// NO.20-011 | 03/2020

DISCUSSION PAPER

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Climate Policies Under Dynamic International Economic Cycles: A Heterogeneous Countries DSGE Model

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Abstract: In light of increased economic integration and global warming, addressing critical issues such as the role of multilateral climate policies and the strategic interaction of countries in climate negotiations becomes paramount. We thus established for this paper an open economy environmental dynamic stochastic general equilibrium model with heterogeneous production sectors, bilateral climate policies, asymmetric economies, and asymmetric stochastic shocks, using China and the EU as case studies in order to analyze the interaction and linking of international carbon markets under dynamic international economic cycles. This led us to some major conclusions. First, with various methods we verified that, due to deadweight loss, the efficiency of the separate carbon market is lower than that of the joint carbon market. Second, the intensity of the spillover effects depends partly on different climate policies. This means that, in terms of supply-side shocks, the EU's economy in a joint carbon market is more sensitive because its cross-border spillover effects are enhanced, while demand-side shocks have a stronger impact on the EU's economy under a separate carbon market. Third, the Ramsey policy rule revealed that both China's and the EU's emission quotas should be adjusted pro-cyclically under separate carbon markets. The cross-border spillover effects of the joint carbon market, however can change the pro-cyclical characteristics of foreign (EU's) optimal quotas.

JEL classification: E32 F41 Q53 Q56 Q58

Keywords: International economic cycle; Carbon market; China; the European Union (EU); Dynamic Stochastic General Equilibrium (DSGE)

Acknowledgements: *The authors are grateful to Prof. Dr. Martin Kesternich, Dr. Wolfgang Habla, Dr. Claire Gavard and all the colleagues in department of Environmental and Resource Economics, Environmental Management in the ZEW – Leibniz Centre for European Economic Research. The authors also gratefully acknowledge the financial support from the National Natural Science Foundation of China (Grant No.71974001) and the financial support from the China Scholarship Council (No. 201806020120).*

1. Introduction

Given the acceleration of the process of economic integration, international trade has paved the way for deeper international connections. And since global warming is indeed a global problem, "common but differentiated responsibilities" require all countries in the world to fulfill their obligations to tackle climate change. As Stern (2008) pointed out, the economic analysis of climate change must “be global, deal with long time horizons, have the economics of risk and uncertainty at center stage.” The discussion of unilateral climate policies has therefore gradually led to discussions about the role of bilateral and multilateral climate policies in international trade, and the strategic interaction of countries in climate negotiations (Falkner et al., 2010). Policymakers and economists around the world have long worried about how these international climate policy regimes will play out in light of the economic behaviours of different countries and international trade.

Over the past few decades, integrated assessment models (IAMs) have been widely used for analyzing the climate issues involving the characterization i.e. study of international trade and the effects of climate policies in an open economy. Particularly literature adopting the multi-regional computable general equilibrium (CGE) models stands out (Ochuodho et al., 2016; Li et al., 2019). However, one of the most salient issues is that IAMs cannot deal with deep uncertainty in the economic system (Pindyck, 2013). To tackle this, another strand of models, namely the environmental dynamic stochastic general equilibrium (hereafter E-DSGE) models, have been emerging in the environmental and climate economics. Markedly different from IAMs, E-DSGE models explicitly incorporate future uncertainty by introducing several kinds of stochastic shocks to the economy. In light of dynamic and stochastic behaviour under the E-DSGE model, we are able to not only evaluate the long-term effects of climate policies, but also focus on the interactions between climate policies and dynamic economic cycles (Fischer and Springborn, 2011). Following Angelopoulos et al., (2010), a large number of scholars have conducted a more in-depth discussion of the relationship between economic cycles and unilateral climate policies while utilizing E-DSGE models (Doda, 2014).[1] Yet most of their research only focused on the effects of unilateral climate policies in a single economy; so far, there has been relatively little work on the two-way impact mechanism of economic cycles and climate policy regimes in open economies. While the importance of assessing the relationship between international trade and climate policy is undisputed, the complex connections between them and economic uncertainty pose great challenges to the assessment. Furthermore, on the one hand, international climate policies will undoubtedly affect the international transmission of a country's economic cycle and international trade balance. On the other hand, a country's economic cycle and trade balance will determine the allocation of its emission reduction resources and the international flow of carbon dioxide emissions, thereby affecting the potential impact of climate policies. Under these circumstances, we establish an open economy E-DSGE model and attempt to analyze the interactions between international economic cycles and different international climate policy regimes. The results shed light on how countries choose and implement climate policies under certain economic cycles. However, climate policy measures have multiple international dimensions, which has led to the need for joint agreements to seriously consider multilateral environmental and trade issues. Besides taking into account the cross-border externalities of CO_2 emissions and the corresponding interest issues of public goods, a country's climate policy must also consider trade-related impacts with other countries (Schenker, and Bucher, 2010). Thus, the issue of strategic interaction between multilateral climate negotiations and climate policy arises when countries have the ability to choose their own climate policies. In this paper, the E-DSGE model is extended to a Ramsey setup, which makes it possible to analyze optimal climate policies while utilizing Ramsey optimal policy rules. Here, we attempt to explore the Ramsey rule for optimal strategic interaction of

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[1] All previous research can be methodologically divided into two categories according to the setting of nominal friction. The first category, appearing earlier, is the flexible prices model without considering nominal friction, in which the real business cycle models (RBC) are established on the E-DSGE models. See Fischer and Springborn (2011), Heutel (2012), Heutel and Fischer (2013), Lintunen and Vilmi (2013), Bosetti and Maffezzoli (2014) and Khan et al., (2019). Another category, appearing later, is the improving and modifying RBC framework, in which the nominal rigidities are added to the E-DSGE models through a new Keynesian framework. See Annicchiarico and Di Dio (2015), Xu et al., (2016), Annicchiarico et al., (2018), and Xiao et al., (2018).

climate policies between different countries.

Ganelli and Tervala (2011) is the only closest predecessor of our research. They extended the E-DSGE to an open economy model by modeling symmetric economies, and analyzed the international transmission process of unilateral environmental policies. Compared to their models, our model has several distinct characteristics: heterogeneous production sectors, bilateral climate policies, asymmetric economies, and asymmetric stochastic shocks. First, we embed heterogeneous production sectors into our E-DSGE model, modelling energy sectors in detail. Establishing a model that contains inter-sectoral linkages very important for being able to understand the transmission mechanism of stochastic shocks in the economy (Dissou and Karnizova, 2016). A detailed description of different fossil fuel and renewable energy sectors can also reveal energy substitution effects under climate policies in more detail, while the imperfect substitution between different energy sources can be modelled by heterogeneous energy sectors--a step which previous E-DSGE literature has missed. The setting of unilateral climate policy is then replaced by bilateral climate policy in our E-DSGE model, allowing us to analyze the role of bilateral climate policies in shaping the transmission of international economic cycles. Moreover, based on the Ramsey policy method, bilateral climate policy allows us to discuss the strategic interactions between different countries on climate policies. We therefore model asymmetric economies instead of symmetric economies. The heterogeneity with respect to the countries' production behaviors in our E-DSGE model can help us shed light on the internal causes of different economic behaviors and thus the effects of economic cycle transmission across countries in terms of short-term fluctuations and long-term general equilibrium. The last distinctive characteristic involves the different types of asymmetric stochastic shocks treated in our E-DSGE model. Based on this feature, we are not only able to analyze how the international economic cycle is transmitted in different economies, but also how the international cross-border spillover effects of climate policies are caused by the international transmission of asymmetric stochastic shocks in heterogeneous economies.

With this E-DSGE model, we choose a typical climate policy tool-carbon emission trading market and then calibrate it based on data from China and the EU while taking the following three questions into consideration: (1) How will the economic behaviours of different countries and international trade interact with different climate policy regimes? (2) How will a country's economic uncertainty spread through international trade and different climate policy regimes? (3) In the face of international business cycles, what are the optimal strategic interactions of climate policies between different countries?

The rest of the paper is organised as follows: Section 2 presents the model, Section 3 presents the data and parameters, Section 4 presents the long term effects of China's and EU's carbon markets, Section 5 presents the international economic dynamics under carbon markets and Ramsey climate policy, Section 6 presents conclusions.

2. The E-DSGE model

Here we consider two countries: domestic country (marked by subscript H) and foreign country (marked by subscript F). The economic variables and parameters in foreign country are represented by a star superscript.[2] Domestic production structures and foreign production structures are modeled asymmetrically to depict the different economic structure. The intermediate goods markets in home and foreign are all monopolistic competition, whose price rigidity comes from staggered price adjustment à la Calvo (1983). The final goods and the government bonds are mobile between countries. The framework of open economy E-DSGE model is shown in Figure 1. In what follows, the economic behavior in domestic country are specified and the differences in foreign will be clarified.

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Figure 1

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2.1 Household

The domestic economy contains numerous homogenous families. The representative household is endowed with labor dedicated to different goods-producing firms. Notice that labor in every household is equivalent to homogeneous goods as the agent does not distinguish between different jobs. The

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[2] For example, $C^*_{H,t}$ is foreign consumption of domestic goods and $C_{F,t}$ is domestic consumption of foreign goods.

representative infinitely lived household maximizes the following lifetime utility:

$$\underset{(C_t,L_t,B_t,D_t,M_t,K_t)}{U} = E_t\sum_{t=0}^{\infty}\beta^t s_t^{\beta}\{\frac{[\psi(Q_t)^{1-\varsigma_H}(C_t)^{\varsigma_H}]^{1-\theta_1}}{1-\theta_1} - s_t^L\frac{L_t^{1+\theta_2}}{1+\theta_2} + \frac{[M_t/P_t]^{1-\theta_3}}{1-\theta_3}\} \tag{1}$$

in which the time preference shock s_t^{β} and labour supply preference shock s_t^L all follow AR(1) stochastic process:

$$\ln s_t^{\beta} - \ln s^{\beta} = \rho_{s^{\beta}}\ln s_{t-1}^{\beta} - \rho_{s^{\beta}}\ln s^{\beta} + \varepsilon_{t,s^{\beta}} \quad \varepsilon_{t,s^{\beta}} \sim i.i.d.N(0,\sigma_{s^{\beta}}^2) \tag{2}$$

$$\ln s_t^{L} - \ln s^{L} = \rho_{s^{L}}\ln s_{t-1}^{L} - \rho_{s^{L}}\ln s^{L} + \varepsilon_{t,s^{L}} \quad \varepsilon_{t,s^{L}} \sim i.i.d.N(0,\sigma_{s^{L}}^2) \tag{3}$$

where U is the utility of a representative family, E_t represents a conditional expectation based on the t period, L_t represents the labor supply, M_t is the domestic currency, C_t is a composite consumption index defined by

$$C_t = [\phi^{\frac{1}{\varepsilon}}C_{H,t}^{\frac{\varepsilon-1}{\varepsilon}} + (1-\phi)^{\frac{1}{\varepsilon}}C_{F,t}^{\frac{\varepsilon-1}{\varepsilon}}]^{\frac{\varepsilon}{\varepsilon-1}} \tag{4}$$

The optimal allocation of consumption between domestic and imported goods are given by:

$$C_{H,t} = \phi(\frac{P_{H,t}}{P_t})^{-\varepsilon}C_t \quad \text{and} \quad C_{F,t} = (1-\phi)(\frac{P_{F,t}}{P_t})^{-\varepsilon}C_t \tag{5}$$

The purchasing power parity condition is satisfied by the following equations

$$P_{F,t} = P_{F,t}^{*}S_t\,, \quad S_tP_{H,t}^{*} = P_{H,t} \quad \text{and} \quad P_t = [\phi P_{H,t}^{1-\varepsilon} + (1-\phi)P_{F,t}^{1-\varepsilon}]^{\frac{1}{1-\varepsilon}} \tag{6}$$

where the import price $P_{F,t}$ and domestic price $P_{H,t}$ for domestic country are all expressed by domestic currency and the import price $P_{H,t}^{*}$ and foreign price $P_{F,t}^{*}$ for foreign country are all expressed by foreign currency. S_t is the nominal exchange rate.

The budget constraint in units of goods:

$$P_tC_t + P_tI_t + B_t + D_tS_t + M_t = (1-\tau_t^L)W_tL_t + (1-\tau_t^K)K_{t-1}R_t^K + B_{t-1}R_{t-1}^B + M_{t-1} + D_{t-1}S_tR_{t-1}^D \tag{7}$$

Under budget constraints, the household uses income to satisfy consumption, investment and bond acquisition. I_t is the investment, B_t and D_t is the domestic and foreign government bond, and they sold at price R_t^B and R_t^D, K_t is capital stock at renting price R_t^K, τ_t^L and τ_t^K is the labor and capital tax rate, P_t is the overall price level, W_t is the nominal wage.

