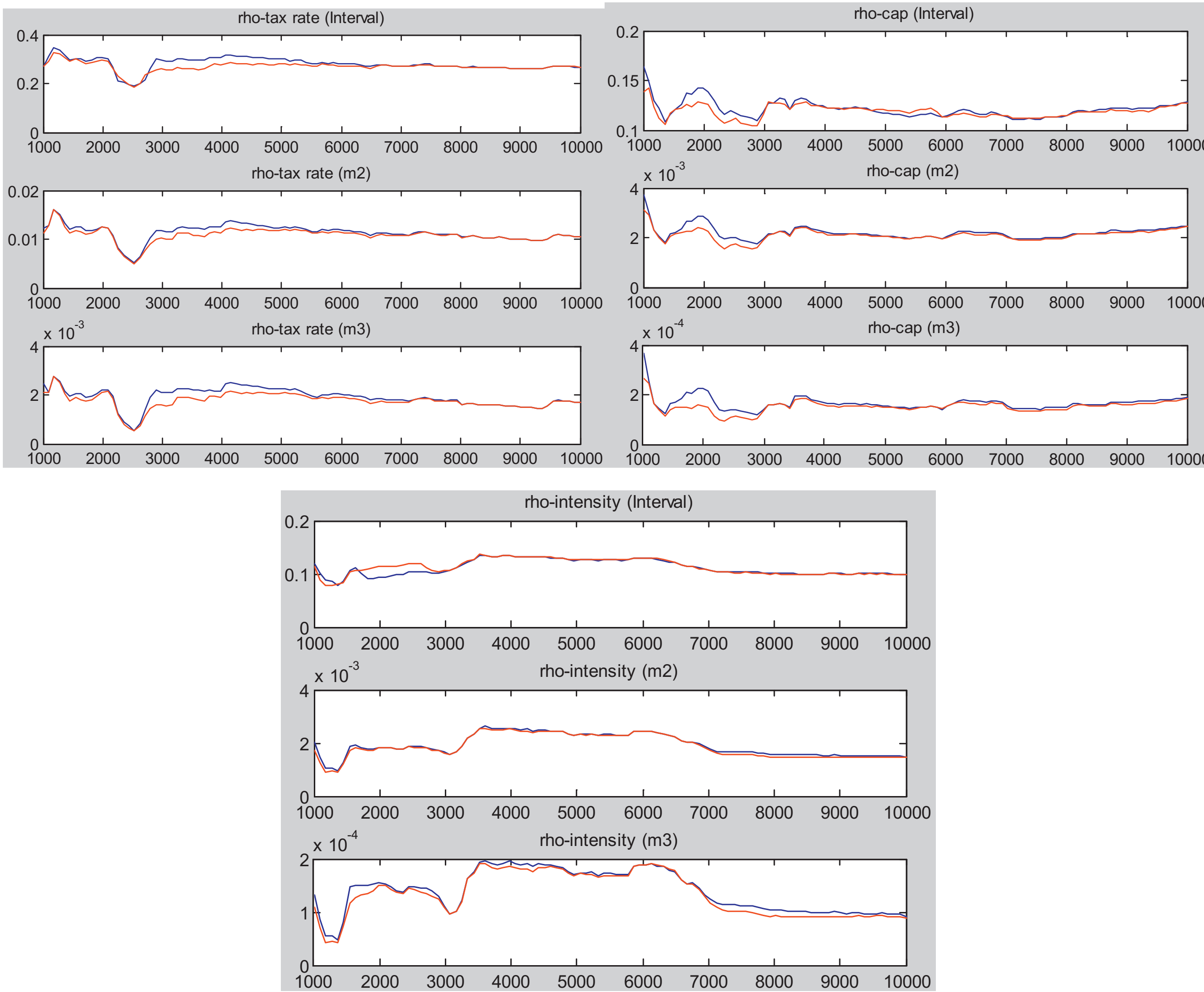

Fig. B.5. Multivariate diagnostic

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2018.10.028.

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