Carbon Bubble, Stranded Assets and the Path of Carbon Emission Reduction

——A View from Policy Regulation[1]

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Abstract: We construct a multi-sector dynamic general equilibrium model with heterogeneous energy production firms and fossil fuel asset accumulation and discuss the impact of different emission reduction policies on carbon emissions, stranded assets, social welfare, and energy companies' behavior. Mechanically, emission reduction policies will lead to a decline in the value of fossil fuel reserve of energy firms, causing the burst of the "carbon bubble" and the gradual stranding of fossil fuel assets, affecting the financing and production of the energy sector and ultimately causing a decline in total output and total consumption. Based on parameter calibration using data from China and the United States, we simulated the macro impacts of taxation, adjustment of financing constraints, and implementation of environmental, industrial policies and characterize the emission reduction paths and the scale of stranded assets corresponding to different policies.

Keywords: Carbon Bubble; Credit Constraint; Environment Policy; Stranded Assets

1 Introduction

"Carbon peaking" and "carbon neutrality" are important issues facing the development and transformation of all countries today. After the signing of the Paris Agreement, all major countries have promulgated their emission reduction targets: China announced that it will achieve a "carbon peak" in 2030 and "carbon neutrality" in 2060; the United States announced that in 2025, annual greenhouse gas emissions will fall by about 25% compared with 2005, while achieving carbon neutrality in 2050; the EU claims that greenhouse gas emissions in 2030 will be 55% lower than in 1990, while achieving carbon neutrality in 2050. The report of the 20th National Congress of the Communist Party of China pointed out that it is necessary to "improve the regulation of the total amount and intensity of energy consumption, focus on controlling fossil energy consumption, and gradually shift to a 'dual control' system of the total amount and intensity of carbon emissions." Currently, China's carbon emission reduction policies mainly include price policies such as carbon prices and carbon taxes, industrial policies, and financial policies for different sectors. In this context,

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studying the relationship between different policies and economic low-carbon transformation is essential and then discussing policy options.

In recent years, there has been increasing discussion about the issue of stranded assets caused by environmental policies. Carbon bubbles and stranded assets are two sides of the same coin. According to Wikipedia, a carbon bubble is “a hypothetical bubble in the valuations of companies that rely on fossil fuel energy production, caused by the decline in the value of fossil fuel reserves in the future because they cannot be used to meet carbon budgets and the valuation of the stock market of companies.” Most current research does not consider the asset stranding problem caused by carbon emission reduction policies, and the few literatures that study this issue mainly discuss it from the perspective of climate policy uncertainty affecting asset prices and investor behavior (Sen and Von Schickfus, 2020; Barnett, 2023). There is less discussion on how asset stranding will affect the behavior of energy companies and thus affect macroeconomic operations. Fossil energy reserves are essential assets for energy companies and will significantly affect their valuation. In January 2004, Shell cut its fossil energy reserves by 20%, and its stock price fell by 10% within a week. In an environment with financial frictions and financing constraints, the value of a company determines the upper limit of its financing capacity (Miao and Wang, 2018). Emission reduction policies may lead to a decline in the value of fossil energy reserves of energy companies, compress financing space, and further amplify emission reductions. The inhibitory effect of emission policies will bring greater output and welfare losses on the emission reduction path.

Currently, research that directly discusses policies and low-carbon transition is relatively limited, and most studies focus on the response of steady-state peripheral policies to carbon emission-related shocks (Dissou and Karnizova, 2016; Annicchiarico and Di Dio, 2015), as well as the substitution of green technology and brown technology in the policy context (Acemouglu et al., 2012), there is less discussion on the low-carbon transfer paths corresponding to different policies under given goals (Fried et al., 2022; Carattini et al., 2023). In addition, green transformations are often fueled by financial, industrial, or price policies targeting specific industries. These policies may bring about intra-sector resource misallocation (Hsieh and Klenow, 2009; Tombe and Winter, 2015), affecting policy analysis results. This paper introduces intra-sector resource misallocation and financial friction into the traditional dynamic general equilibrium model, including energy use and pollution accumulation, and discusses the impact of different policies on emission reduction paths and welfare.

By constructing a multi-sector dynamic general equilibrium model that includes heterogeneous energy companies and financing constraints, we calculate the steady-state emission reduction effects and dynamic emission reduction paths corresponding to different policies and discuss the impact of different policies on energy company behavior, carbon emissions, and welfare implications. Enterprises in the energy sector in the model have heterogeneous investment efficiencies, use fossil energy reserves and labor to produce energy products, and make investment decisions for the accumulation of fossil energy reserves. Emission reduction policies may affect the borrowing behavior of enterprises and thus affect resource allocation. The theoretical analysis found that using unified policies such as financing constraints or environmental industry policies to reduce emissions will increase the misallocation of resources within the energy sector, reduce overall investment efficiency, and lead to greater asset stranding and production suppression. In contrast, adopting price policies such as carbon taxes has a more minor impact on resource misallocation.

Based on the energy consumption data of China and the United States in 2021, we choose model parameters and discuss the intensity of different policies required under given emission reduction targets and the corresponding emission reduction paths. The quantitative analysis found that resource investment taxes and financial policies have less room for emission reduction, while industrial policies have the most significant room for emission reduction. Although the energy corporate tax also has a large room for emission reduction, a tax rate much higher than the current level is required to achieve high emission reduction targets. From the perspective of steady-state welfare, the use of financial policies and industrial policies to reduce emissions will lead to a decline in steady-state welfare, among which the welfare losses of industrial policies are more significant; the steady-state consumption effect of tax policies is higher than that of industrial policies and financial policies. In contrast, the use of energy policies has a more significant welfare loss. The steady-state welfare achieved by tax or energy corporate tax is higher. From the perspective of dynamic welfare effects, both financial and industrial policies will lead to a decline in long-term welfare, and the long-term welfare loss through emission reduction through industrial policy is more significant; using tax policy to reduce emissions may increase welfare in the long-term, and long-term welfare will increase more when energy taxes are adopted. In terms of "carbon bubble", the "carbon bubble" corresponding to the use of energy tax or energy corporate tax for emission reduction is the smallest, that is, the total value of fossil energy reserves $P^M M$ decreases the least when the same emission reduction effect is achieved; emission reduction through financial policy and industrial policy The corresponding "carbon bubble" is more prominent. Using resource investment tax to reduce emissions directly reduces the price of fossil energy, and the corresponding "carbon bubble" is the largest.

Theoretically, this paper innovatively introduces heterogeneous enterprises and financing constraints into the energy sector, regards fossil energy reserves as an essential asset of energy enterprises, and explores how different emission reduction policies affect the value of fossil energy reserve assets and the performance of energy enterprises. Investment and financing behavior and the economic carbon emission reduction path, and then analyze the steady-state and dynamic welfare effects of the policy; in terms of policy, this article combines the energy consumption data of China and the United States to analyze the consequences of adopting different policies for carbon emission reduction under the current circumstances. The macro impact of the project is given, and the emission reduction costs and benefits under different single policies are given, which provides a specific reference for the selection and formulation of environmental policy tools.

The structure of this article is as follows: the second part is a literature review, the third part gives the model setting, the fourth part discusses the model solution, the fifth part is a quantitative analysis, and the sixth part is a summary and discussion.

2 Related Literature

This article mainly discusses the emission reduction effects of different policies and the corresponding asset price changes and macroeconomic impacts. As problems such as pollution and global warming become increasingly severe, many economists have begun to explore how to consider environmental pollution factors in traditional economic models and use this to discuss optimal environmental regulatory policies. There are two main methods for introducing energy, emissions, and pollution into the production of traditional models: the first is to introduce emissions as a specific production factor into the production function, corresponding to the actual use of fossil energy; the other is to introduce emissions into the production function. As an undesired output, emissions are introduced into the production process together with the desired output (such as GDP); the production structure remains unchanged, and emissions are a function of total output. The pollution caused by emissions may affect total factor productivity.

Some studies directly introduce resources or environment as factors in the production function, and pollution corresponds to the consumption of specific energy or environmental factors (Copeland and Taylor, 1994). Mohtadi (1996) regards the environment as a factor of production and believes that capital accumulation will consume the environment (pollution). In recent years, more research has focused on analyzing the optimal policy response when energy is used as a specific input and discussed fiscal policies such as energy taxes (Golosov et al., 2014; Barrage, 2020) and how monetary policies targeting pollution (Economides and Xepapadeas, 2018; Diluiso et al., 2021) affect economic operations, Fischer and Springborn (2011), Tombe and Winter (2015) and Dissou and Karnizova (2016) discuss different environmental policies effects and synergistic relationships. Some articles use the computable general equilibrium model (CGE) to analyze the impact of carbon emission reduction policies on the economy (Goto, 1995; Floros et al., 2005; Guo et al., 2014). To facilitate analysis, these studies often believe that the energy sector uses capital and labor to produce energy intermediates (Diluiso et al., 2021; Dissou and Karnizova, 2016), and a few articles believe that the energy sector uses natural resources to produce energy (Golosov et al., 2014; Economides and Xepapadeas, 2018), but the critical role of fossil energy reserves as assets of energy companies is generally ignored: the value of energy companies largely depends on the amount of fossil energy reserves they hold, which in turn will affect the company's Financing capabilities and investment behavior; at the same time, existing research generally discusses representative energy production sectors, but does not discuss the impact of policies on efficiency when there is heterogeneity within the energy sector.