The stock of capital follows the following law motion àla Christiano et al., (2005):

$$K_t = (1-\delta_K)K_{t-1} + [1 - \frac{\vartheta}{2}(\frac{I_t}{I_{t-1}} - 1)^2]I_t \tag{8}$$

To solve the household problem, the Langrangian function was formed:[3]

$$\begin{aligned} \ell = E_t \sum_{t=0}^{\infty} \beta^t \{ s_t^{\beta} [\frac{[\psi(Q_t)^{1-\varsigma_H}(C_t)^{\varsigma_H}]^{1-\theta_1}}{1-\theta_1} - s_t^L \frac{L_t^{1+\theta_2}}{1+\theta_2} + \frac{[M_t / P_t]^{1-\theta_3}}{1-\theta_3}] + \nu_t [K_t - (1-\delta_K)K_{t-1} - [1 - \frac{\vartheta}{2}(\frac{I_t}{I_{t-1}} - 1)^2]I_t] \\ + \lambda_t [P_t C_t + P_t I_t + B_t + D_t S_t + M_t - (1-\tau_t^L)W_t L_t - (1-\tau_t^K)K_{t-1}R_t^K - B_{t-1}R_{t-1}^B - M_{t-1} - D_{t-1}S_t R_{t-1}^D] \end{aligned} \tag{9}$$

2.2 Enterprises

2.2.1 Final goods producers

The representative final goods producer uses $Y_t(j)$ units of each intermediate good $j \in [0,1]$ to produce the final good Y_t, according to the function proposed by Dixit and Stiglitz (1977), where $\varphi > 1$ is the elasticity of the substitution between the different intermediate goods.[4]

$$Y_t = [\int_0^1 Y_t(j)^{\frac{\varphi-1}{\varphi}} dj]^{\frac{\varphi}{\varphi-1}} \tag{10}$$

2.2.2 Intermediate goods producers

We disaggregated intermediate goods producers' behaviours into four levels of the production nesting.[5] The framework of the intermediate goods producers' production is shown in Figure 2.

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Figure 2

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In the first layer, a firm that produces intermediate outputs purchases energy composite $E_t(j)$ at price P_t^E, hires the labor $L_t^Y(j)$ and rents the capital $K_t^Y(j)$ to produce intermediate outputs $Y_t(j)$

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[3] The F.O.C. for household can be found in Appendix

[4] The F.O.C for final goods producer can be found in Appendix

[5] Here we only provide the optimal behavior of those producing firms. The F.O.Cs of every level can be found in Appendix

by Cobb-Douglas function. and η_t^L is labor efficiency which is decided by the climate quality. The problem for representative intermediate goods producing firm can be written as follows:

$$\begin{aligned} &MAX\ \pi_t^Y = P_t(j)Y_t(j) - R_t^K K_{t-1}^Y(j) - W_t L_t^Y(j) - P_t^E E_t(j) \\ &s.t \qquad Y_t(j) = A_t(\eta_t^L L_t^Y(j))^{\alpha_1} \cdot (K_{t-1}^Y(j))^{\beta_1} E_t(j)^{1-\alpha_1-\beta_1} \end{aligned} \tag{11}$$

The total factor productivity A_t is a stochastic shock follows AR(1) process.

$$\ln A_t - \ln A = \rho_A \ln A_t - \rho_A \ln A + \varepsilon_{t,A} \quad \varepsilon_{t,A} \sim i.i.d.N(0,\sigma_A^2) \tag{12}$$

In the second layer, energy producing firm purchase use fossil energy $FE_t(j)$ at price P_t^{FE} and renewable energy $NE_t(j)$ at price P_t^{NE} to produce energy composite by CES function. The energy producing firm's problem can be written as follows:

$$\begin{aligned} &MAX\ \pi_t^E = P_t^E E_t(j) - P_t^{NE} NE_t(j) - P_t^{FE} FE_t(j) \\ &s.t\ E_t(j) = A_t[\gamma FE_t(j)^\rho + (1-\gamma) NE_t(j)^\rho]^{1/\rho} \end{aligned} \tag{13}$$

In the third layer, fossil energy producing firm purchase three different kinds of fossil fuels: coal $M_t(j)$, oil $O_t(j)$ and natural gas $NG_t(j)$ at price P_t^M, P_t^O and P_t^{NG} to produce fossil energy composite by Cobb-Douglas function.

$$FE_t(j) = A_t M_t(j)^{\alpha_2} \cdot O_t(j)^{\beta_2} \cdot NG_t(j)^{1-\alpha_2-\beta_2} \tag{14}$$

CO2 emissions $E_t^{CO2}(j)$ are a by-product of fossil fuels. The emission coefficients of three fossil fuels are μ_M, μ_O *and* μ_{NG}. Also the representative enterprise can determine its proportions of emission reductions re_t^M, re_t^O *and* re_t^{NG} .

$$E_t^{CO2}(j) = [1 - re_t^M(j)]\mu_M M_t(j) + [1 - re_t^O(j)]\mu_O O_t(j) + [1 - re_t^{NG}(j)]\mu_{NG} NG_t(j) \tag{15}$$

The marginal abatement costs of coal, oil and natural gas ($MCE_t^M, MCE_t^O, MCE_t^{NG}$) are functions of the proportion of emission reductions as follows.

$$MCE_t^M = \Lambda_M \ln(1 - re_t^M), \quad MCE_t^O = \Lambda_O \ln(1 - re_t^O) \quad \text{and} \quad MCE_t^{NG} = \Lambda_{NG} \ln(1 - re_t^{NG}) \tag{16}$$

The fossil energy producing firm's problem can be written as follows:

$$\begin{aligned} MAX\ \pi_t^E &= P_t^{FE} FE_t(j) - P_t^M M_t(j) - P_t^O O_t(j) - P_t^{NG} NG_t(j) - P_t^{CO2} E_t^{CO2}(j) - P_t[CE_t^M(j) + P_t CE_t^O(j) + CE_t^{NG}(j)] \\ s.t \qquad & FE_t(j) = A_t M_t(j)^{\alpha_2} \cdot O_t(j)^{\beta_2} \cdot NG_t(j)^{1-\alpha_2-\beta_2} \end{aligned} \tag{17}$$

Renewable energy producing firm use labor $L_t^{NE}(j)$ and capital $K_t^{NE}(j)$ to produce renewable energy composite by Cobb-Douglas function. Meanwhile, it can also produce certified emission reduction $CER_t(j)$ and sell it at price P_t^{CER} to other firms to offset CO2 emissions. Since the supply of CERs is independent from the EU-ETS, which will impact the price stability, there is a ceiling on certified emission reduction.[6]

$$CER_t(j) = NE_t(j)^{\varsigma_3} \tag{18}$$

The renewable energy producing firm's problem can be written as follows:

$$\begin{aligned} MAX\ \pi_t^{NE} &= P_t^{NE} NE_t(j) - R_t^K K_{t-1}^{NE}(j) - W_t L_t^{NE}(j) + P_t^{CER} CER_t(j) + Tr_t(j) \\ s.t \qquad & NE_t = A_t TI_t(j)(\eta_t^L L_t^{NE}(j))^{\alpha_3} \cdot (K_{t-1}^{NE}(j))^{\beta_3} \end{aligned} \tag{19}$$

In addition, the government can provide financial support for renewable producers $Tr_t(j)$. It is proved that the R&D investment can increase the technology level. The relationship between the financial support $Tr_t(j)$ and technology level $TI_t(j)$ can be expressed as the following non-decreasing, though bounded, function (Blackburn and Cipriani, 2002):

$$TI_t(j) = \frac{1 + d_1 \upsilon Tr_t(j)^{\xi}}{1 + \upsilon Tr_t(j)^{\xi}} \tag{20}$$

In the fourth layer, coal, oil and natural gas producers hire labor $L_t^M(j)$, $L_t^O(j)$, $L_t^{NG}(j)$ and rent capital $K_t^M(j)$, $K_t^O(j)$, $K_t^{NG}(j)$ to produce coal, oil and natural gas products by Cobb-Douglas functions. The coal, oil and natural gas producing firm's problem can be written as follows:

$$\begin{aligned} MAX\ \pi_t^{NG} &= P_t^{NG} NG_t(j) - R_t^K K_{t-1}^{NG}(j) - W_t L_t^{NG}(j) \\ s.t\ NG_t &= A_t(\eta_t^L L_t^{NG}(j))^{\alpha_4} \cdot (K_{t-1}^{NG}(j))^{\beta_4} \end{aligned} \tag{21}$$

$$\begin{aligned} MAX\ \pi_t^O &= P_t^O O_t(j) - R_t^K K_{t-1}^O(j) - W_t L_t^O(j) \\ s.t\ O_t &= A_t(\eta_t^L L_t^O(j))^{\alpha_5} \cdot (K_{t-1}^O(j))^{\beta_5} \end{aligned} \tag{22}$$

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[6] The use of CER is no more than 5% of total EU emissions

$$
\begin{aligned}
MAX\ \pi_t^M &= P_t^M M_t(j) - R_t^K K_{t-1}^M(j) - W_t L_t^M(j) \\
s.t\ M_t &= A_t(\eta_t^L L_t^M(j))^{\alpha_6} \cdot (K_{t-1}^M(j))^{\beta_6}
\end{aligned}
\tag{23}
$$

Following Calvo (1983), the probability of an intermediate firm change its nominal price during any given period is $1-\omega$. Representative firm will change its price to maximise the expected sum of discounted future real profits.

$$
\max_{P_t(j)} \Re = E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{\lambda_{t+i}^H}{\lambda_t^H} Y_{t+i} [\frac{P_t(j)}{P_{t+i}} (\frac{P_{t+i}}{P_t(j)})^{\varphi} - MC_{t+i} (\frac{P_{t+i}}{P_t(j)})^{\varphi}] \tag{24}
$$

$$
MC_t = MC_t(j) = \frac{\partial TC_t(j)}{\partial Y_t(j)} \tag{25}
$$

2.3 Climate quality and CO$_2$ concentration

The relationship between temperature rise ($\mathit{\Delta}_t$) since the pre-industrial age and concentrations of CO$_2$ in the atmosphere ($C_{CO2,t}$) can be calculated as follows (Acemoglu et al., 2009):

$$
\mathit{\Delta}_t = 3\log_2(C_{CO2,t} / 280) \tag{26}
$$

The relationship between climate quality (Q_t), temperature rise and tipping point of temperature for extreme disasters (Δ_{tp}) can be read as follows:

$$
\Delta(Q_t) = 3\log_2(2^{\Delta_{tp}/3} - Q_t / 280) \tag{27}
$$

The cost from degradation of climate quality $\psi(Q_t)$ can influence their utilities.

$$
\psi(Q_t) = \frac{[\Delta_{tp} - \Delta(Q_t)]^{\chi} - \chi\Delta_{tp}^{\chi-1}[\Delta_{tp} - \Delta(Q_t)]}{(1-\chi)\Delta_{tp}^{\chi}} \tag{28}
$$

The evolution of climate quality:

$$
Q_{t+1} = (1-0.005)Q_t + 0.005 \times 280 \times 2^{\mathit{\Delta}_{tp}/3} - (E_t^{CO2} + E_t^{CO2*} + \overline{E_t^{rest}}) \tag{29}
$$

The negative externality will decline the labor efficiency. Referring to Annicchiarico and Di Dio (2015), we adopt the following equation:

$$
\eta_t^L = 1 - (\eta_0 + \eta_1 Q_t + \eta_2 Q_t^2) \tag{30}
$$

2.4 Government and climate policy

The domestic governments issue the money and domestic bonds, and levy taxes on labour and capital, and auction CO_2 emission quota to intermediate producers to satisfy their public consumption G_t and financial support for renewable energy. They balance their budget by following behaviour:

$$P_t G_t + R^B_{t-1} B_{t-1} + Tr_t + M_{t-1} = \tau^L_t W_t L_t + \tau^K_t R^K_t K_{t-1} + P^{CO2}_t E^{CO2}_t + B_t + M_t \tag{31}$$

Fiscal policies aim to maintain economic stability by controlling government balance and output gap. The fiscal policy rules for G_t, τ^K_t and τ^L_t are as follows:

$$\ln\tau^K_t - \ln\tau^K = \rho_K \ln\tau^K_{t-1} - \rho_K \ln\tau^K + \phi^K_G(\ln G_t / Y_t - \ln G / Y) + \phi^K_Y(\ln Y_t - \ln Y) + \varepsilon_{t,K} \quad \varepsilon_{t,K} \sim i.i.d.N(0, \sigma^2_K) \tag{32}$$

$$\ln\tau^L_t - \ln\tau^L = \rho_L \ln\tau^L_{t-1} - \rho_L \ln\tau^L + \phi^L_G(\ln G_t / Y_t - \ln G / Y) + \phi^L_Y(\ln Y_t - \ln Y) + \varepsilon_{t,L} \quad \varepsilon_{t,L} \sim i.i.d.N(0, \sigma^2_L) \tag{33}$$

$$\ln G_t - \ln G = \rho_G \ln G_{t-1} - \rho_G \ln G + \phi^G_B(\ln B_{t-1} - \ln B) + \phi^G_Y(\ln Y_{t-1} - \ln Y) + \varepsilon_{t,G} \quad \varepsilon_{t,G} \sim i.i.d.N(0, \sigma^2_G) \tag{34}$$

The governments in home and aboard can choose among different four possible climate policies. The baseline is all countries do not apply CO_2 emission trading market (we name this case as "*BAU*"). If the emission trading market in each country is separate, the government in home and abroad should set their own emission target and auction the CO_2 emission quotas. According to the clean development mechanism, developed countries can obtain certified emission reductions by supporting greenhouse gas emission reduction projects in developing countries, which can be used as an offset for CO_2 emissions. So, we obtain $E^{CO2}_t = \overline{E^{CO2}}$ and $E^{CO2*}_t = \overline{E^{CO2*}} + CER_t$. At this case, governments can choose to use the revenue from the CO_2 quota auction as part of the public budget $Tr_t = Tr^*_t = 0$ (we name it as "*SE*") or to support renewable energy $Tr_t = P^{CO2}_t \overline{E^{CO2}}$ and $Tr^*_t = P^{CO2*}_t \overline{E^{CO2*}}$ (we name it as "*SER*"). In addition, if there is joint emission trading market in home and aboard, the CO_2 emission quota can be traded in foreign market. At this case, the equilibrium carbon prices are equal in home and foreign markets. $E^{CO2}_t + E^{CO2*}_t = \overline{E^{CO2}} + \overline{E^{CO2*}} + CER_t$ is hold (we name it as "*JE*"). Also, the revenue from the CO_2 quota auction can be used for supporting renewable energy in each country (we name it as "*JER*").