Other studies treat emissions and pollution as undesirable outputs, which are produced together with desirable outputs, thereby introducing trade-offs between production and pollution. Chung et al. (1997) and Färe et al. (2007) believe that reducing pollution faces social costs, and then the optimal output can be analyzed through the output distance function method - Pollution combination. In recent years, more research has introduced pollution into the traditional DSGE model, constructed an environmental DSGE (E-DSGE) model, and discussed the impact of various environment-related fiscal, monetary, financial, and other economic policies. Heutel (2012) provides a basic framework for this model type: production brings emissions, emissions increase pollution, and pollution affects productivity. Since then, a large number of articles have discussed how conventional fiscal and monetary policies (Annicchiarico and Di Dio, 2015, 2017; Chan, 2020; Rishanty et al., 2021), unconventional policies (Dafermos et al., 2018; Ferrari and Landi, 2023), and green finance and credit (Punzi, 2018) affect output, pollution, etc. The advantage of this model is that it can easily embed emission factors into the traditional DSGE model framework to study the impact of environment-related policies. However, most policy discussions based on DSGE models focus on a given steady state and study optimal policies under different shocks. This research paradigm ignores the economic transformation process of carbon emission reduction; emission reduction is a transition path from one steady state to another, and any policy analysis should be conducted on this transfer path. In recent years, some studies have attempted to discuss the risks of green transition paths brought about by policies. Fried et al. (2022) and Carattini et al. (2023) discuss how environmental protection policies affect the economy's transition between a high-carbon steady state and a low-carbon steady state and whether this transition may bring instability and risk. However, research based on the green transformation path is generally relatively limited.

At the same time, this article discusses the "carbon bubble", that is, the problem of stranded assets of fossil energy reserves caused by policy regulations. According to the financial accelerator theory, when financing constraints exist, the stranding of asset values may lead to a decline in corporate investment and financing capabilities, creating a vicious cycle (Kiyotaki and Moore, 1997). McGlade and Ekins (2015) estimated the amount of energy that would need to be reduced to limit the global average temperature increase to no more than 2°C by 2050. They found that about 1/3 of oil reserves, 1/2 of natural gas reserves, and more than 80% of coal reserves cannot be used. According to estimates by Mercure et al. (2018), implementing the Paris Agreement will bring about US$9 trillion in stranded assets, equivalent to 11% of global GDP in 2016. Sen and Von Schickfus (2020) used German data to estimate the impact of environmental protection policies on the stock market. They found that the announcement of climate policies caused the valuation of related companies to drop by approximately 20% within five days. Barnett (2019), Kalkuhl et al. (2020), and Comerford and Spiganti (2023) specifically discussed how environmental policies affect the investment behavior, asset prices, and policy transformation effects of energy companies in the presence of stranded asset problems. Compared with the literature, this article introduces the energy sector containing heterogeneous enterprises, regards fossil energy reserves as substantial asset reserves for energy enterprises, and discusses the impact of policy changes on asset prices and macroeconomics in a model including financial frictions. Impact.

The overall framework of this article is relatively close to Golosov et al. (2014), that is, a resource sector does the exploration and mining of fossil energy, and energy companies use fossil energy reserves to produce energy products (such as electricity). The final product department uses energy to produce products. At the same time, this article introduces fossil energy reserves as "assets" of energy companies into the model and introduces heterogeneous energy production companies concerning literature such as Wang and Wen (2012) and Dong and Xu (2022), discuss how emission reduction policies will affect asset prices and resource allocation within the department when there is both heterogeneity of energy companies and financial frictions, and then discuss corresponding transition paths and welfare effects.

3 The Model

This paper constructs a dynamic general equilibrium model with multi-sector and heterogeneous enterprises to reflect the industrial chain structure of "exploration and extraction-energy enterprise production-final goods production" in the economy and the resource misallocation among energy firms. In particular, this paper considers the industrial chain structure, referring to Golosov et al. (2014), and constructs a production department model structure of "resource exploration and mining-energy enterprises-final product department".

3.1 Representative Household

There is one representative household in the economy that supplies labor $L_t = 1$ inelastically, hold all the firms' stock and maximizes her lifetime utility:

$$\max_{C_t, s_{t+1}} E_0 \sum_{t=0}^{\infty} \beta_t u(C_t), \tag{1}$$

The budget constraint of this household is:

$$C_t + \int_0^1 s_{t+1}(i)[V_t(i) - d_t(i)]di = W_t L_t + \Pi_t^M + \int_0^1 s_t(i)V_t(i)di + D_t^F + D_t^K, \tag{2}$$

here $s_t(i)$ denotes the shareholding of energy firm i, Π_t^M denotes the profit of the exploration sector, D_t^F denotes the dividend from the final sector, D_t^K denotes the dividend from the capital producer. The first order conditions of the household are:

$$\Lambda_t = u'(C_t), \tag{3}$$

$$V_t(i) = d_t(i) + \beta E_t \frac{\Lambda_{t+1}}{\Lambda_t} V_{t+1}(i). \tag{4}$$

The production department has three parts according to the industrial chain: resource department, energy department, and final product department.

3.2 The Exploration and Extraction Sector

The resource exploration and extraction sector employs labor to explore and exploit natural resources that cannot be used directly (such as coal mines, oil wells, etc.) into fossil energy products (such as raw coal, crude oil, etc.) that energy companies can utilize. In particular, assume that its production function is:

$$M_t^n = A_t^M (L_t^M)^\psi, \tag{5}$$

where M_t^n represents the new flow of fossil energy products in period t, and L_t^M represents the total labor force in the resource extraction sector. The optimal labor employment condition is:

$$\psi A_t^M P_t^M (L_t^M)^{\psi-1} = W_t, \tag{6}$$

where P_t^M is the market price of resource products, and W_t is the wage. To simplify the analysis, we assume that wages are the same across industries and that labor can move freely

3.3 The Energy Sector

There are a series of heterogeneous energy companies $i \in [0,1]$ in the energy production sector, which use fossil energy reserves and labor to produce energy. Different energy companies have different utilization rates of natural resource products, which means different resource investment efficiency. Assume that the enterprise's production function is Cobb-Douglas:

$$e_t(i) = A_t^E m_t(i)^\alpha l_t^E(i)^{1-\alpha}, \tag{7}$$

where $m_t(i)$ represents the fossil energy stock of enterprise i in period t, and $l_t^E(i)$ represents the total amount of labor employed by it. Resource product stock $m_t(i)$ is the state variable of the enterprise, and the resource accumulation equation is:

$$m_{t+1}(i) = (1 - \delta_m)m_t(i) + i_t^M(i)\epsilon_t(i), \tag{8}$$

where δ_m represents the depreciation rate of resource products, $i_t^M(i)$ is the investment of enterprise i in resource products in period t, that is, the purchase of resource products to increase the resource stock, $\epsilon_t(i)$ represents the enterprise's investment efficiency in resource products. For the convenience of analysis, we assume that the resource investment efficiency $\epsilon_t(i)$ is independently and identically distributed (i.i.d.).

Solving the intratemporal problem of the energy firms, we get the optimal labor hiring decision:

$$\max_{l_t^E} \pi_t = \max_{l_t^E} P_t^E e_t - W_t l_t^E \Rightarrow \mathrm{P_t^E A_t^E}(1-\alpha)\left(\frac{\mathrm{m_t}}{\mathrm{l_t^E}}\right)^\alpha = \mathrm{W_t}, \tag{9}$$

so the profit of the energy firms can be expressed as $\pi_t = R_t^M m_t$ where:

$$R_t^M = \frac{\alpha W_t}{(1-\alpha)P_t^E}\left[\frac{(1-\alpha)A_t^E P_t^E}{W_t}\right]^{\frac{1}{\alpha}}. \tag{10}$$

:Energy firm i's budget constraint is：

$$d_t(i) = R_t^M m_t(i) + \frac{b_{t+1}(i)}{R_{ft}} - b_t(i) - P_t^M i_t^M(i), \tag{11}$$

where $b_t(i)$ denotes the total borrowing of firm i, R_{ft} denotes the interest rate, and $d_t(i)$ is the dividend. Following Miao and Wang (2018), we assume that the firms are faced with credit constraints:

$$\frac{b_{t+1}(i)}{R_{ft}} \leq \mu E_t \frac{\Lambda_{t+1}}{\Lambda_t} \bar{V}_{t+1}(m_{t+1}(i), 0), \tag{12}$$

Λ_t is stochastic discount factor (SDF), the expected value of firm is $\bar{V}_{t+1}\left(m_{t+1}(i), b_{t+1}(i)\right) = E_t V_{t+1}\left(m_{t+1}(i), b_{t+1}(i), \epsilon_{t+1}(i)\right)$. The energy firms choose labor hiring, borrowing and resource investment to optimize the discounted value of its dividend flow:

$$\max_{m_{t+1}(i), l_t^E(i), b_{t+1}(i)} E_0 \left[\sum_{t=0}^{\infty} \beta^t \Lambda_t d_t(i)\right]. \tag{13}$$