3. Data and parameters

After establishing the model, we calibrate the model for China and the EU. The domestic country marked by subscript H in above model represents China here, and the foreign country marked by subscript F represents the EU here. In this paper, calibration and mix frequency Bayesian estimation were used to get parameter values of China and the EU.

Based on existing researches and relevant statistic data, those standard parameters related to household preference, labor elasticity and risk aversion etc., are determined by calibration method. With regards to the economic part of the model, we estimate the parameters of production structure in China and the EU using GTAP database. With regards to the climate-related parameters, we refer to integrated assessment models, for instance, we estimate the marginal abatement costs by our CGE models (Xiao et al., 2015; Xiao et al., 2017). Table 1 shows the specific source and estimation method of those parameters.

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Table 1

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For some deep structural parameters, Bayesian estimation method is a good tool to extract them from the real economy. China's and EU's quarterly GDP data from 2008 Q1 to 2018 Q4 were selected. We also selected monthly consumption, energy input and public expenditure data in China and EU and monthly exchange rate from January 2008 to December 2018. Due to the different frequencies of available data, we use the mix frequency Bayesian estimation method to unify the time frequency of all the observed variables and estimate the structural parameters of China and the EU. The time frequency is measured in months. Moreover, we use Census X12 method to deseasonalize them and one side Hodrick-Prescott filter to obtain the volatile components of the observed variables. Table 2 presents the results of mix frequency Bayesian estimation for those deep structural parameters.

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Table 2

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4. Long term effects of China's and EU's carbon markets

Table 3 shows the steady-state values of the main variables. We focus on the long-term equilibrium of variables. Therefore, we simulate the long-term emission reduction targets of China and the EU.[7] In SE scenario, the emission caps are 90% and 62% in China and EU separately. The EU reduced its overall emissions by 33%, with the remaining 5% emission reduction offset by CER purchasing from outside.

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Table 3

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Notice that real output in China and the EU will decrease by 0.87% and 1.48% in *SE* scenario when they both apply separate emission trading market. There is no doubt that the emission trading market will reduce the economic level of China and the EU, but it will bring about environmental improvement. As two major CO_2 emitters, the EU and China's 2030 emission reduction targets will result in a 3.64% reduction in atmospheric CO_2 concentration. Due to differences in resource endowments, China and the EU have different ways to achieve emission reduction targets. In China, the coal industry will be most affected, followed by oil and gas. In the EU, however, the oil and gas industry has suffered far more than the coal industry. Although the mechanism of carbon market restraining economic activity has been analyzed by most literatures, the transmission mechanism of different carbon markets in open economy has been seldom analyzed. The results show that economic activity in both China and the EU has been suppressed, while the negative effects are quite different. This differences comes not just from different emission reduction targets, but from the impact of carbon markets on trade in open economies. Due to different emission reduction targets and the relative independence of carbon market in China and the EU, the production costs of domestic and foreign enterprises are different. This will lead to changes in the competitiveness of each country's goods in the international market. Under the current emission reduction target, China's emission reduction cost is lower than that of the EU, so the cost imposed on

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[7] The EU stated that by 2030, the emissions from the carbon market will be 43% lower than in 2005. Here we build the DSGE model based on 2010 data, so the emission reduction target is converted from the base period of 2005 to the base period of 2010. China has pledged to cut emissions intensity per unit of GDP by 60-65% by 2030 from 2005 levels. Since it is intensity reduction, it is impossible to know the specific reduction proportion. Here, we use the GDP growth rate to calculate the actual GDP in 2030, and then convert the emission reduction target into 2010. GDP growth rate is measured using a lower growth scenario, according to Oxford Economics' China economic forecast.

enterprises is also lower, which is conducive to the international competitiveness of Chinese goods in EU-China trade. The impact of different separate carbon markets on international trade is reflected in changes in the relative prices of goods. For example, in *SE* scenario, the relative devaluation of the euro has led to an increase in exports from the EU and a decrease in imports from China, which in turn has led to a larger decline in consumption in the EU. By contrast, the relative appreciation of currency in China lead to a small decline of China's overall consumption level, and increased external investments, which induce a smaller output decline than the EU.

Comparing *SE* with *SER* scenario, we found that using the revenue from carbon quota auctions to subsidize renewable energy could offset some of the negative effects of the carbon market in China and the EU. When the government provides financial support for R&D investment of renewable producers, it will significantly promote the development of renewable energy. However, the degree to which R&D subsidies promote renewable energy varies widely. This is due to the high utilization rate of renewable energy and the low efficiency of subsidized research and development in the EU, resulting in a limited increase in technology level. In addition, the EU's carbon quota auction generates less revenue than China's, which also causes China's R&D investment to be higher than the EU's.

In what follows, we consider that Chinese and EU’s carbon quotas can flow perfectly in both emission trading markets and the emission reduction target in joint carbon market is same as separate carbon market. For CO_2 emissions, in the separate carbon market, the EU has a higher proportion of emission reduction target, so the marginal cost of emission reduction is higher, which is manifested in the fact that EU's equilibrium carbon price is higher than the China's equilibrium carbon price (when converted into the same currency). When carbon quota can flow perfectly in a joint carbon market, the EU with high marginal emission reduction cost can decrease its marginal abatement cost by buying carbon quotas from China with low emission reduction cost. Eventually, under the condition of meeting the emission reduction target, China will reduce emission by 15.55% and the EU by 13.91%.

Since the separate carbon market will cause the inconsistency of equilibrium carbon price across the countries, it provides space for border regulation tax, which also indirectly reflects that the efficiency of the separate carbon market is lower than that of the joint carbon market. To verify that, we compare the total welfare of China and the EU under *SE* scenario with the total welfare under *JE* scenario (TW_t in Table 3). The results show that the total welfare under *JE* scenario is higher than that under *SE* scenario. We also noticed that the total real output under *JE* scenario is higher than that under *SE* scenario (TY_t in Table 3). Thus, separate carbon market can bring the loss of social welfare which can also be reflected in the total real output of China and the EU. Compared with *SE* scenario, in the *JE* scenario, as the EU's 19% emission reduction will be achieved by purchasing quotas from China, China's emission reduction ratio increases, coupled with the devaluation of RMB, the output will decrease.

We obtained the marginal abatement cost curve for the EU and China by continuously applying different emission limits. Figure 3(a) and 3(b) are the marginal emission reduction cost curves of the EU and China. To compare the marginal cost of reducing emissions, we explain the marginal abatement cost as a percentage of the country's overall price level as the y-axis (which can be deemed as a percentage of the price markup). Under the same emission reduction target, the marginal emission reduction cost of EU is higher than that of China. When we put two marginal abatement cost curves together, we can explain more intuitively that the efficiency of the joint carbon market is higher than that of the separate carbon market. In Figure 3(c), to unify the emission reduction ratio, the horizontal axis is the percentage of China’s and the EU’s emission reductions as a percentage of sum of total emissions from the EU and China. This figure perfectly replicates the results of *SE* scenario and *JE* scenario in Table 3. Equilibrium results of joint carbon market and separate market are marked by green and red dotted line separately. Shadow area in Figure 3(c) is the deadweight loss from separate carbon market, which is the loss of total welfare.

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Figure 3

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A joint carbon market could automatically reallocate countries' emissions reductions to minimize the emission reduction cost. We simulate the optimal allocation of emission reductions ratio between China and the EU under different total emission reduction ratios. The results are shown in Figure 3(d). The combination of emission reduction ratios on this curve is optimal and the total cost of emission reduction is the minimum. For example, a combination of a 9% cut for China and an 8% cut for the EU can minimize the total abatement cost under the current total emission reduction target. The combination of emission reduction targets above the curve makes the EU pay extra abatement costs and reduces the competitiveness of EU goods in China-EU trade. Undoubtedly, this is good for China, but it will cause deadweight loss. It would be bad for international trade if the EU covered the extra costs by imposing carbon tariffs on imports.

We notice that the curve is always below the 45-degree line, which shows that China needs to undertake more emission reductions in the optimal portfolio. Since China's emission reduction space is larger than the EU, the cost of abatement is lower than that of the EU, so it is understandable that China will bear more emission reductions. The difference between the curve and the 45-degree line is the additional emission reductions that China needs to bear. We found that although the curve is always below the 45-degree line, it is basically consistent with the 45-degree line. This shows that there are not many additional emission reduction parts that need to be undertaken by China (maximum only up to 5% of the EU emission reduction ratio). This is because China, as a responsible big country, has committed itself to reducing its carbon intensity target internationally. The marginal cost of emission reduction is also increasing year by year, and the cost gap with the EU is gradually narrowing.

5. International economic dynamics and carbon markets

5.1 Technology shock

Figure 4 shows the responses to a transitory increase in TFP hitting only China. In response to a positive TFP shock on China, it is possible to see that China’s main macroeconomic variables positively react. The first is the positive and rapid response of China’s total output. As the marginal productivity of various factors of production rises, enterprises are induced to expand production. Therefore, the investment follows positive “hump-shaped” dynamics à la Christiano et al., (2005). As expected and similar to most NK literatures, labor exhibits counter-cyclical dynamics in response to positive technological shocks. Nominal rigidity has a negative effect on the labor market. This result is also consistent with empirical researches, which shows the positive technological shocks lead to temporary declines in employment.

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Figure 4

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Looking the effects of asymmetric TFP shock on the EU, we found that the situation is more complex than that of a single country, and even more complex than previous homogeneous economic models. The EU’s economies are affected in two ways: first, the aggregate demand effect, and second, the competitiveness effect. The increase in the EU’s consumption and investment generates a higher demand for imports, which can push up the total EU’s demand. Meanwhile the technological progress at home leads to comparative competitive disadvantage abroad. A rising EU’s trade deficit has forced the RMB to appreciate in EU-China trade. At last, unfavorable terms of trade led to a small decline in the level of the EU’s economies. Different from Annicchiarico and Diluiso (2019), they studied the impact of heterogeneous TFP shocks on symmetric economies and concluded that positive domestic TFP growth leads to simultaneous domestic and foreign output growth. This paper considers asymmetric economies and portrays the actual economic situation of the two economies with the data of China and the EU. As a major exporter, China has always maintained a trade surplus in Sino-European trade. China's technological progress will significantly reduce the competitiveness of goods of the EU, thus exacerbating the trade deficit between the EU and China. The increased trade deficit will directly damage manufacturing and employment opportunities, and will have a contraction effect on EU’s output.

In what follows we look how the different climate policies can influence the international business cycle. Generally speaking, under different climate policies, there is not much difference in the response of major China’s macroeconomic variables. Positive effects of China’s output is magnified when there is no climate policy, because enterprises do not have to bear the costs associated with the CO_2 emissions, and they are allowed to emit more. Meanwhile, due to the decline in the EU’s output, the demand for fossil energy is reduced, resulting in a decline in the EU’s CO_2 emissions.

Now let's look at what happens when there are carbon markets. When enterprises need to undertake climate-related costs, economic expansion is partially inhibited, and they need to pay abatement costs. When there are separate carbon markets, both China and the EU must meet their own emission caps. The international flow of quotas is not allowed. So both China’s and the EU’s CO_2 emissions remain unchanged. The China’s carbon markets would require China’s enterprises to expand their economies while meeting emissions caps, which incur an increased pressure to reduce emissions and a sharp rise in quota prices. Meanwhile, to comply with the emission cap while increasing output, enterprises need to devote more resources in emission reduction and replace fossil fuels with renewable energy.

Compared with separate carbon market, China’s output under joint carbon market is more sensitive to the positive temporary technology shock, because quotas can be circulated internationally, and China’s emission reduction pressures are alleviated by purchasing the EU’s quotas. There is a small increase in China’s CO_2 emissions under joint emission market, implying that China’s enterprises indeed reduce their pressure to reduce emissions by buying the EU’s quotas. As a result, China’s CO_2 quota prices and abatement cost have not risen as much as they would have done in a separate carbon market. The EU’s enterprises are forced to cut CO_2 emissions, resulting in an increase in their abatement costs. At the same time, higher emission reduction pressure will lead to a decline in demand for fossil fuels and a rise in demand for renewable energy. Comparative competitive disadvantage and compressed emission space in the EU reinforce the negative effects of its output. As a quota exporter, the euro has recovered slightly and trade has improved slightly (compared with *BAU*).