3.4 The Final Sector

The final product production department includes a series of homogeneous manufacturers $j \in [0,1]$, which use labor, capital and energy to produce final products. We assume that the price of the final product is 1, which is the unit of measurement. According to Carlstrom and Fuerst (2006), the final product production function is set to the CES form：

$$Y_t(j) = A_t \left[\gamma E_t(j)^{\frac{\sigma-1}{\sigma}} + (1-\gamma)\left(K_t(j)^a N_t(j)^{1-a}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{14}$$

Due to the homogeneity of the enterprise and the constant returns to scale of the production function, the production department can be simplified into a competitive representative manufacturer; that is, the individual parameter j is omitted:

$$Y_t = A_t \left[\gamma E_t^{\frac{\sigma-1}{\sigma}} + (1-\gamma)\left(K_t^a N_t^{1-a}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}, \tag{15}$$

where σ is the elasticity of substitution between energy factors and other factors, γ represents the importance of energy factors in production, and a is the proportion of capital in the sum of capital and labor. The capital accumulation equation in the final goods sector is：

$$K_{t+1} = (1-\delta_k)K_t + I_t, \tag{16}$$

The final sector maximizes its discounted profit flow:

$$\max_{K_{t+1}, N_t, E_t} E_0 \sum_{t=0}^{\infty} \beta^t \Lambda_t \Pi_t, \tag{17}$$

where $\Pi_t = Y_t - W_t N_t - P_t^K I_t - P_t^E E_t$. The first order conditions are:

$$W_t = (1-\gamma)(1-a)A_t \left[\gamma E_t^{\frac{\sigma-1}{\sigma}} + (1-\gamma)\left(K_t^a N_t^{1-a}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{1}{\sigma-1}} \left(K_t^a N_t^{1-a}\right)^{-\frac{1}{\sigma}} \left(\frac{K_t}{N_t}\right)^a, \tag{18}$$

$$P_t^E = \gamma A_t \left[\gamma E_t^{\frac{\sigma-1}{\sigma}} + (1-\gamma)\left(K_t^a N_t^{1-a}\right)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{1}{\sigma-1}} E_t^{-\frac{1}{\sigma}}, \tag{19}$$

$$P_t^K = \beta E_t \frac{\Lambda_{t+1}}{\Lambda_t}\left[Y_{K,t+1} + (1-\delta_k)P_{t+1}^K\right], \tag{20}$$

where $\quad Y_{K,t+1}=(1-\gamma)aA_{t+1}\left[\gamma E_{t+1}^{\frac{\sigma-1}{\sigma}}+(1-\gamma)(K_{t+1}^{a}N_{t+1}^{1-a})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{1}{\sigma-1}}(K_{t+1}^{a}N_{t+1}^{1-a})^{-\frac{1}{\sigma}}\left(\frac{K_{t+1}}{N_{t+1}}\right)^{1-a}$.

Note that here the final sector does not consider the production externality of emission.

3.5 The Capital Producer

There is a representative capital producer that uses final output to produce capital goods and maximizes its discounted value:

$$\max_{I_t} E_0\sum_{t=0}^{\infty}\beta^t\Lambda_t D_t^k, \tag{21}$$

where:

$$D_t^K=P_t^K I_t-\left[1+\frac{\Omega_k}{2}\left(\frac{I_t}{I_{t-1}}-1\right)^2\right]I_t, \tag{22}$$

The first order condition is:

$$P_t^K=\left[1+\frac{\Omega_k}{2}\left(\frac{I_t}{I_{t-1}}-1\right)^2\right]+\Omega_k\left(\frac{I_t}{I_{t-1}}-1\right)\frac{I_t}{I_{t-1}}+\beta\Omega_k E_t\frac{\Lambda_{t+1}}{\Lambda_t}\left(\frac{I_{t+1}}{I_t}-1\right)\left(\frac{I_{t+1}}{I_t}\right)^2. \tag{23}$$

3.6 The Carbon Cycle and Production Externality

The energy firms generate emission when they use resources to produce energy, which increases the total pollution S_t. The total pollution accumulation equation is:

$$S_t=(1-\delta_s)S_{t-1}+\phi E_t, \tag{24}$$

where δ_s denotes the depreciation rate of pollution in the environment. Pollution will generate negative externality and reduce the final sector's productivity.

$$A_t=A\big(1-F(S_t)\big), \tag{25}$$

following Golosov et al. (2014), we assume that $1-F(S_t)=exp(-\nu S_t)$.

For the social optimal equilibrium, the final sector should take the externality into account, and the first order condition of energy usage is changed to:

$$\frac{P_t^E}{\phi}-Y_{S,t}=\beta E_t\frac{\Lambda_{t+1}}{\Lambda_t}\left[-\frac{1-\delta_s}{\phi}Y_{E,t+1}+\frac{1-\delta_s}{\phi}P_{t+1}^E\right], \tag{26}$$

where $\quad Y_{S,t}=Ae^{-\nu S_t}\left[\gamma E_t^{\frac{\sigma-1}{\sigma}}+(1-\gamma)(K_t^aN_t^{1-a})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{1}{\sigma-1}}\left\{-\nu\left[\gamma E_t^{\frac{\sigma-1}{\sigma}}+(1-\gamma)(K_t^aN_t^{1-a})^{\frac{\sigma-1}{\sigma}}\right]+\frac{\gamma}{\phi}E_t^{-\frac{1}{\sigma}}\right\}$, $Y_{E,t+1}=Ae^{-\nu S_{t+1}}\left[\gamma E_{t+1}^{\frac{\sigma-1}{\sigma}}+(1-\gamma)(K_{t+1}^aN_{t+1}^{1-a})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{1}{\sigma-1}}\gamma E_{t+1}^{-\frac{1}{\sigma}}$

3.7 Market Clearing

Define aggregate investment $I_t^M=\int i_t^M(i)di$, $L_t^E=\int l_t^E(i)di$. Market clearing conditions include:

Final goods market clearing:

$$Y_t=C_t+\left[1+\frac{\Omega_k}{2}\left(\frac{I_t}{I_{t-1}}-1\right)^2\right]I_t, \tag{27}$$

Labor market clearing:

$$L_t^M+L_t^E+N_t=1, \tag{28}$$

Resource market clearing:

$$M_t^n=I_t^M, \tag{29}$$

Energy market clearing:

$$E_t = \int e_t(i)di, \tag{30}$$

Bond market clearing:

$$\int b_t(i)di = 0. \tag{31}$$

4 Model Solution

We first solve the energy firms' investment problem.

Proposition 1: The expected value of an energy firms is:

$$E_t \frac{\Lambda_{t+1}}{\Lambda_t} \bar{V}_{t+1}(m_{t+1}, b_{t+1}) = Q_t^M m_{t+1} - \frac{1}{R_{ft}} b_{t+1}, \tag{31}$$

and the resource investment follows a trigger policy:

$$i_t^M(i) = \begin{cases} \frac{1}{P_t^M}[(R_t^M + \mu Q_t^M)m_t(i) - b_t(i)], \ \epsilon_t(i) \geq \epsilon_t^* \\ 0, \ \epsilon_t(i) < \epsilon_t^* \end{cases}, \tag{32}$$

where $\epsilon_t^* = \frac{P_t^M}{Q_t^M}$, Q_t^M is Tobin's Q of resource reserves, satisfying an Euler Equation:

$$Q_t^M = \beta E_t \frac{\Lambda_{t+1}}{\Lambda_t}[R_{t+1}^M(1 + \Gamma_{t+1}) + (1 - \delta_m)Q_{t+1}^M + \mu\Gamma_{t+1}Q_{t+1}^M], \tag{33}$$

where $\Gamma_t = \int max\{\epsilon_t/\epsilon_t^* - 1, 0\} dF(\epsilon_t)$ denotes the liquidity premium

The interest rate is determined by:

$$\frac{1}{R_{ft}} = \beta E_t \frac{\Lambda_{t+1}}{\Lambda_t}(1 + \Gamma_{t+1}), \tag{34}$$

and the energy firms' borrowing is given by:

$$\frac{b_{t+1}(i)}{R_{ft}} = \begin{cases} \mu Q_t^M m_t(i), \ \epsilon_t(i) \geq \epsilon_t^* \\ indeterminate, \ \epsilon_t(i) < \epsilon_t^* \end{cases}. \tag{35}$$

The proof of proposition 1 is in Appendix A. Proposition 1 shows that whether an energy company invests depends on its investment efficiency. One unit of investment in resources will bring $\epsilon_t(i)/P_t^M$ units of resource products, and the value of each unit of resource products to the enterprise is Q_t^M, so if and only if $Q_t^M \epsilon_t(i)/P_t^M \geq 1$, that is, the company will choose to invest only when $\epsilon_t(i) \geq \epsilon_t^*$. At the same time, once a company invests, it will use all available resources, that is, it will not pay any dividends, and carry out mortgage loans as much as possible, that is, the total amount of borrowings of the company meets $\frac{b_{t+1}}{R_{ft}} = \mu Q_t^M m_t$. Γ_t represents the liquidity premium in the economy, that is, the net income that unit profit cash flow brings to the enterprise after taking into account heterogeneous investment efficiency: if the enterprise has higher investment efficiency, This unit of cash flow will be used for investment to obtain $\frac{\epsilon_t(i)}{P_t^M}$ units of resource stock and $\frac{Q_t^M}{P_t^M}\epsilon_t$. The net income of $\epsilon_t(i) - 1$; and if the enterprise has low investment efficiency, it will not choose to invest and will not bring any net income. Q_t^M represents the current value of one unit of resource product stock to the enterprise. According to asset pricing theory, Q_t^M

is equal to the discount of all future income of resource products, which mainly includes three parts: First, one unit of resource products can generate R_{t+1}^{M} units of profit. After considering liquidity constraints, The actual value of profit cash flow per unit is $(1+\Gamma_{t+1})$; secondly, the value of resource products after depreciation in the next period will remain $(1-\delta_m)Q_{t+1}^{M}$; at the same time, one unit of resource products as collateral can bring μQ_{t+1}^{M} units of financing, and the net value to the enterprise is $\mu Q_{t+1}^{M}\Gamma_{t+1}$.

By aggregating the individual investment equation we can get the aggregate resource investment:

$$I_t^M = \frac{1}{P_t^M}[\alpha P_t^E E_t + \mu Q_t^M M_t]\big(1-F(\epsilon_t^*)\big), \tag{36}$$

where $[\alpha P_t^E E_t + \mu Q_t^M M_t]$ denotes the intensive margin of investment: if a firm wants to investment, it has two resources: the revenue from resource reserves $\alpha P_t^E E_t$和 and the borrowing $\mu Q_t^M M_t$. The term $\big(1-F(\epsilon_t^*)\big)$ denotes the extensive margin: only firms with $\epsilon_t(i) \geq \epsilon_t^*$ will choose to invest. Therefore, without considering the price effect, changes in financing constraints μ will affect the total investment in resource products in the economy from two aspects: on the extensive margin, relaxing financing constraints will lead to better resource allocation, that is, the choice of investment There are fewer enterprises (ϵ_t^* increases); at the intensive margin, the relaxation of financing constraints improves the financing capabilities of enterprises, making more energy available to enterprises that wish to invest. We assume that $\epsilon_t(i)$is independently and identically distributed, so the enterprise is homogeneous ex-ante and heterogeneous ex-post. Before the investment decision is made, the resources available to any enterprise are, on average, the same.

The aggregate resource reserve accumulation equation is:

$$M_{t+1} = (1-\delta_m)M_t + \omega(\epsilon_t^*)I_t^M, \tag{37}$$

where $\omega_{\epsilon_t^*} = \frac{\int_{\epsilon>\epsilon_t^*}\epsilon dF}{1-F(\epsilon_t^*)}$ denotes the average resource investment efficiency in the economy.

Proposition 2：The equilibrium system is:

$$Y_t = A_t\left[\gamma E_t^{\frac{\sigma-1}{\sigma}} + (1-\gamma)(K_t^a N_t^{1-a})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}},$$

$$K_{t+1} = (1-\delta_k)K_t + I_t,$$

$$W_t = (1-\gamma)(1-a)A_t\left[\gamma E_t^{\frac{\sigma-1}{\sigma}} + (1-\gamma)(K_t^a N_t^{1-a})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{1}{\sigma-1}}(K_t^a N_t^{1-a})^{-\frac{1}{\sigma}}\left(\frac{K_t}{N_t}\right)^a,$$

$$P_t^E = \gamma A_t\left[\gamma E_t^{\frac{\sigma-1}{\sigma}} + (1-\gamma)(K_t^a N_t^{1-a})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{1}{\sigma-1}} E_t^{-\frac{1}{\sigma}},$$

$$P_t^K = \beta E_t\frac{u'(C_{t+1})}{u'(C_t)}\left[Y_{K,t+1} + (1-\delta_k)P_{t+1}^K\right],$$

$$P_t^K = \left[1+\frac{\Omega_k}{2}\left(\frac{I_t}{I_{t-1}}-1\right)^2\right] + \Omega_k\left(\frac{I_t}{I_{t-1}}-1\right)\frac{I_t}{I_{t-1}} + \beta\Omega_k E_t\frac{u'(C_{t+1})}{u'(C_t)}\left(\frac{I_{t+1}}{I_t}-1\right)\left(\frac{I_{t+1}}{I_t}\right)^2,$$

$$S_t = (1-\delta_s)S_{t-1} + \phi E_t,$$

$$A_t = A\exp(-\nu S_t),$$

$$W_t = \psi A_t^M P_t^M (L_t^M)^{\psi-1},$$

$$Q_t^M = \beta E_t \frac{u'(C_{t+1})}{u'(C_t)} \left[\alpha \frac{P_{t+1}^E E_{t+1}}{M_{t+1}} (1 + \Gamma_{t+1}) + (1 - \delta_m) Q_{t+1}^M + \mu \Gamma_{t+1} Q_{t+1}^M \right],$$
$$\frac{1}{R_{ft}} = \beta E_t \frac{u'(C_{t+1})}{u'(C_t)} (1 + \Gamma_{t+1}),$$
$$I_t^M = \frac{1}{P_t^M} [\alpha P_t^E E_t + \mu Q_t^M M_t] \big(1 - F(\epsilon_t^*)\big),$$
$$M_{t+1} = (1 - \delta_m) M_t + \omega(\epsilon_t^*) I_t^M,$$
$$W_t = (1 - \alpha) P_t^E A_t^E M_t^\alpha (L_t^E)^{-\alpha},$$
$$L_t^M + L_t^E + N_t = 1,$$
$$Y_t = C_t + \left[1 + \frac{\Omega_k}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \right] I_t,$$
$$I_t^M = A_t^M (L_t^M)^\psi,$$
$$E_t = A_t^E M_t^\alpha (L_t^E)^{1-\alpha}.$$

Note that the system above is the *competitive equilibrium*, if we consider the *social optimal equilibrium*, we should change the first order condition for energy use.

5 Quantitative Analysis

In this section, we discuss the quantitative properties of the model. We first discuss how to solve the steady state of the model, then calibrate the parameters and discuss the model's steady state and dynamic properties under different policies.

5.1 Steady State Solution

From the first order condition of the capital producer, we immediately get that in the steady state $P_K = 1$, then:

$$Y_K = (1-\gamma) a A e^{-\nu S} \left[\gamma E^{\frac{\sigma-1}{\sigma}} + (1-\gamma)(K^a N^{1-a})^{\frac{\sigma-1}{\sigma}} \right]^{\frac{1}{\sigma-1}} (K^a N^{1-a})^{-\frac{1}{\sigma}} \left(\frac{K}{N} \right)^{a-1}$$
$$= \frac{1 - \beta(1 - \delta_k)}{\beta}. \quad (38)$$

To solve for the steady state we should solve the price system (W, P^M, P^E). First consider the exploration sector. Given the prices (W, P^M) we get:

$$L^M = \left(\frac{W}{\psi A^M P^M} \right)^{\frac{1}{\psi - 1}}, \quad (39)$$

$$M^n = A^M (L^M)^\psi. \quad (40)$$

Then consider the energy sector. In the steady state the resource stock remains unchanged:

$$\omega(\epsilon^*) I^M = \delta_m M, \quad (41)$$

then we can solve for the resource reserve return:

$$\alpha \frac{P^E E}{M} = \frac{1}{1 - F(\epsilon^*)} \frac{I^M}{M} P^M - \mu \frac{P^M}{\epsilon^*}, \quad (42)$$

Plug this result into the resource investment equation, and we get:

$$\frac{P^M}{\epsilon^*} = \beta \left[\alpha \frac{P^E E}{M} \big(1 + \Gamma(\epsilon^*)\big) + \big(1 - \delta_m + \mu \Gamma(\epsilon^*)\big) \frac{P^M}{\epsilon^*} \right]. \quad (43)$$

and we can solve for the cutoff investment efficiency ϵ^*:

$$\frac{1}{\epsilon^*} = \beta\left[\left(\frac{1}{1-F(\epsilon^*)}\frac{\delta_m}{\omega(\epsilon^*)} - \mu\frac{1}{\epsilon^*}\right)\left(1+\Gamma(\epsilon^*)\right) + \left(1-\delta_m+\mu\Gamma(\epsilon^*)\right)\frac{1}{\epsilon^*}\right], \tag{44}$$

Note that the equation above shows that the cutoff investment efficiency is unrelated to the steady-state price system, and is only determined by the model parameters and credit constraint μ.

Corollary 1: A tightening financial policy (reduce μ) or a tightening industrial policy (increase δ_m) will both cause a decrease in ϵ^* and worsen the resource allocation within sector.