Subsidizing renewable energy can boost China’s output. Therefore, whether it is a separate carbon market or a joint carbon market, subsidizing renewable energy can bring about higher China’s economic expansion effects under positive technology shock, although the differences from non-subsidized renewable energy is small. Since the benefits of the carbon market are used to subsidize renewable energy, when the carbon price rises sharply, the development of renewable energy is extremely beneficial. Therefore, China's renewable energy has the greatest expansion effect under the separate carbon market. Similarly, the EU's renewable energy benefits when the carbon prices are pushed up by joint carbon market.

5.2 Subjective shock

There are two kinds of exogenous uncertainties in household decision-making behaviors, namely subjective discount rate and labor supply uncertainties. The former mainly affects the utility function by interfering with the time preference, whereas the latter influences the labor supply preference. We now focus on the China's time preference shock.

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Figure 5

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As displayed in Figure 5, the results of China's time preference shock were simulated. When the expectation of a discount rate of households is increased, macroeconomic variables, such as investment, labor, and output, all respond positively. Someone with a high time preference will focus substantially on his or her own well-being in the future. Therefore, a higher discount rate means that the preferences of households are clearly directed toward the future period. The higher discount rate will also have an impact on the intertemporal optimization behaviors of households. The current consumption is replaced by inter-temporal investment behavior to ensure a higher level of consumption in the future. Output rises rapidly in the early stage of the impact, reaches the bottom after reaching the peak, and then gradually rises to steady state. In the early stage, residents prefer working in the current period, thereby increasing the labor supply. The positive effects of capital, investment, labor, and other factors will lead to more factors available for production, which will consequently result in the increase of total outputs. Then, as the discount rate declines, residents gradually increase consumption, which negatively affects investment. On the other hand, the increase in emissions from economic expansion has led to a decline in the labor efficiency of residents and a decrease in welfare. The economy is gradually cooling down.

The relative depreciation of the Euro has reduced the EU's import demand and expanded demand for domestically produced goods. Meanwhile, the EU's investment was negatively affected, which in turn led to a decline in the EU's labor demand. At last the EU's output fell slightly.

We found that China's carbon price is in line with its output trend. As output rises, the demand for emission quotas increases, leading to a rise in the carbon price. The upward pressure on emissions cuts and carbon prices has been partially alleviated by internationally tradable quotas. Therefore, the increase of China's carbon price under joint carbon market is milder than separate carbon market. The EU's quota prices rise, and the pressure is transmitted to the production sector, which is ultimately reflected in the output. The rise in the EU's CO_2 price under joint carbon market exacerbate the negative effects on its output. When output begin to fall, the surplus of quotas supply incurs price declines, and the cost of emission reduction also fall. Meanwhile, the EU's abatement cost and CO_2 quota price also decline. The drop of China's CO_2 quotas price caused by the quota surplus is partially mitigated in the joint carbon market. We noticed a redistribution of CO_2 emission permits from China to the EU and a fall in their price. The EU's producers buy emission permits at lower price on the market, and emit more CO_2. Compared with separate carbon market, in this case, the adjustment of emission reduction cost can amplify the decline in permits demand, thereby amplifying the decline in permit prices. This fall in the emission permits price under joint carbon market alleviates the negative effects on the EU's output.

Recalling the Figure 4, the positive response of both China's and the EU's macroeconomic variables to expansionary shocks will be amplified by the condition of the absence of climate policies. The existence of a carbon market reduces the impact of exogenous shocks on both China's and the EU's output, investment and consumption etc. Therefore, carbon markets can act as an automatic stabilizer of the China's and the EU's economy in that they smooth economic fluctuations (Sim, 2006; Annicchiarico and Di Dio, 2015).

5.3 Fiscal policy shock

There are three kinds of shocks about fiscal policy hitting China's economy, i.e. public consumption shock, labor and capital tax rate shocks. Since their mechanism of action on the economy is basically similar, we only select labor tax rate shock hitting only China to analyze.

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Figure 6

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As displayed in Figure 6, the results of China's labor tax rate shock were simulated. A positive labor tax rate shock can exert negative effects on labors. Thus, the preferences of households are clearly directed toward leisure rather than toward labor supply, which consequently leads to a rapid reduction in labor supply. Undoubtedly, household wealth will decrease, followed by a decline in household consumption. The demand for labor by enterprises leads to shortages in the labor market, while residents demand higher wages to make up for the high labor income tax, consequently increasing the equilibrium real wage. The increase in the utility brought about by high wages counteracts the negative effects brought about by the aversion to labor, such that the labor supply quickly bounces back. High wages and a lack of labor supply in the labor market increase the marginal cost of labor, pushing up the cost of production, which leads to a contraction in output and a negative impact on investment. The decline in China's income has led to a decline in demand for all China's and the EU's goods through aggregate demand channels. The EU's economies, by contrast, grew slightly at beginning. Subsequently, with the slight rebound in China's market competitiveness, this, coupled with the decline in China's income caused by the shrinking China's labor and capital markets, have reduced the demand for the EU's goods, which has negatively impacted the EU's output. The relative increase of the EU's output leads to the increase of income effect of its residents, so residents increase labor supply, which has a slight negative impact on its investment. We observed that the response amplitude of macroeconomic variables under all shocks is small. This is largely due to the rules of fiscal policy. Recalling Eqs (32), (33) and (34), the government uses fiscal policy rules to control government debt and maintain economic stability.

Consider now the differences in international transmission of business cycle caused by different climate policies. As we mentioned in above chapter, the responses of China's variables in the *BAU* scenario ranked first, followed by that in the joint carbon market and the separate carbon markets scenario (*BAU>JE>SE*). We also found that the responses of China's variables in scenario with renewable energy subsidy is larger than scenario without renewable energy subsidy (*JER>JE* and *SER>SE*).

Then, we focus on the EU. Still, subsidizing renewable energy will amplify the sensitivity of the EU's variables to asymmetric China's shocks. However, when we look at the response of the EU's variables in the separate carbon market and the joint carbon market, the results are different. Under China's technology shock and labor tax rate shock, the response of the EU's variables in the joint carbon market is more sensitive than separate carbon market. The same results also appear in the case of capital tax rate and labor supply shocks (*BAU>JE>SE*). But, under the impact of China's time preference shock, the situation is just the opposite. The same is true of public spending shock (*BAU>SE>JE*).

We found common ground that labor tax rate shock, capital tax rate shock and labor supply shock all affect the supply side of economic production (supply-side shock), while time preference shock and public spending shock can exert impacts on demand side directly (demand-side shock). Supply-side shocks affect the EU's economy through price and competitive effects. Since the efficiency of price transmission in the joint carbon market is higher than that of the separate carbon market, the joint carbon market is better able to amplify the supply side impact. However, the demand-side impact affects the EU's economy through the aggregate demand effect, and with the flow of demand, the carbon quota will be redistributed under the joint carbon market. Compared with the separate carbon market with fixed carbon quota, when the quota flows to the EU, it suffers less pressure from carbon market. Therefore, the negative impact of the economy under joint carbon market is smaller than that of the separate carbon market.

5.4 Ramsey climate policy

In what follows we discuss the strategic interaction of China and EU in climate policies. Here in we conduct our research by employing Ramsey optimal policy rule where benevolent China's and EU's governments maximize the utility of China's and EU's household subject to the constraints provided by the equilibrium path and under commitment to this optimal policy. We want to solve the question: what is the best strategic interaction between China and the EU under different climate policies? The results of adopting a Ramsey approach to climate policy under a China's technology shock are shown in Figure 7. We consider three situations, i.e. Both Chinese and EU's governments treat CO_2 emission quota as policy instruments to maximize the utility of China's and EU's household in separate carbon market (*SE-all*); Only Chinese government treat CO_2 emission quota as a policy instrument to maximize the utility of China's household in joint carbon market (*JE-China*); Both Chinese and EU's governments treat CO_2 emission quota as policy instruments to maximize the utility of China's and EU's household in joint carbon market (*JE-all*).

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Figure 7

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In Figure 7(a), it was found that the China's CO_2 emissions cap in separate carbon market should respond pro-cyclically to its business cycle. Similar with the results of China's technology shock, in Figure 7(c), we observe that the China's output is also positively responded. As the Chinese government actively adjusts CO_2 emission quotas according to the economic cycle, enterprises can emit more CO_2 while the economy is expanding, thus reducing the marginal cost. Therefore, compared with the results of China's technology shock the output expansion is amplified here. Meanwhile, as we mentioned above, the EU's output is negatively affected. The best strategy for the EU is to reversely adjust its CO_2 emission quotas, rendering it respond pro-cyclically to its own business cycle. That is, in the separate carbon market, both China's and the EU's CO_2 emission quotas should be optimally adjusted pro-cyclically, which is consistent with the results of most literatures.

Then, looking at the Ramsey policy results in joint carbon market. The black and blue line in Figure 7(a) show that the China's CO_2 emission quota in joint carbon market is also pro-cyclical with its business cycle. Now, the black and blue line in Figure 7 (b) show that the best strategy for the EU's government here in joint carbon market is to positively adjust its CO_2 emission quota, showing counter-cyclical to its business cycle. Why is the optimal strategy for the EU completely different under different climate policies? In the joint carbon market, if the EU reduces its carbon quota, the cost of emission reduction will rise, and the demand for import quotas will increase, leading to a decline in the international competitiveness of products. Therefore, the optimal strategy is to increase the quota, thus reducing the demand for import quotas. This result shows that the carbon market is not only affected by the business cycle, but also by the international market. The cross-border spillover effects of the joint carbon market can change the pro-cyclical characteristics of optimal quotas in the foreign economic cycle. The only difference between *JE-China* and *JE-all* is whether EU's governments adjust their policies actively or passively. When EU's government can actively adjust CO_2 emission quota, the positive adjustment of EU's CO_2 emission quota is larger so that the EU can maximize its social welfare. Therefore, compared with JE-China, the increase of China's output is stronger and the decline of EU's output is milder.

The dynamic paths of China's and the EU's output in joint carbon market are basically similar to the situation in separate carbon market. However, the different response amplitude of the economy under joint and separate carbon market is evident. The increase of China's output is stronger and the decline of EU's output is milder than in the case of separate carbon market. This is mainly due to the increase in China's and the EU's CO_2 quotas and the perfect circulation of quotas in the international market can lead to a sharp drop in carbon price, further reducing the marginal cost of China's and the EU's production.

6. Conclusion

In this paper, we established an open economy E-DSGE model in order to study the international climate action under dynamic international economic cycles for two fully interdependent economies complete with various uncertainties. The model used China and EU as real cases for analyzing three questions raised at the beginning of the paper.

From the perspective of long term equilibrium, we analyzed how China's and the EU's economic behaviors and international trade interacted with the international carbon market. There is no doubt that the carbon markets will constrain the economic level of China and the EU, but they will bring about environmental improvements as well, while the income utilized from carbon quota auctions to subsidize renewable energy innovations can offset some negative effects caused by carbon markets. We also simulated the marginal abatement cost curves of China and EU, proving that, due to deadweight loss, the efficiency of the separate carbon market is lower than that of the joint carbon market. The high efficiency of the joint carbon market was due to the fact that it could automatically reallocate national emission reduction tasks to minimize abatement costs. We furthermore simulate the optimal allocation of emission reductions ratio between China and the EU. The results indicate that while China needs to undertake more emission reductions in the optimal portfolio, however, it needs to undertake only a slightly larger share of the emission reduction than the EU.

When studying how economic uncertainty spreads through international trade and carbon markets, we consider the different asymmetric shocks hitting China exclusively. The existence of the carbon market makes China less sensitive to external shocks; as a result, the carbon market can be an automatic stabilizer in that it is able to smooth economic fluctuations. Different climate policies can also lead to different business cycles in China. Compared with the separate carbon market, where CO_2 quotas can be circulated internationally, the Chinese economy under the joint carbon market is more sensitive to stochastic shocks. The spillover effects of asymmetric shocks are transmitted to the EU's economy through two channels: the aggregate demand effect, and the competitive effect. The intensity of the spillover effects caused by asymmetric shocks depends not only on the nature of them, but also on different climate policies. Regarding supply-side shocks, the EU's economy in the joint carbon market is more sensitive than the separate carbon market, as the joint carbon market brings more cross-border pressures and enhances cross-border spillovers. However, under the separate carbon market, demand-side shocks have a stronger impact on the EU than the joint carbon market. The results are mainly due to the fact that supply-side shocks affect the EU's economy through price and competitive effects, whereas demand-side shocks are transmitted through aggregate demand effects. Since the efficiency of price transmission in the joint carbon market is higher than that of the separate carbon market, the joint carbon market is better able to amplify the supply-side shocks.

Lastly, we used the Ramsey optimal policy rule to study the optimal strategic interactions of climate policies in China and the EU under asymmetric shocks, finding out that China's and the EU's CO_2 emission quotas should be adjusted pro-cyclically to business cycles in separate carbon markets. In a joint carbon market, the Chinese government should also adjust CO_2 emission quotas pro-cyclically with its business cycle. The best strategy for the EU's government here, however, is to adjust its CO_2 emission quotas counter-cyclically with its business cycle. The results indicate that carbon markets are affected not only by business cycles but also international markets. The cross-border spillover effects of the joint carbon market can change the pro-cyclical characteristics of foreign (EU’s) optimal quotas.

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Figures

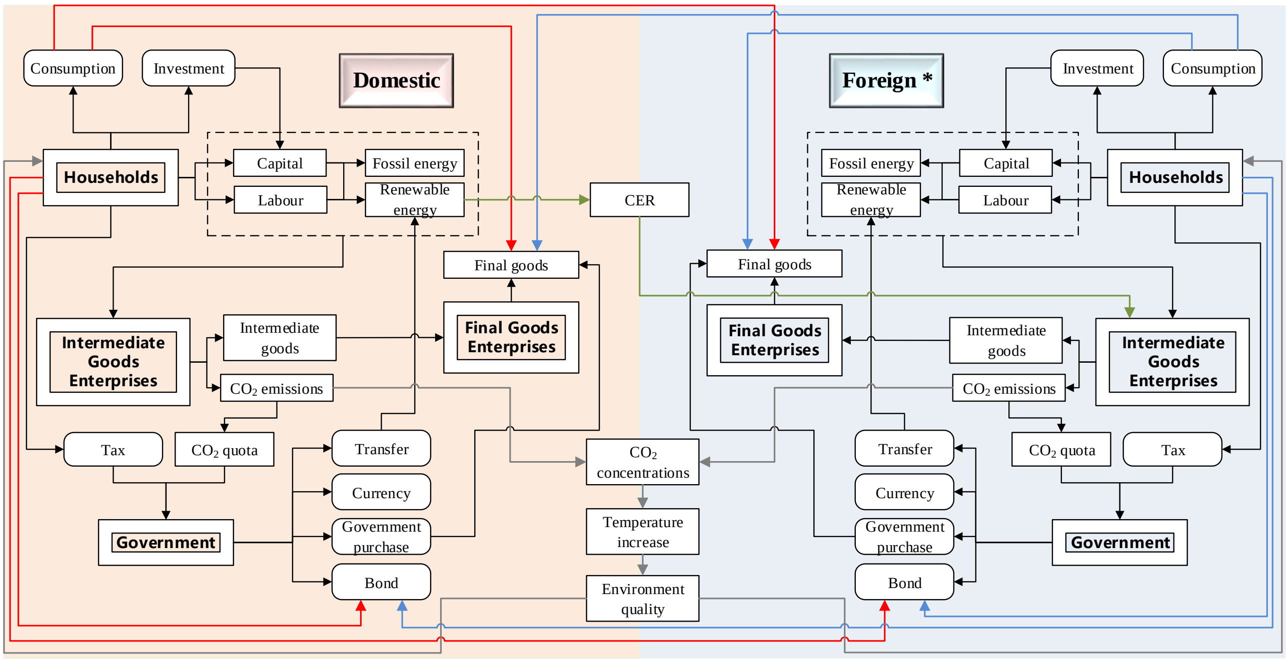


Figure 1. The framework of open economy environmental DSGE model

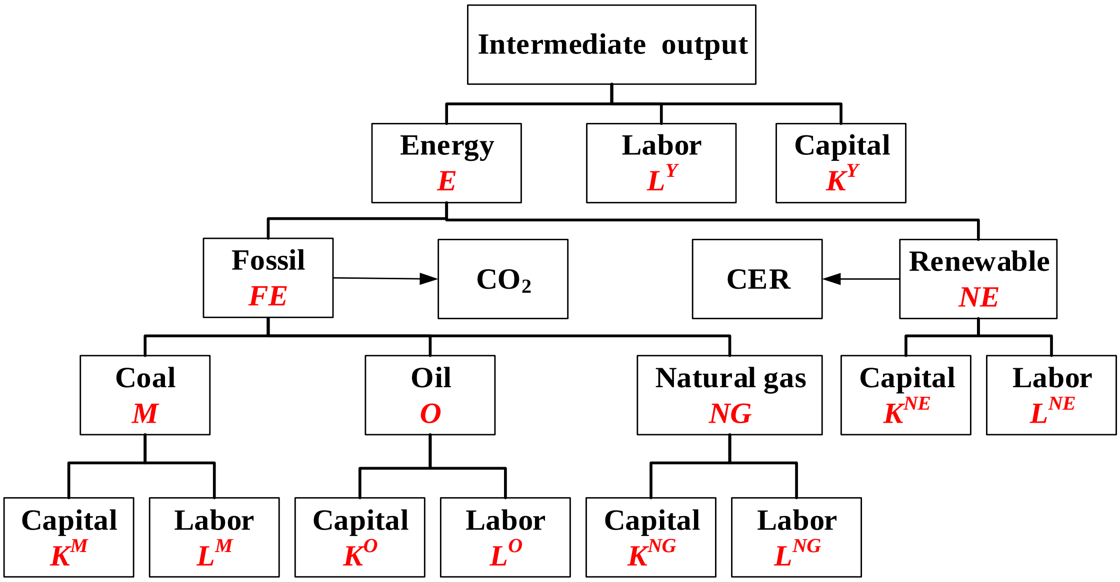
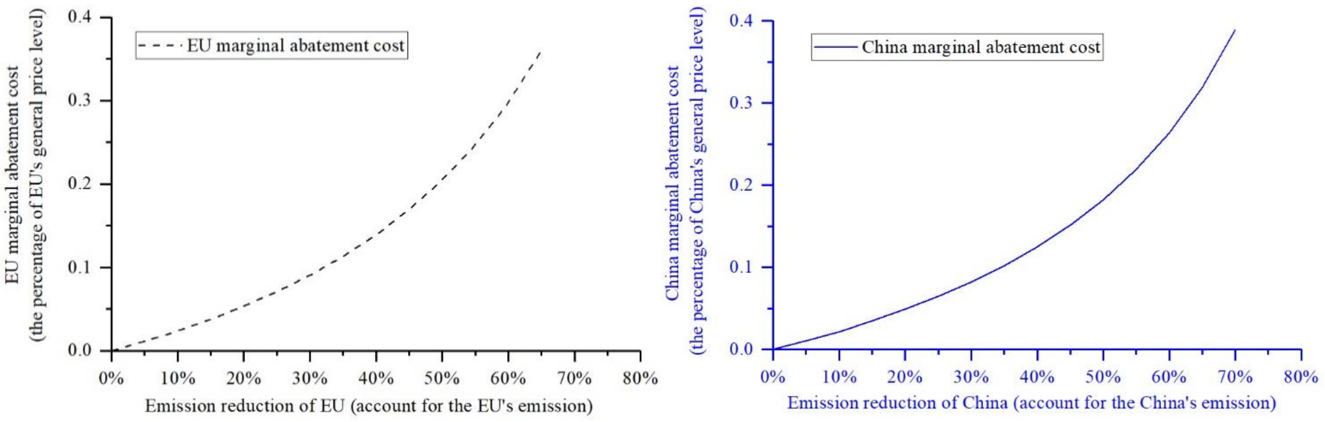
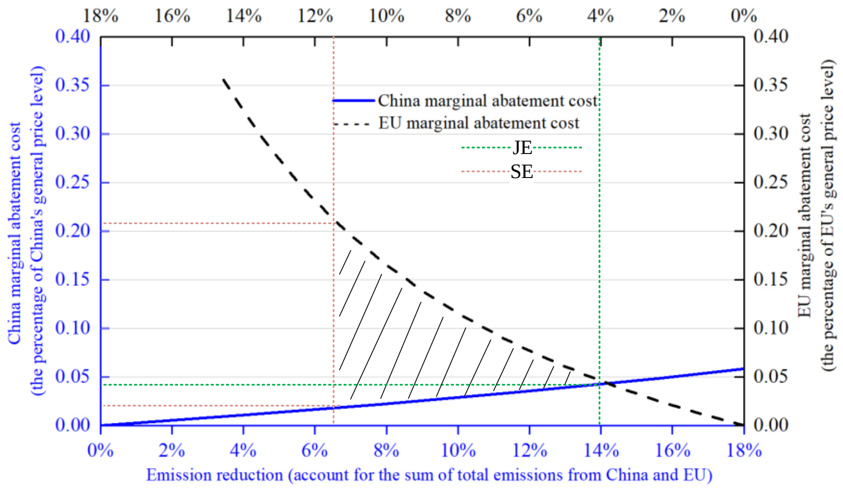


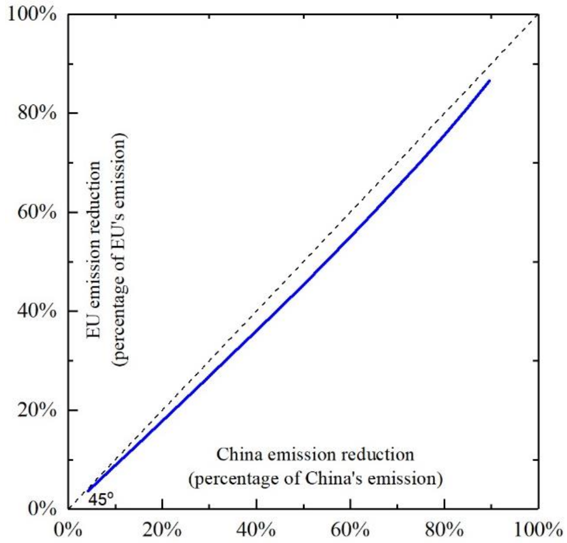
Figure 2. The framework of the intermediate goods producers' production



(a) The EU’s marginal abatement cost curve **(b)** China’s marginal abatement cost curve



(c) China’s and the EU’s marginal abatement costs



(d) The optimal allocation of emission reduction ratios between China and the EU

Figure 3. The marginal abatement costs and optimal allocation of emission reduction ratios