Now we consider the final sector. In a competitive steady state, we have:

$$(1-\gamma)aAe^{-\nu S}\left[\gamma\left(\frac{E}{K^a N^{1-a}}\right)^{\frac{\sigma-1}{\sigma}} + (1-\gamma)\right]^{\frac{1}{\sigma-1}}\left(\frac{K}{N}\right)^{1-a} = \frac{1-\beta(1-\delta_k)}{\beta}, \tag{45}$$

$$(1-\gamma)(1-a)Ae^{-\nu S}\left[\gamma\left(\frac{E}{K^a N^{1-a}}\right)^{\frac{\sigma-1}{\sigma}} + (1-\gamma)\right]^{\frac{1}{\sigma-1}}\left(\frac{K}{N}\right)^{a} = W, \tag{46}$$

$$\gamma Ae^{-\nu S}\left[\gamma\left(\frac{E}{K^a N^{1-a}}\right)^{\frac{\sigma-1}{\sigma}} + (1-\gamma)\right]^{\frac{1}{\sigma-1}}\left(\frac{E}{K^a N^{1-a}}\right)^{-\frac{1}{\sigma}} = P^E, \tag{47}$$

where $S = \frac{\phi}{\delta_s}E$. Given the prices (W, P^E), we can solve for (E, K, N) from the above system, and labor market clear implies $L^E = 1 - N - L^M$。

Proposition 3: When we consider the production externality, the energy price will be lower. In a competitive equilibrium, the energy price is determined by:

$$P^E = Y_E, \tag{48}$$

After considering the production externality, the energy pricing equation becomes:

$$P^E = Y_E - \frac{\phi}{1-\beta(1-\delta_s)}\mathcal{E}, \tag{49}$$

where Y_E denotes the marginal profitability of energy, and $\mathcal{E}$ represents the production externality.

The proof of proposition 3 is in Appendix A.

Lastly, using the resource market clearing condition, energy market clearing condition and FOC for the energy sector, we get a system of three equations for three unknowns:

$$W = (1-\alpha)P^E A^E M^\alpha (L^E)^{-\alpha}, \tag{50}$$

$$E = A^E M^\alpha (L^E)^{1-\alpha}, \tag{51}$$

$$\frac{1}{P^M}[\alpha P^E E + \mu Q^M M](1-F(\epsilon^*)) = M^n. \tag{52}$$

According to the above system, the steady state of the model under any parameters can be solved. In particular, this article discusses the impact of different policy interventions on carbon emissions and the value $P_t^M M_t$ of resource products M_t, thereby analyzing the impact of the bursting of the "carbon bubble" on the economy under different policy emission reduction scenarios, and how to adjust the policy bundle to make carbon bubbles burst more smoothly, reducing welfare losses.

5.2 Parameterization and Calibration

Since this article studies the green transformation of the economy under policy conditions, which is a mid-to-long-term issue, one period is 5 years, corresponding to $\beta = 0.97^5$. Standardize the productivity under the benchmark conditions of different departments and take $A = A^M = A^E = 1.\delta_k$ and δ_m are the depreciation rates of two types of assets within 5 years. We choose $\delta_k = \delta_m = 0.3$, which means that the annual depreciation of the two types of assets is 7%, consistent with the value in the literature. a and α represent the proportion of labor in the energy sector and final goods sector. According to the calibration of Carlstrom and Fuerst (2006) and the estimation of Dissou et al. (2021), this article takes $a = \alpha = 0.5$, which represents labor income. The proportion is about 50%. μ represents the tightness of financing constraints. This paper takes the commonly used value $\mu = 0.7$ in the literature. η represents the degree of dispersion of the investment efficiency of enterprises in the energy sector. We refer to Dong and Xu (2022), and take $\eta = 2.5$. σ represents the elasticity of substitution between energy and capital-labor combinations in the production process. According to Kim and Loungani (1992), we use $\sigma = 0.59$.

γ determines the proportion of energy consumption in total GDP at steady state $P^E E/Y$. According to the U.S. Energy Information Administration (EIA), the ratio of U.S. energy consumption to total output is about 6%, and China's energy intensity in 2021 is about 1.5 times that of the United States (the energy intensity of China's GDP is 2.13kWh/USD, and the U.S.'s is 1.48kWh/USD). At the same time, the energy prices in China and the United States are similar (taking the electricity price most commonly used in industrial production as an example, the average electricity price in the United States in 2021 is 0.87 CNY/kWh (0.11 US dollars/kWh), and China's industrial electricity price is 0.725 CNY/kWh during the normal periods, and 1.025 CNY/kWh during peak hours, close to the United States), so the corresponding proportion of energy in total output $P^E E/Y$ is about 1.5 times that of the United States, or about 9%. This article takes $\gamma = 0.04$ to ensure that the proportion of energy consumption in total GDP at steady state $P^E E/Y$ is about 9%.

ψ determines the proportion of added value of the energy extraction sector in GDP at steady state $P^M M^n/Y$. Fossil energy includes oil, natural gas and coal. According to the 2020 input-output table, we identify the "coal mining and processing sector" and the "oil and natural gas extraction sector" as natural resource extraction sectors. At the same time, some products from the "petroleum, coking products and nuclear fuel sector" should also belong to the natural resource extraction. The "coal mining and processing sector" and the "oil and natural gas extraction sector" accounted for 1.8% of the total output value, and the total output value including "petroleum, coking products and nuclear fuel processed products" accounted for 2.8% of the GDP. We select $\psi = 0.9$, so that in the steady state, the total output value of the energy extraction sector accounts for approximately 2.4% of GDP, consistent with reality.

ϕ and δ_s determines the generation and accumulation rate of pollution in the air. According to Golosov et al. (2014), we take $\phi = 0.5$, which corresponds to the baseline coefficient ϕ_0 of the depreciable part of carbon emissions. According to Heutel (2012), the half-life of carbon dioxide is 83 years, and the corresponding annual depreciation is 0.008, so the 5-year depreciation is 0.04, that is, $\delta_s = 0.04$. For the production externality parameter ν, we set $\nu = 0.04$ according to Golosov et al. (2014) under the baseline state. The values of all parameters and calibration standards are shown in Table 1:

Table 1 Parameter Values

Parameters	Value	Target
A	1	Normalization
A^M	1	Normalization
A^E	1	Normalization
δ_k	0.3	Standard
δ_m	0.3	Standard

δ_s	0.04	Heutel（2012）
γ	0.04	Energy Consumption
σ	0.59	Kim and Loungani（1992）
a	0.5	Standard
β	0.97[5]	Standard
ϕ	0.5	Golosov et al.（2014）
ψ	0.9	Extraction Sector Output
α	0.5	Standard
η	2.5	Dong and Xu（2022）
ν	0.04	Golosov et al.（2014）

5.3 Steady State Analysis

In this section we analyze the steady state of the model. We fix the externality parameter $\nu = 0.04$, change the policy variables, and discuss the emission reduction effects brought by different policies and the corresponding steady-state output and consumption losses. At the same time, for each type of policy, we calculate the change in the total value $P^M M$ of fossil energy reserves M at steady state, and defines it as the "carbon bubble" in the current value of fossil energy: in the context of policy constraints on emission, existing fossil energy reserves cannot exert their current value, so their value will shrink significantly, causing the assets of energy companies to be stranded. At the same time, due to the existence of financing constraints, the stranded assets of energy companies will lead to a decline in their financing capabilities and inhibited production, which will then affect the output and welfare of the overall economy, that is, the welfare losses caused by the bursting of the "carbon bubble".

In this paper, we discuss three types of policies: financial policy, industrial policy and tax policy. Financial policy is the government's changes in μ. Tightening financing constraints will reduce the financing capabilities of energy sector enterprises and reduce investment demand for fossil energy reserves, thus causing the value of fossil energy reserves to shrink. Industrial policy refers to government changes to δ_m. In the context of "carbon peak" and "carbon neutrality", the government is accelerating the elimination of low-level production capacity. In the model of this article, it can be regarded as limiting the energy sector's reserve of fossil energy capital, thus forcing the final product sector to reduce the use of fossil energy and increase the usage of capital-labor combination products that do not produce emissions, that is, to carry out low-emission transformation. A higher δ_m corresponds to a lower steady-state fossil energy reserve M and lower investment efficiency (Corollary 1), which may lead to a lower total value of fossil energy. In the tax policy section, we discuss three categories of policies: taxes on energy purchases by the final goods sector, taxes on energy sector operating income, and taxes on energy sector purchases of resource reserves. For each type of tax policy, this article calculates the emission reduction effects and welfare effects under different policy intensities and compares them.

5.3.1 The Impact of Credit Tightening

We first consider the impact of changes in credit constraint μ, and the results are shown in Figure 1.