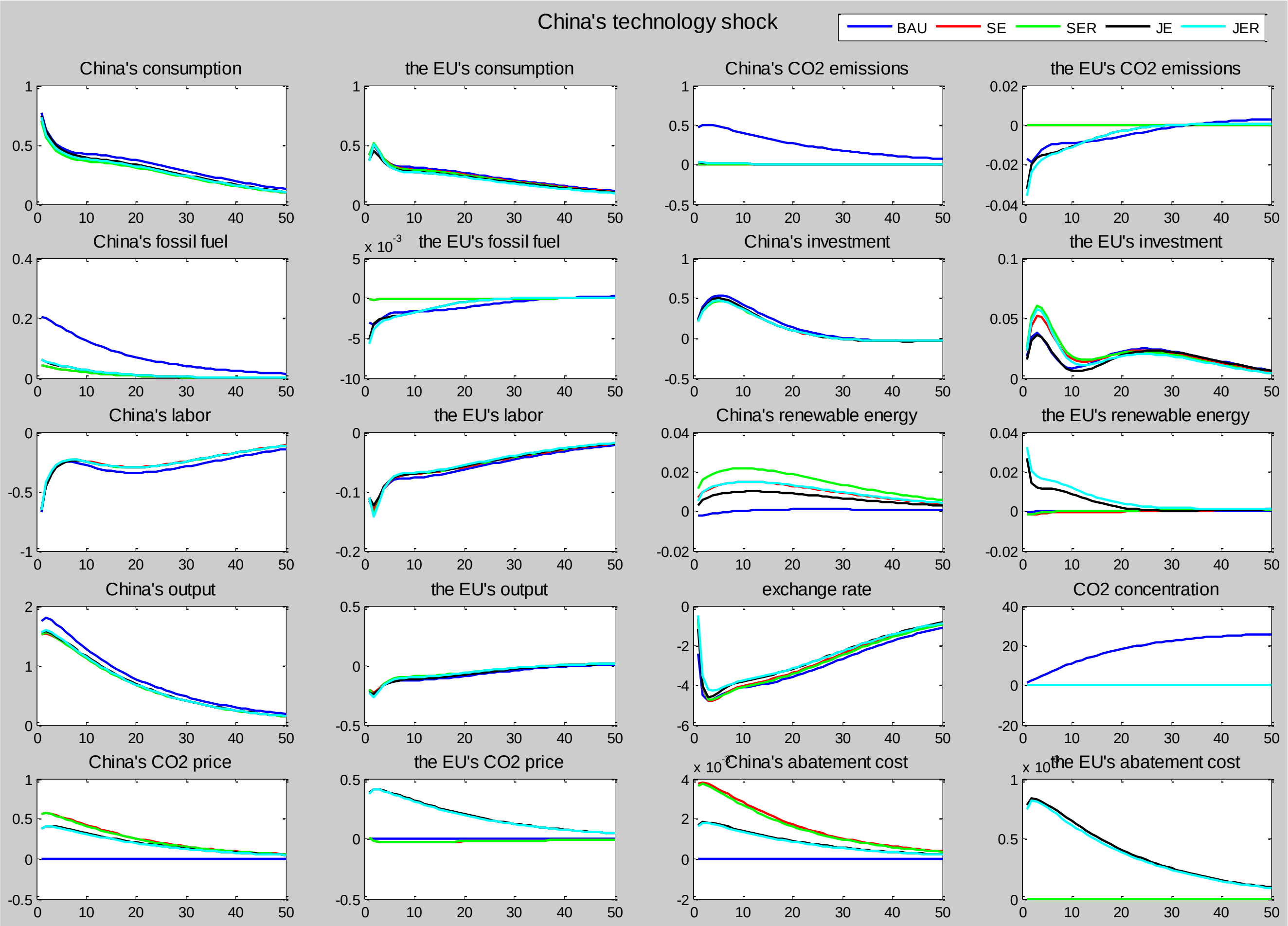


Figure 4. The responses to a transitory technology shock hitting only China

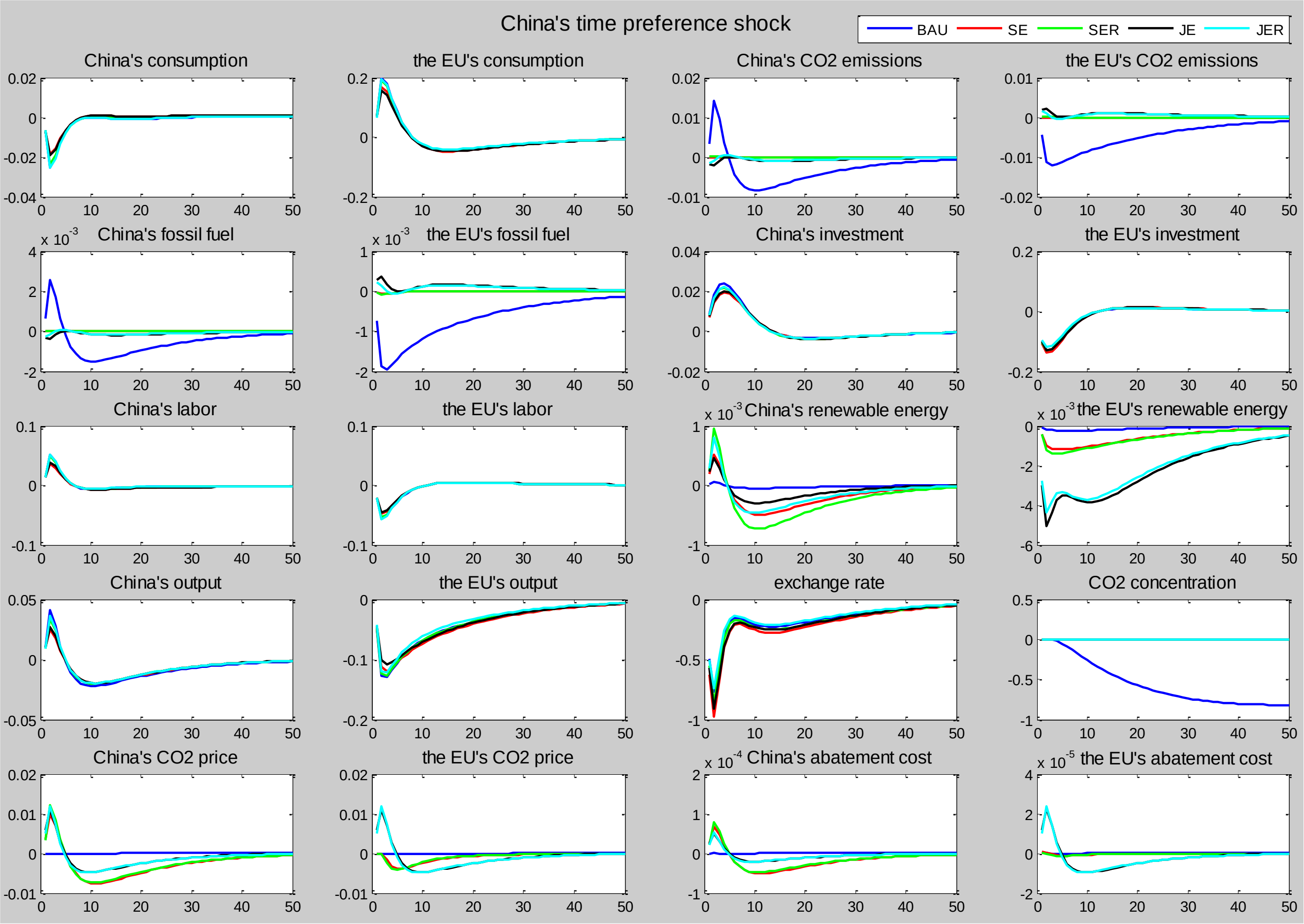


Figure 5. The responses to a transitory time preference shock hitting only China

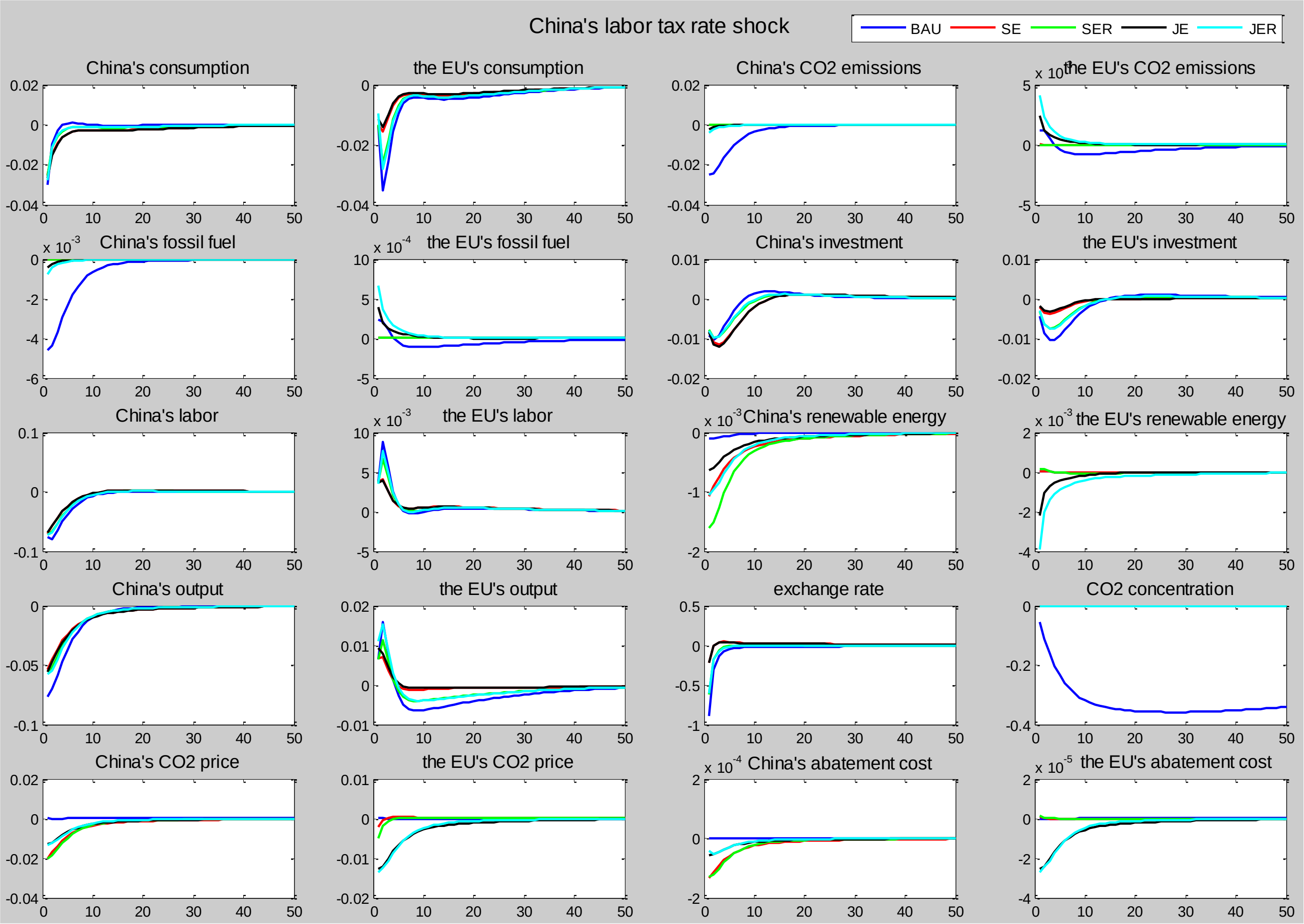
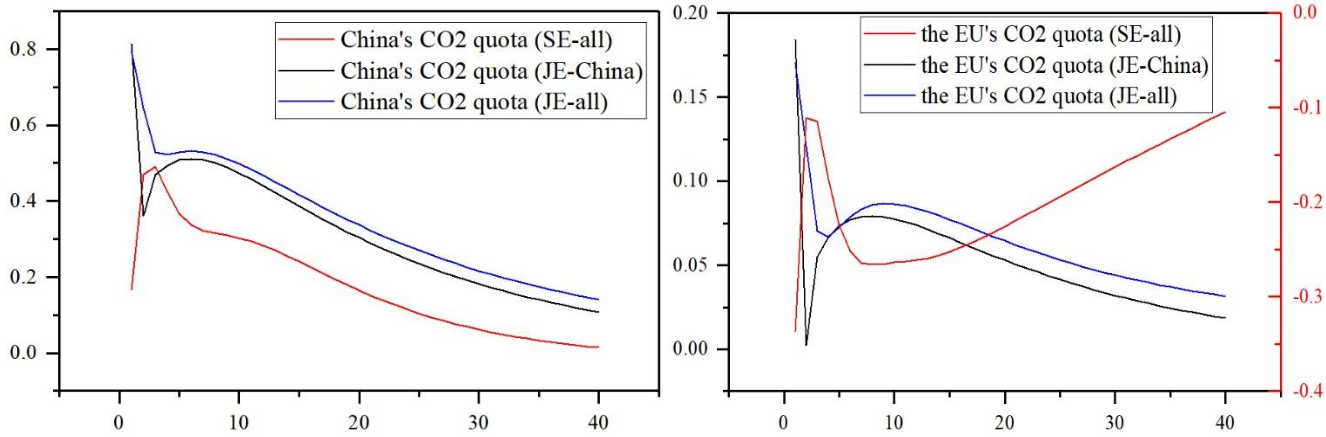
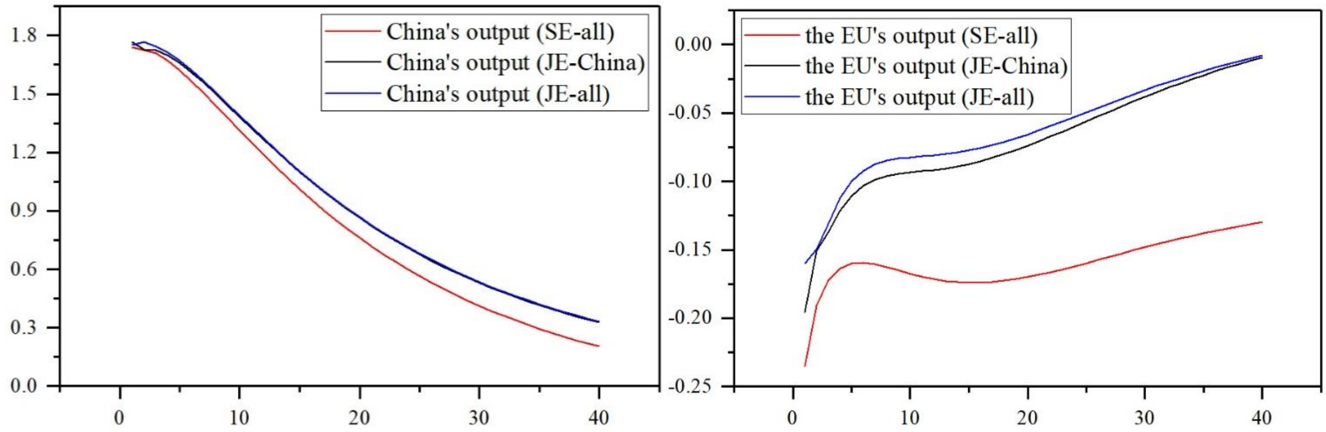


Figure 6. The responses to a transitory labor tax rate shock hitting only China



(a) China's CO2 quota

(b) the EU's CO2 quota



(c) China's output

(d) the EU's output

Figure 7. The results of Ramsey environmental policy under a China's technology shock

Tables

Table 1. The parameters and values

No.	Parameter	Value	Description
(1)	β	0.95	Discount factor
(2)	θ_1	2	Relative risk aversion
(3)	θ_2	1	Elasticity of labor supply
(4)	ς_H	0.6	The weight of environmental quality
(5)	ϑ	2	Investment adjustment cost parameter
(6)	Δ_{tp}	6.9°C	Disaster temperature rise
(7)	χ	0.35	Environment quality parameter
(8)	θ_3	3.42	Real money balances elasticity
(9)	ε	1.372	Elasticity of substitution across consumption
(10)	ϕ	0.75	The ratio of domestic products to domestic demand
(11)	φ	0.8976	Elasticity of CER production
(12)	μ_M	2.7716	Emission coefficient of coal, oil and natural gas (kg/tce)
	μ_O	2.0306	
	μ_{NG}	1.6438	
(13)	Δ	100	Parameter for innovation efficiency
	d_1	1.2	The efficiency of government supports on the innovation level
	ξ	1.1	Exponent parameter for innovation level
(14)	Λ_O	-460.8 (China) -802.5 (EU)	Emission reduction cost parameter
	Λ_{NG}	-486.08 (China) -878.35 (EU)	
	Λ_M	-80.152 (China) -189.77 (EU)	
(15)	η_0	1.3950e-3	Labor efficiency parameters
	η_1	-6.6722e-6	
	η_2	1.4647e-8	

(1). Fischer and Springborn (2011):0.95; Andrés et al., (2013): 0.95;

(2). Stern (2008): 2; Weitzman (2007): 2; Angelopoulos et al., (2010): 2; Acemoglu et al., (2012). 2;

(3). Gerali et al., (2010): 1; Yang and Liu, (2014): 1;

(4). Angelopoulos et al., (2010): 0.6; Yang and Liu, (2014):0.6;

(5). Burnside et al., (2003): 2;

(6). According to Acemoglu et al., (2012). 6.9°C corresponds to 1.5 times the highest estimate of the temperature increase that would eventually lead to the melting of the Greenland Ice Sheet (Pachauri and Reisinger, 2007);

(7). Acemoglu et al., (2012): 0.3492; Wu et al., (2014): 0.3501;

(8). Neiss and Pappa (2005): 3.42;

(9). Liu (2013): 1.372; Adolfson et al., (2007): 1.468;

(10). Liu (2013): 0.75; Adolfson et al., (2007): 0.69;

(11). Wu et al., (2014) used Bayesian estimation to estimate the elasticity of CER after establishing carbon market.