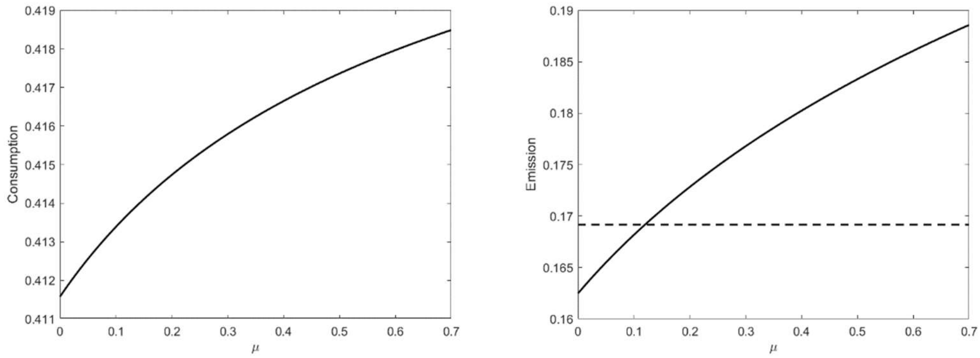

Figure 1: The Impact of Credit Tightening

The left graph in Figure 1 shows the changes in steady-state consumption as financing constraints tighten. The right picture shows the changes in steady-state energy use as financing constraints tighten. The dotted line represents the baseline case ($\mu = 0.7,\ \nu = 0.04$) the socially optimal level of carbon emissions. It can be seen that tightening financing constraints can effectively reduce carbon emissions: reducing μ from 0.7 to 0.4 can bring carbon emissions to the optimal level under the baseline situation. However, under the model parameters of this article, the emission reduction effect brought by tightening financing constraints is limited: even if the financing constraints are completely tightened to $\mu = 0$, only about 14% of emission reduction can be achieved, and the corresponding emissions intensity decrease is approximately 12%. At the same time, reducing μ may lead to a decrease in consumption, thus causing welfare losses in the steady state. In the model of this paper, the tightening of financing constraints affects production and investment in the energy sector in three aspects: firstly, a smaller μ limits the available funds that companies can use to reserve fossil energy at the intensive margin; secondly, a smaller μ limits the available funds that companies can use to reserve fossil energy; in the meantime, according to Corollary 1, tightening financing constraints will lead to a decrease in critical investment efficiency ϵ^*, that is, in the presence of financing constraints, the tightening of financial policies worsens the resource misallocation within the department, leading to a decrease in overall investment efficiency. At the same time, the decline of ϵ^* increases the total number of enterprises choosing to invest on the extensive margin, and there is a certain crowding-in effect. The three effects work together to bring lower investment and energy production, which in turn leads to the suppression of final product production and a decline in consumption, resulting in steady-state welfare losses.

At the same time, tightening financing constraints has inhibited the financing, investment and production behavior of enterprises in the energy sector, which may lead to a decrease in the price of fossil energy reserves P^M, causing stranding of the assets of energy enterprises. According to the definition in practice, this article defines the reduction in the value of fossil energy reserves $P^M M$ after μ decreases compared to its original value $P_0^M M_0$ as "carbon bubble", and calculates the size of the "carbon bubble" under different μ, The results are shown in Figure 2. As the emission reduction effect increases, the size of the "carbon bubble" is also increasing. To achieve the final 14% carbon emission reduction effect, the corresponding "carbon bubble" size will be more than 30% of the original asset value.

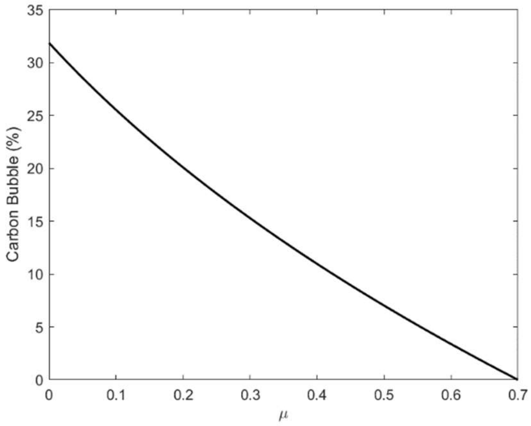

Figure 2: Credit Tightening and the "Carbon Bubble"

5.3.2 The Impact of Tightening Industrial Policy

This section discusses environmental industrial policy, i.e. the impact of changing δ_m on the steady state. The government can restrict energy companies from storing fossil energy through administrative orders, which is represented in the model by regulating the depreciation rate \delta_m of fossil energy reserves. In this article, δ_m changes on $[0.3, 0.7]$, which corresponds to an annual depreciation rate of 7%-22%. The impact of changes in δ_m on the steady state is discussed. The results are shown in Figure 3:

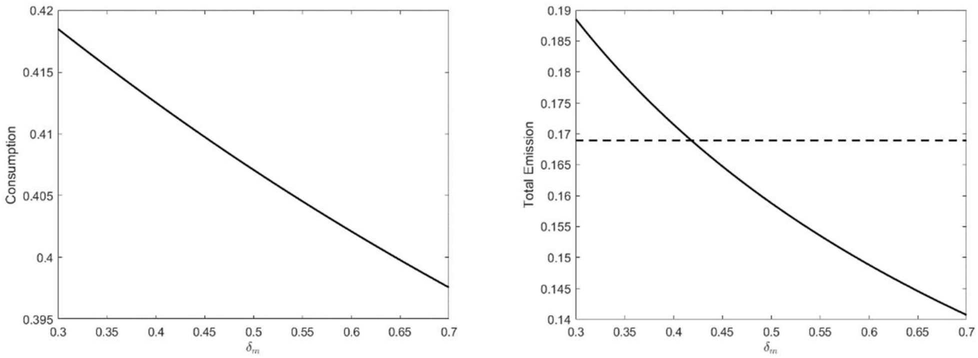

Figure 3: The Impact of Industrial Policy

Similar to the results of tightening financing constraints, higher δ_m will inhibit the energy sector's accumulation of fossil energy reserves, thereby inhibiting its energy production and reducing total carbon emissions. According to our simulation, increasing δ_m from 0.3 to about 0.41 can reduce carbon emissions to the socially optimal value under the baseline. At the same time, according to Corollary 1, tightening industrial policies will also increase the degree of resource misallocation and cause a loss of investment efficiency. In the steady state, a higher depreciation rate δ_m will bring lower output and consumption, resulting in welfare losses. Compared with tightening financial constraints, the tightening of industrial policies brings greater room for emission reduction. Raising δ_m to 0.7 (corresponding to approximately 22.4% of annual depreciation of fossil energy reserves) can achieve a 25% emission reduction. The corresponding emissions The intensity drop is approximately 19%. Similarly, the change range of fossil energy value $P^M M$ under different industrial policy intensities δ_m can be calculated, and then the size of the "carbon bubble" corresponding to emission reduction can be calculated. The results are shown in Figure 4. Similar to the previous results, stronger industrial policies and higher emission reductions correspond to a larger "carbon bubble". When δ_m rises to 0.7, the total value of fossil energy reserves in the economy will shrink by more than 50%, and according to financial According to the accelerator theory, fossil reserves are an important factor affecting the financing of energy companies. Therefore, the decline in their value will further restrict the financing, production, and investment behaviors of energy companies, thereby further inhibiting the use of energy and causing a decline in total output and total consumption.

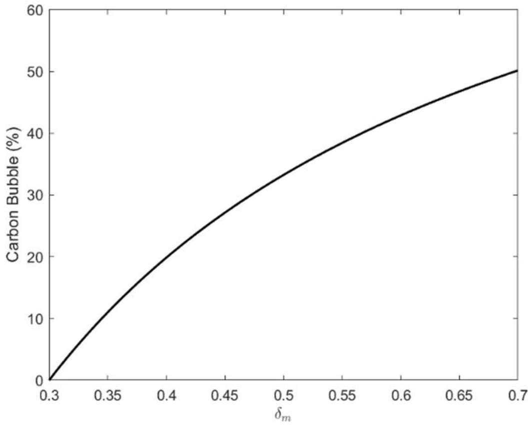

Figure 4: Industrial Policy and the "Carbon Bubble"

5.3.3 The Impact of Taxes

In this section we discuss the impact on taxes on the steady state. We mainly discuss three types of taxation: tax on energy purchase of the final sector (energy tax), tax on the energy firms' income (energy firm tax) and tax on the resource purchase of the energy firms (resource tax). We keep all the tax rates below 60%.

Different from the two policies we studied above, we can prove that the price policies will not affect the resource allocation with in sector:

Proposition 4： The taxation policies discussed in this paper will not change ϵ^*.

The economic intuition of Proposition 4 is as follows: tax policy is essentially a price policy and therefore has the same effect on all enterprises in the energy sector and is not affected by heterogeneity among enterprises. In contrast, financial policies and industrial policies have heterogeneous effects on companies that choose to invest and those that do not: only companies with higher investment efficiency will choose to invest, and their decisions will be subject to financing constraints μ and fossil energy The impact of reserve depreciation rate δ_m. Therefore, financial policies and industrial policies will affect enterprises with higher investment efficiency to a greater extent, resulting in more serious resource misallocation.

We keep all other parameters and change the tax rates between 0 and 0.6. The results are shown in Figure 5:

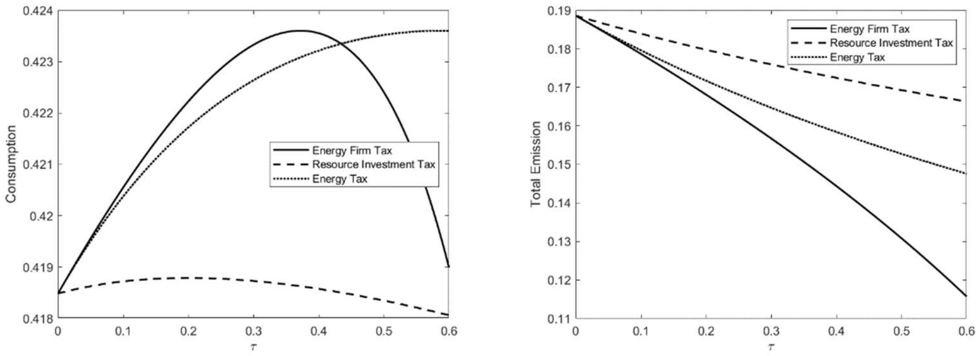

Figure 5: The Impact of Taxation

It can be seen from the figure that as taxes increase, total consumption shows an inverted "U"-shaped trend, and there is an optimal tax rate. In the model of this article, taxation has two effect: on the one hand, taxation can offset the effects of negative externalities in production to a certain extent, bringing energy use closer to the social optimal level, thereby increasing output and consumption; On the one hand, the existence of taxes distorts the production incentives of the energy sector and inhibits the production of the energy sector. Therefore, higher taxes will cause the shrinkage of the energy sector, thereby reducing output and consumption. The two work together to create an inverted "U"-shaped consumption curve. Comparing different tax policies, we find that taxing the purchase of energy by the final goods sector and taxing the total income of the energy sector can achieve the same maximum consumption, while taxing the purchase of fossil energy reserves by the energy sector can achieve relatively different optimal consumption. Low. This is because neither a tax on the total revenue of the energy sector nor an energy tax on the final goods sector affects the critical investment efficiency at steady state ϵ^* and the Tobin Q value of fossil energy reserves $Q^M = P^M/\epsilon^*$, thus not causing any resource misallocation. At the same time, due to the equivalence of taxes levied on buyers and sellers, energy sector income taxes and final sector energy taxes can achieve completely consistent steady-state policy effects, that is, the same carbon emission reductions correspond to the same steady-state consumption level. However, when taxing the purchase of fossil energy reserves by energy sector companies, the equation that satisfies the critical investment efficiency of the energy sector is modified to:

$$\epsilon_t^* Q_t^M = (1+\tau)P_t^M, \tag{53}$$

Note that the price received by the exploration and production sector at this time is still P_t^M, but the price received by the energy sector must take taxes into account, so higher taxes may increase the Tobin Q value at steady state, allowing energy sector companies to obtain Higher financing is used to reserve fossil energy stocks, so it can only bring about a smaller improvement in welfare than the other two policies. Differences between different tax policies can also be expressed by their emission reduction effects. When the tax rate is limited to no more than 60%, model simulations show that the energy sector profit tax has the best emission reduction effect. A 60% tax on energy sector income can reduce emissions by 35% and reduce the emission intensity of output by about 28%; The emission reduction effect of the final sector energy tax is second. A 60% ad valorem tax on energy purchased by the final sector can reduce emissions by 20%, corresponding to an 18% reduction in emission intensity. The fossil energy investment tax has the worst emission reduction effect. A 50% ad valorem tax on fossil energy reserves would only reduce emissions by 11% and reduce emissions intensity by 8%.

We also calculate the changes in resource reserve value $P^M M$ under different tax rates, and compare the scale of "carbon bubbles", and the results are shown in Figure 6:

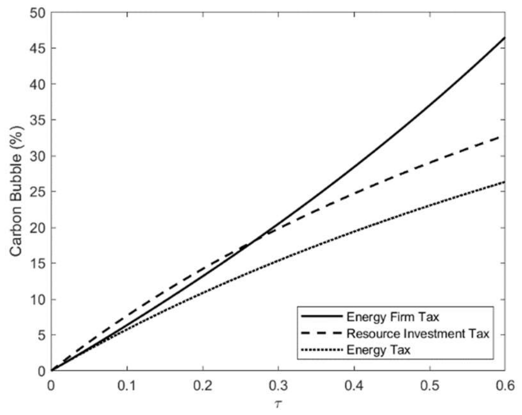

Figure 6: Taxation and the "Carbon Bubble"

It can be seen that under the same tax rate, the energy sector profit tax corresponds to the largest "carbon bubble" while reducing emissions. When $\tau = 60\%$, the corresponding "carbon bubble" size is close to 50% of its original value. The size of the "carbon bubble" corresponding to the energy investment tax is smaller, which is about 35% of its original value; the carbon bubble corresponding to the final sector energy tax is the smallest, and the carbon bubble corresponds to the 60% energy tax is only 25% of its original value. Relatively speaking, taxing companies in the energy sector to reduce investment in fossil energy reserves will have limited emission-reduction effects while create a relatively large carbon bubble. Compared with energy taxes and energy firm taxes that directly correct externalities, resource investment tax is the second-best option.

5.3.4 Comparing the Steady-State Effect of Policies

Now we can compare the steady-state effects of different policies. In particular, the "benefit" of the policy is defined as the steady-state emission reduction, while the "cost" of the policy is defined as the loss of consumption or the size of the "carbon bubble". Since the previous section has shown that the effect of the fossil energy investment tax is worse than the energy tax and energy firm tax, and there is no structural difference between the latter two taxes, we only consider energy sector tax here. Under different emission reduction effects, the changes in consumption at steady state and the size of the corresponding carbon bubble are are shown in Figures 7 and 8.

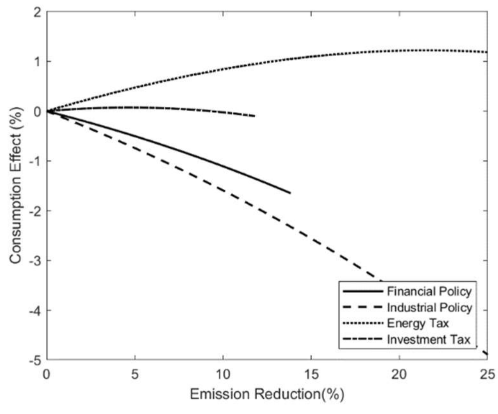

Figure 7: Steady-State Consumption and Emission Reduction

Among the three types of policies, tax policy will not bring about additional misallocation of resources among enterprises within the department, so it has the smallest impact on economic efficiency and corresponds to the highest steady-state consumption. Industrial policy δ_m directly affects the accumulation of fossil energy reserves, so it has a greater impact on economic efficiency and causes greater consumption losses. According to our simulation, to achieve a 25% emission reduction effect, the use of industrial policies will bring about a steady state of about 5% consumption losses. Financial policy has a smaller impact on economic efficiency than industrial policy, but its emission reduction effect is the most limited among the three types of policies, since it can only achieve a maximum emission reduction of about 14%; the steady-state efficiency of tax policy is higher, but higher emission reduction requires unreasonably high tax rates: to achieve a 25% emission reduction, a tax rate of about 40% needs to be added to the existing basis. This tax rate is not reasonable considering the actual situation.

Figure 8 shows the size of the "carbon bubble" corresponding to given emission reduction targets under different policy scenarios. Compared with financial and industrial policies, energy tax has a smaller impact on economic efficiency, so it has a limited impact on the value of fossil energy reserve assets, and the corresponding "carbon bubble" is also smaller. In comparison, financial policy has a greater impact on prices and may lead to a larger "carbon bubble" with the same emission reduction effect. In addition, the investment tax for the energy sector will directly reduce the market price of fossil energy reserves P^M, and will also create a large "carbon bubble"

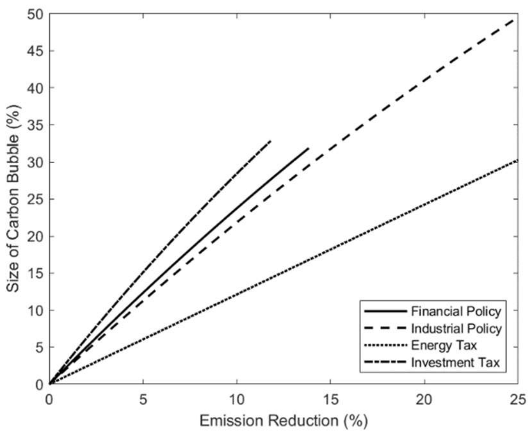

Figure 8: Emission Reduction and the "Carbon Bubble"

5.4 Dynamic Analysis

In this section, we compare of the dynamic effects of different policies. To ensure the comparability of policies, we calculate the transfer paths corresponding to different single policies under the same emission reduction effect. In particular, we calculate the transfer paths corresponding to different policies when reducing emissions by 10%.

We first consider the comparison of different tax policies. Previous analysis has shown that to get a 10% emission reduction, the corresponding tax rates are: energy tax $\tau = 0.2291$, energy firm tax $\tau = 0.1869$ and resource investment tax $\tau = 0.4854$. The transition paths under different tax policies are shown in Figure 9. We find that on the transfer path, taxing enterprises in the energy sector and taxing energy purchases in the final goods sector can achieve the same effect. In contrast, the imposition of an investment tax will lead to a greater decline in short-term fossil energy investment demand, resulting in more dramatic labor market flows, that is, the outflow of labor from the exploration and extraction sector, and lead to greater increases in output and consumption. After an initial boom, labor gradually returns to the resource sector, and output and consumption decline to new steady-state levels. Steady-state consumption is lower when an investment tax is applied. It can be seen from the transfer path that although the adoption of investment tax corresponds to lower steady-state consumption, consumption rises more in the early stage of the transfer path. In the following analysis, we use τ_e to denote energy tax (or energy firm tax), and τ_m to represent resource investment tax.