(12). Emission coefficients of coal, oil and natural gas are calibrated by Guidelines for National Greenhouse Gas Inventories (IPCC)

(13). Fanti and Gori, (2010): $\Delta > 0$ for a "S" shape curve. $\xi > 1$ for a "S" shape curve. When $Tr_t = 0$, the level of innovation is 1 and when $Tr_t \to \infty$, the level of innovation is 1.2.

(14). Estimated by authors. Our CGE model was used to estimate marginal abatement cost of CO_2 in China and EU. We performed a sequence of carbon tax rates. We thereby generated the sequence of marginal abatement costs, i.e., carbon tax rates, and the associated emissions reductions.

(15). Labor efficiency parameters are calibrated by Annicchiarico and Di Dio (2015)

Table 2. The results of mix frequency Bayesian estimation

Parameters		**Prior mean**	**Posterior mean**	**90% high posterior density interval**		**Prior distribution**	**Prior standard deviation**
China	ρ_A	0.8	0.9147	0.9074	0.9226	Beta	0.1
	ρ_K	0.8	0.7881	0.7208	0.8552	Beta	0.1
	ρ_L	0.8	0.7131	0.5893	0.8285	Beta	0.1
	ρ_G	0.8	0.7381	0.6698	0.7995	Beta	0.1
	ρ_{s^β}	0.8	0.6967	0.6219	0.767	Beta	0.1
	ρ_{s^L}	0.8	0.7802	0.6564	0.8729	Beta	0.1
	ϕ_G^K	0.05	0.0495	0.0184	0.085	Inverse gamma	0.05
	ϕ_G^L	0.05	0.0566	0.0173	0.1092	Inverse gamma	0.05
	ϕ_Y^K	0.05	0.0426	0.0165	0.0721	Inverse gamma	0.05
	ϕ_Y^L	0.05	0.0462	0.017	0.0756	Inverse gamma	0.05
	ϕ_B^G	0.05	0.0586	0.0466	0.0732	Inverse gamma	0.05
	ϕ_Y^G	0.05	0.0332	0.016	0.0507	Inverse gamma	0.05
The EU	ρ_A^*	0.8	0.8023	0.7312	0.8726	Beta	0.1
	ρ_K^*	0.8	0.6434	0.5044	0.8114	Beta	0.1
	ρ_L^*	0.8	0.6602	0.5623	0.7834	Beta	0.1
	ρ_G^*	0.8	0.6342	0.4004	0.8218	Beta	0.1
	$\rho_{s^\beta}^*$	0.8	0.6183	0.527	0.6998	Beta	0.1
	$\rho_{s^L}^*$	0.8	0.7945	0.705	0.8949	Beta	0.1
	ϕ_G^{K*}	0.05	0.0519	0.0195	0.0885	Inverse gamma	0.05
	ϕ_G^{L*}	0.05	0.0465	0.0171	0.0812	Inverse gamma	0.05
	ϕ_Y^{K*}	0.05	0.0346	0.0175	0.0532	Inverse gamma	0.05
	ϕ_Y^{L*}	0.05	0.0467	0.0188	0.0804	Inverse gamma	0.05
	ϕ_B^{G*}	0.05	0.0604	0.0407	0.0809	Inverse gamma	0.05
	ϕ_Y^{G*}	0.05	0.0666	0.0181	0.1222	Inverse gamma	0.05

Table 3. The steady-state values of the main variables in China and the EU

	BAU	**SE**		**SER**		**JE**		**JER**	
Y_t	1.0381	1.0291	-0.87%	1.0295	-0.83%	1.0195	-1.79%	1.0200	-1.74%
C_t	0.5650	0.5601	-0.86%	0.5603	-0.83%	0.5571	-1.40%	0.5573	-1.36%
E_t^{CO2}	0.3752	0.3377	-10.00%	0.3377	-10.00%	0.3168	-15.55%	0.3168	-15.57%
NE_t	0.0020	0.0045	126.35%	0.0051	160.70%	0.0033	67.58%	0.0041	106.95%
M_t	0.0890	0.0796	-10.54%	0.0796	-10.53%	0.0744	-16.38%	0.0744	-16.38%
O_t	0.0585	0.0532	-9.14%	0.0531	-9.15%	0.0502	-14.26%	0.0501	-14.29%
NG_t	0.0060	0.0056	-6.13%	0.0056	-6.19%	0.0054	-9.58%	0.0054	-9.67%
P_t^{CO2}	0.0000	0.0213	/	0.0209	/	0.0362	/	0.0357	/
TI_t	1.0000	1.0000	0.00%	1.0828	8.28%	1.0000	0.00%	1.1062	10.62%
η_t^L	0.9774	0.9790	0.16%	0.9790	0.16%	0.9790	0.16%	0.9790	0.16%
CER_t	0.0000	0.0055	/	0.0055	/	0.0055	/	0.0055	/
Y_t^*	1.0798	1.0633	-1.53%	1.0635	-1.52%	1.0777	-0.20%	1.0778	-0.20%
C_t^*	1.2779	1.2628	-1.19%	1.2631	-1.16%	1.2703	-0.60%	1.2705	-0.58%
E_t^{CO2*}	0.1092	0.0731	-33.00%	0.0731	-33.00%	0.0940	-13.91%	0.0940	-13.85%
NE_t^*	0.0023	0.0037	62.83%	0.0040	76.08%	0.0027	21.19%	0.0029	25.82%
M_t^*	0.0074	0.0057	-23.01%	0.0057	-23.08%	0.0067	-8.68%	0.0067	-8.68%
O_t^*	0.0218	0.0148	-32.02%	0.0148	-32.03%	0.0189	-13.24%	0.0189	-13.18%
NG_t^*	0.0271	0.0166	-38.50%	0.0167	-38.46%	0.0225	-16.95%	0.0225	-16.86%
P_t^{CO2*}	0.0000	0.0288	/	0.0286	/	0.0097	/	0.0096	/
TI_t^*	1.0000	1.0000	0.00%	1.0346	3.46%	1.0000	0.00%	1.0165	1.65%
S_t	3.6911	3.6719	-0.52%	3.6713	-0.54%	3.7393	1.31%	3.7378	1.27%
$C_{CO2,t}$	404.0	389.3	-3.64%	389.3	-3.64%	389.3	-3.64%	389.3	-3.64%
TW_t	-54.2765	-54.5061	-0.42%	-54.5067	-0.42%	-54.4997	-0.41%	-54.4968	-0.41%
TY_t (2)	2.1179	2.0923	-1.21%	2.0929	-1.18%	2.0972	-0.98%	2.0977	-0.95%

(1) Y_t and Y_t^* are real output in China and the EU. $TY_t = Y_t + Y_t^*$ is the total real output.

(2) TW_t is the total welfare in China and the EU.

Appendix A. The Model Derivation

A.1 Household

To solve the household problem, the Langrangian function was formed:

$$\begin{aligned}\ell = E_t\sum_{t=0}^{\infty}\beta^t\{s_t^{\beta}[\frac{[\psi(Q_t)^{1-\varsigma_H}(C_t)^{\varsigma_H}]^{1-\theta_1}}{1-\theta_1}-s_t^L\frac{L_t^{1+\theta_2}}{1+\theta_2}+\frac{[M_t/P_t]^{1-\theta_3}}{1-\theta_3}]+\nu_t[K_t-(1-\delta_K)K_{t-1}-[1-\frac{\vartheta}{2}(\frac{I_t}{I_{t-1}}-1)^2]I_t]\\ +\lambda_t[P_tC_t+P_tI_t+B_t+D_tS_t+M_t-(1-\tau_t^L)W_tL_t-(1-\tau_t^K)K_{t-1}R_t^K-B_{t-1}R_{t-1}^B-M_{t-1}-D_{t-1}S_tR_{t-1}^D]\end{aligned} \tag{A.1}$$

F.O.C. for the household’s problem:

$$\frac{\partial\ell}{\partial C_t}: s_t^{\beta}\varsigma_H\cdot\psi(Q_t)^{(1-\varsigma_H)(1-\theta_1)}(C_t)^{\varsigma_H(1-\theta_1)-1}+\lambda_tP_t=0 \tag{A.2}$$

$$\frac{\partial\ell}{\partial L_t}:-s_t^{\beta}s_t^LL_t^{\theta_2}-\lambda_t(1-\tau_t^L)W_t=0 \tag{A.3}$$

$$\frac{\partial\ell}{\partial B_t}:\lambda_t=\beta E_t[R_t^B\lambda_{t+1}] \tag{A.4}$$

$$\frac{\partial\ell}{\partial D_t}:S_t\lambda_t=\beta E_t[S_{t+1}R_t^D\lambda_{t+1}] \tag{A.5}$$

$$\frac{\partial\ell}{\partial K_t}:\nu_t-\beta E_t[\lambda_{t+1}(1-\tau_{t+1}^K)R_{t+1}^K+(1-\delta_K)\nu_{t+1}]=0 \tag{A.6}$$

$$\frac{\partial\ell}{\partial I_t}:\lambda_tP_t-\nu_t[1-\frac{\vartheta}{2}(\frac{I_t}{I_{t-1}}-1)^2]+\nu_t\vartheta I_t(\frac{I_t}{I_{t-1}^2}-\frac{1}{I_{t-1}})-\beta E_t[\vartheta\nu_{t+1}\frac{I_{t+1}^2}{I_t^2}(\frac{I_{t+1}}{I_t}-1)]=0 \tag{A.7}$$

$$\frac{\partial\ell}{\partial M_t}:(\frac{M_t}{P_t})^{-\theta_3}\frac{1}{P_t}+\lambda_t-\beta E_t[\lambda_{t+1}]=0 \tag{A.8}$$

A.2 Enterprises

A.2.1 Final goods producers

$$\begin{aligned}&\max_{Y_t(j)} P_tY_t-\int_0^1Y_t(j)P_t(j)dj\\ &s.t\ Y_t=[\int_0^1Y_t(j)^{\frac{\varphi-1}{\varphi}}dj]^{\frac{\varphi}{\varphi-1}}\end{aligned} \tag{A.9}$$

F.O.C. for the final goods producer's problem:

$$Y_t(j)P_t^{\varphi}(j) = Y_t P_t^{\varphi} \tag{A.10}$$

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

The intermediate goods producing firm's problem can be written as follows:

$$\begin{aligned} MAX\ \pi_t^Y &= P_t(j)Y_t(j) - R_t^K K_{t-1}^Y(j) - W_t L_t^Y(j) - P_t^E E_t(j) \\ s.t \quad Y_t(j) &= A_t(\eta_t^L L_t^Y(j))^{\alpha_1} \cdot (K_{t-1}^Y(j))^{\beta_1} E_t(j)^{1-\alpha_1-\beta_1} \end{aligned} \tag{A.11}$$

F.O.C. for the intermediate goods producing firm's problem

$$\frac{\partial \pi_t^Y}{\partial K_{t-1}^Y} : \beta_1 P_t(j)\frac{Y_t(j)}{K_{t-1}^Y(j)} = R_t^K \tag{A.12}$$

$$\frac{\partial \pi_t^Y}{\partial L_t^Y} : \alpha_1 P_t(j)\frac{Y_t(j)}{L_t^Y(j)} = W_t \tag{A.13}$$

$$\frac{\partial \pi_t^Y}{\partial E_t} : (1-\alpha_1-\beta_1)P_t(j)\frac{Y_t(j)}{E_t(j)} = P_t^E \tag{A.14}$$

The energy producing firm's problem can be written as follows:

$$\begin{aligned} MAX\ \pi_t^E &= P_t^E E_t(j) - P_t^{NE} NE_t(j) - P_t^{FE} FE_t(j) \\ s.t\ E_t(j) &= A_t[\gamma FE_t(j)^{\rho} + (1-\gamma)NE_t(j)^{\rho}]^{1/\rho} \end{aligned} \tag{A.15}$$

F.O.C. for the energy producing firm's problem

$$\frac{\partial \pi_t^E}{\partial NE_t} : P_t^{NE} = P_t^E A_t[\gamma FE_t(j)^{\rho} + (1-\gamma)NE_t(j)^{\rho}]^{1/\rho-1}(1-\gamma)NE_t(j)_t^{\rho-1} \tag{A.16}$$

$$\frac{\partial \pi_t^E}{\partial FE_t} : P_t^{FE} = P_t^E A_t[\gamma FE_t(j)^{\rho} + (1-\gamma)NE_t(j)^{\rho}]^{1/\rho-1}\gamma FE_t(j)^{\rho-1} \tag{A.17}$$

The fossil energy producing firm’s problem can be written as follows:

$$\begin{aligned} &MAX\ \pi_t^E = P_t^{FE} FE_t(j) - P_t^M M_t(j) - P_t^O O_t(j) - P_t^{NG} NG_t(j) - P_t^{CO2} E_t^{CO2}(j) - P_t[CE_t^M(j) + P_t CE_t^O(j) + CE_t^{NG}(j)] \\ &s.t \qquad FE_t(j) = A_t M_t(j)^{\alpha_2} \cdot O_t(j)^{\beta_2} \cdot NG_t(j)^{1-\alpha_2-\beta_2} \end{aligned} \tag{A.18}$$

$$CE_t^M = \int_0^{RE_t^M} \Lambda \ln(1 - \frac{RE_t^M}{\mu_M M_t}) dRE_t^M = -\Lambda_M \mu_M M_t [\ln(1 - re_t^M)(1 - re_t^M) + re_t^M] \tag{A.19}$$

$$CE_t^O = \int_0^{RE_t^O} \Lambda \ln(1 - \frac{RE_t^O}{\mu_O O_t}) dRE_t^O = -\Lambda_O \mu_O O_t [\ln(1 - re_t^O)(1 - re_t^O) + re_t^O] \tag{A.20}$$

$$CE_t^{NG} = \int_0^{RE_t^{NG}} \Lambda \ln(1 - \frac{RE_t^{NG}}{\mu_{NG} NG_t}) dRE_t^{NG} = -\Lambda_{NG} \mu_{NG} NG_t [\ln(1 - re_t^{NG})(1 - re_t^{NG}) + re_t^{NG}] \tag{A.21}$$

F.O.C. for the fossil energy producing firm’s problem

$$\frac{\partial \pi_t^E}{\partial M_t} : \alpha_2 P_t^{FE} \frac{FE_t(j)}{M_t(j)} - P_t^M - P_t^{CO2} \mu_M (1 - re_t^M(j)) + \Lambda_M \mu_M [\ln(1 - re_t^M(j))(1 - re_t^M(j)) + re_t^M(j)] = 0 \tag{A.22}$$

$$\frac{\partial \pi_t^E}{\partial O_t} : \beta_2 P_t^{FE} \frac{FE_t(j)}{O_t(j)} - P_t^O - P_t^{CO2} \mu_O (1 - re_t^O(j)) + \Lambda_O \mu_O [\ln(1 - re_t^O(j))(1 - re_t^O(j)) + re_t^O(j)] = 0 \tag{A.23}$$

$$\frac{\partial \pi_t^E}{\partial NG_t} : (1 - \alpha_2 - \beta_2) P_t^{FE} \frac{FE_t(j)}{NG_t(j)} - P_t^{NG} - P_t^{CO2} \mu_{NG} (1 - re_t^{NG}(j)) + \Lambda_{NG} \mu_{NG} [\ln(1 - re_t^{NG}(j))(1 - re_t^{NG}(j)) + re_t^{NG}(j)] = 0 \tag{A.24}$$

$$\frac{\partial \pi_t^E}{\partial re_t^{NG}} : P_t^{CO2} = \Lambda_{NG} \ln(1 - re_t^{NG}(j)) \tag{A.25}$$

$$\frac{\partial \pi_t^E}{\partial re_t^M} : P_t^{CO2} = \Lambda_M \ln(1 - re_t^M(j)) \tag{A.26}$$

$$\frac{\partial \pi_t^E}{\partial re_t^O} : P_t^{CO2} = \Lambda_O \ln(1 - re_t^O(j)) \tag{A.27}$$

The renewable energy producing firm’s problem can be written as follows:

$$\begin{aligned} &MAX\ \pi_t^{NE} = P_t^{NE} NE_t(j) - R_t^K K_{t-1}^{NE}(j) - W_t L_t^{NE}(j) + P_t^{CER} CER_t(j) + Tr_t(j) \\ &s.t \qquad NE_t = A_t TI_t(j)(\eta_t^L L_t^{NE}(j))^{\alpha_3} \cdot (K_{t-1}^{NE}(j))^{\beta_3} \end{aligned} \tag{A.28}$$

F.O.C. for the renewable energy producing firm’s problem

$$\frac{\partial \pi_t^{NE}}{\partial L_t^{NE}} : \alpha_3 P_t^{NE} \frac{NE_t(j)}{L_t^{NE}(j)} + \varsigma_3 \alpha_3 P_t^{CER} \frac{NE_t(j)^{\varsigma_3}}{L_t^{NE}(j)} = W_t \tag{A.29}$$

$$\frac{\partial \pi_t^{NE}}{\partial K_{t-1}^{NE}} : \beta_3 P_t^{NE} \frac{NE_t(j)}{K_{t-1}^{NE}(j)} + \varsigma_3 \beta_3 P_t^{CER} \frac{NE_t(j)^{\varsigma_3}}{K_{t-1}^{NE}(j)} = R_t^K \tag{A.30}$$

The coal, oil and natural gas producing firm's problem can be written as follows:

$$\begin{aligned} MAX\ \pi_t^{NG} &= P_t^{NG} NG_t(j) - R_t^K K_{t-1}^{NG}(j) - W_t L_t^{NG}(j) \\ s.t\ NG_t &= A_t (\eta_t^L L_t^{NG}(j))^{\alpha_4} \cdot (K_{t-1}^{NG}(j))^{\beta_4} \end{aligned} \tag{A.31}$$

$$\begin{aligned} MAX\ \pi_t^{O} &= P_t^{O} O_t(j) - R_t^K K_{t-1}^{O}(j) - W_t L_t^{O}(j) \\ s.t\ O_t &= A_t (\eta_t^L L_t^{O}(j))^{\alpha_5} \cdot (K_{t-1}^{O}(j))^{\beta_5} \end{aligned} \tag{A.32}$$

$$\begin{aligned} MAX\ \pi_t^{M} &= P_t^{M} M_t(j) - R_t^K K_{t-1}^{M}(j) - W_t L_t^{M}(j) \\ s.t\ M_t &= A_t (\eta_t^L L_t^{M}(j))^{\alpha_6} \cdot (K_{t-1}^{M}(j))^{\beta_6} \end{aligned} \tag{A.33}$$

F.O.C. for the coal, oil and natural gas producing firm's problem

$$\frac{\partial \pi_t^{M}}{\partial K_{t-1}^{M}} : \beta_6 P_t^{M} \frac{M_t(j)}{K_{t-1}^{M}(j)} = R_t^K \tag{A.34}$$

$$\frac{\partial \pi_t^{M}}{\partial L_t^{M}} : \alpha_6 P_t^{M} \frac{M_t(j)}{L_t^{M}(j)} = W_t \tag{A.35}$$

$$\frac{\partial \pi_t^{NG}}{\partial K_{t-1}^{NG}} : \beta_4 P_t^{NG} \frac{NG_t(j)}{K_{t-1}^{NG}(j)} = R_t^K \tag{A.36}$$

$$\frac{\partial \pi_t^{NG}}{\partial L_t^{NG}} : \alpha_4 P_t^{NG} \frac{NG_t(j)}{L_t^{NG}(j)} = W_t \tag{A.37}$$

$$\frac{\partial \pi_t^{O}}{\partial K_{t-1}^{O}} : \beta_5 P_t^{O} \frac{O_t(j)}{K_{t-1}^{O}(j)} = R_t^K \tag{A.38}$$

$$\frac{\partial \pi_t^{O}}{\partial L_t^{O}} : \alpha_5 P_t^{O} \frac{O_t(j)}{L_t^{O}(j)} = W_t \tag{A.39}$$

Following Calvo (1983), firms that have the chance to change their prices to maximise the expected sum of discounted future real profits.

$$\max_{P_t(j)} \Re = E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{\lambda^H_{t+i}}{\lambda^H_t} Y_{t+i} \left[\frac{P_t(j)}{P_{t+i}} \left(\frac{P_{t+i}}{P_t(j)}\right)^{\varphi} - MC_{t+i} \left(\frac{P_{t+i}}{P_t(j)}\right)^{\varphi}\right] \tag{A.40}$$

$$MC_t = MC_t(j) = \frac{\partial TC_t(j)}{\partial Y_t(j)} \tag{A.41}$$

F.O.C for Calvo pricing:

$$\frac{\partial \Re}{\partial P_t(j)} : E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{\lambda^H_{t+i}}{\lambda^H_t} Y_{t+i} [(1-\varphi) P_t^*(j)^{-\varphi} P_{t+i}^{\varphi-1} + \varphi MC_{t+i} P_{t+i}^{\varphi} P_t^*(j)^{-\varphi-1}] = 0 \tag{A.42}$$

$$P_t^* = P_t^*(j) = \frac{\varphi}{\varphi-1} \cdot \frac{E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{\lambda^H_{t+i}}{\lambda^H_t} Y_{t+i} MC_{t+i} P_{t+i}^{\varphi}}{E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{\lambda^H_{t+i}}{\lambda^H_t} Y_{t+i} P_{t+i}^{\varphi-1}} \tag{A.43}$$

$$(\varphi-1) E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{\lambda^H_{t+i}}{\lambda^H_t} Y_{t+i} \left(\frac{P_t^*}{P_{t+i}}\right)^{1-\varphi} = \varphi \cdot E_t \sum_{i=0}^{\infty} (\beta\omega)^i \frac{\lambda^H_{t+i}}{\lambda^H_t} Y_{t+i} MC_{t+i} \left(\frac{P_t^*}{P_{t+i}}\right)^{-\varphi} \tag{A.44}$$

$$(\varphi-1) X_{1,t} = \varphi X_{2,t} \tag{A.45}$$

$$X_{1,t} = Y_t (p_t^*)^{1-\varphi} + \beta\omega E_t [\lambda^H_{t+1} (\lambda^H_t)^{-1} X_{1,t+1} (p_t^*)^{1-\varphi} (p_{t+1}^*)^{\varphi-1} \pi_{t+1}^{\varphi-1}] \tag{A.46}$$

$$X_{2,t} = Y_t MC_t (p_t^*)^{-\varphi} + \beta\omega E_t [\lambda^H_{t+1} (\lambda^H_t)^{-1} X_{2,t+1} (p_t^*)^{-\varphi} (p_{t+1}^*)^{\varphi} \pi_{t+1}^{\varphi}] \tag{A.47}$$

Following the Calvo (1983), the price dispersion function can be rewritten as Eq. (A.31) (A.32):

$$V_t^P = \int_0^1 \left(\frac{P_t(j)}{P_t}\right)^{-\varphi} dj \tag{A.48}$$

$$V_t^P = (1-\omega)\left(\frac{P_t^*}{P_t}\right)^{-\varphi} + \omega\left(\frac{P_t}{P_{t-1}}\right)^{\varphi} V_{t-1}^P \tag{A.49}$$

A.3 Market clearing

$$L_t(j) = L_t^Y(j) + L_t^{NE}(j) + L_t^{NG}(j) + L_t^M(j) + L_t^O(j) \tag{A.50}$$

$$K_t(j) = K_t^Y(j) + K_t^{NE}(j) + K_t^{NG}(j) + K_t^M(j) + K_t^O(j) \tag{A.51}$$

In equilibrium and markets clearing, the following conditions are satisfied in all of society, that is,

$$Y_t = (V_t^P)^{-1}\int_0^1 Y_t(j)dj, L_t = \int_0^1 L_t(j)dj, K_t = \int_0^1 K_t(j)dj, E_t = \int_0^1 E_t(j)dj, FE_t = \int_0^1 FE_t(j)dj, NE_t = \int_0^1 NE_t(j)dj,$$

$$E_t^{CO2} = \int_0^1 E_t^{CO2}(j)dj, M_t = \int_0^1 M_t(j)dj, O_t = \int_0^1 O_t(j)dj, NG_t = \int_0^1 NG_t(j)dj, CE_t^M = \int_0^1 CE_t^M(j)dj, \qquad \text{(A.52)}$$

$$CE_t^O = \int_0^1 CE_t^O(j)dj, CE_t^{NG} = \int_0^1 CE_t^{NG}(j)dj, re_t^M = \int_0^1 re_t^M(j)dj, re_t^O = \int_0^1 re_t^O(j)dj, re_t^{NG} = \int_0^1 re_t^{NG}(j)dj,$$

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

$$P_tY_t = P_{H,t}C_{H,t} + S_tP_{H,t}^*C_{H,t}^* + P_t[I_t + G_t + CE_t^M + CE_t^O + CE_t^{NG}] \qquad \text{(A.53)}$$

$$P_t^*Y_t^* = P_{F,t}C_{F,t}S_t^{-1} + P_{F,t}^*C_{F,t}^* + P_t^*[I_t^* + G_t^* + CE_t^{M*} + CE_t^{O*} + CE_t^{NG*}] \qquad \text{(A.53)}$$

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