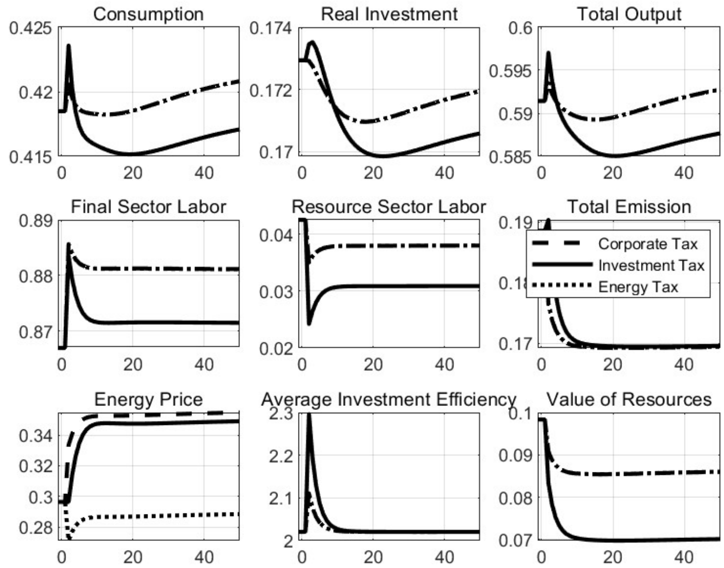

Figure 9: Transition Paths Under Different Tax Policies

We then compare tax policy with other policies. To ensure a 10% emission reduction, the corresponding policy intensities are：$\mu = 0.1302$、$\delta_m = 0.4126$、$\tau_e = 0.1869$、$\tau_m = 0.4854$, and the corresponding transition paths are shown in Figure 10. It can be seen that when financial policies and tax policies are adopted, changes in the price system after the emergence of the policies will lead to a short-term flow of labor from other sectors to the final sector, thereby bringing about short-term output, consumption and physical capital. Rapid increase in investment. After the initial increase in consumption brought about by labor mobility, the rise in energy prices, the fall in wages, and the decline in total energy use caused output and consumption to slowly decline to a new steady-state level, and the labor force in the corresponding sectors was reallocated to the new steady-state level. In contrast, when industrial policies are adopted, the increase in δ_m forces the energy sector to increase its demand for fossil energy extraction. As a result, the labor force in the exploration and mining sector slowly increases after the policy is imposed, and the corresponding labor force in the final product sector slowly decreases. There will be rapid short-term labor market flow, and the corresponding output, consumption, and physical capital investment will slowly decline to new steady-state levels. When tax policies are adopted, enterprises with relatively higher investment efficiency in the short term can accumulate more resources, so the average investment efficiency will increase in the short term, and then slowly decrease to the normal steady-state value; when financial policies are adopted, the decline in μ will immediately drive the critical investment efficiency and the average investment efficiency to decline; while when industrial policy is adopted, the average investment efficiency will slowly shift to the final steady-state level after a small short-term decline. On the transition path, when using financial policy, there may be a temporary rise in energy use in the first period. This is because the output of the final goods sector increases after labor flows into the final goods sector, and the demand for energy increases. After the first period, energy use decreases. The sectoral supply decline effect dominates, with energy use and emissions gradually falling to new steady-state values. According to model simulations, adopting tax policies has the fastest emission reduction effect, reducing emissions by about 6.2% in one period (i.e. 5 years), and then reaching a new steady-state level after about 8 periods (40 years). In contrast, the use of financial or industrial policy can only achieve about 4% emission reduction in the early stage of policy implementation, and then it will take about 10 periods (50 years) to reach a new steady-state level. On the transfer path, the total value of fossil energy reserves $P_t^M M_t$ will gradually decrease. In comparison, the total value of fossil energy reserves decreases the least when the energy use tax policy is used, and the most when the energy investment tax policy is used.

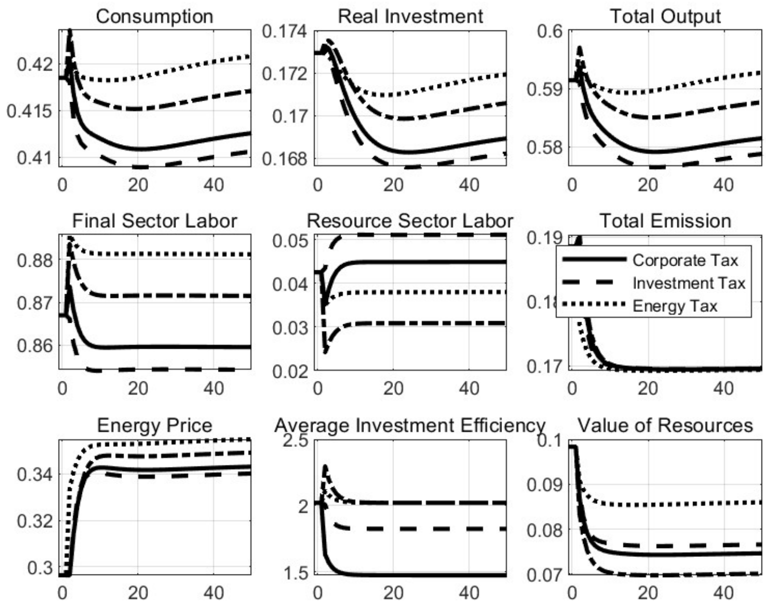

Figure 10: Transition Paths Under Different Policies

Based on the transition paths, we can calculate the welfare effect of the green transition. We define the total welfare on the transition path as follows:

$$W = \sum_{t=1}^{\infty} \beta^t \, log(C_t), \tag{54}$$

Following Lucas (1986), we use consumption equivalent to evaluate the welfare effect of the green transition:

$$\sum_{t=1}^{\infty} \beta^t \, log\big((1 + ce)C_{ss}\big) = W, \tag{55}$$

where ce denotes the welfare effect of green transition. The comparison of welfare effects is shown in Figure 11:

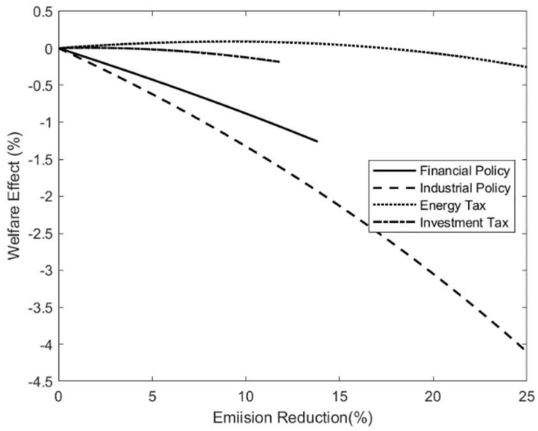

Figure 11: Welfare Effect of Different Policies

Figure 11 shows that from a welfare perspective, using tax policy to reduce emissions is better than using financial policy and industrial policy. In the case of using tax policies to reduce emissions, since the resource distribution among enterprises within the department is not worsened, consumption may increase along the transfer path, and emission reductions can bring about a welfare increase equivalent to a 0.2% increase in consumption. Among the tax policies, energy taxes can generate higher welfare effects and a larger room for emission reductions than the investment taxes. Using financial policies or industrial policies to reduce emissions may cause welfare losses in the long term. Using industrial policies to suppress the accumulation of fossil energy reserves in the energy sector can effectively reduce carbon emissions, but it will bring about greater welfare loss: if only industrial policies are used to reduce emissions, the welfare loss caused by achieving a 25% emissions reduction is equivalent to a permanent drop in consumption of approximately 4%.

5.5 Summary

We summarize the emission reduction and welfare effects of different policies in Table 2:

Table 2: Comparison of Different Policies

Policy		Policy Space	Steady-State Welfare	Dynamic Welfare	Carbon Bubble
Financial Policy		Small	Medium	Medium	Medium
Industrial Policy		Large	Low	Low	Medium
Tax Policy	Energy Tax	Medium	High	High	Small
	Firm Tax	Medium	High	High	Small

In terms of policy space, the space for resource investment tax and financial policy is small and can only achieve less than 15% emission reduction (in the case of $\mu \geq 0$ and $\tau \leq 0.6$). The industrial policy has the largest policy space, by increasing δ_m from 0.3 to 0.7 (corresponding to an increase in annual depreciation from 6.9% to 22.4%) we can reduce carbon emissions by more than 25%. Emission reductions of more than 25% can be achieved through tax increases. However, according to model simulations, it is necessary to increase the tax rate by more than 40% on the existing basis. From the perspective of steady-state welfare, the use of financial policies and industrial policies to reduce emissions will lead to steady-state consumption decline and welfare losses, and industrial policies will cause greater welfare losses. The adoption of energy taxes can lead to higher steady-state consumption. From the perspective of dynamic welfare effects, the use of financial policies and industrial policies to reduce emissions will lead to long-term welfare decline. Between them, the use of industrial policies to reduce emissions will cause greater long-term welfare losses. The use of tax policies to reduce emissions may increase welfare in the long term. In terms of the size of the "carbon bubble", the "carbon bubble" corresponding to the use of energy tax or energy corporate tax for emission reduction is the smallest, that is, the total value of fossil energy reserves $P^M M$ decreases the least when the same emission reduction effect is achieved; the use of financial policies and industrial policies will generate a large “carbon bubble”, among which the "carbon bubble" corresponding to financial policies is larger; the "carbon bubble" corresponding to the adoption of resource investment tax for emission reduction is the largest because the existence of resource investment tax directly reduces the Fossil energy prices.

6 Conclusion

In this paper, we build a model with financial frictions and heterogeneous energy companies and discuss the emission reduction effects and economic impacts of different policies. The exploration and mining sector produces fossil energy reserves; heterogeneous energy companies invest in fossil energy reserves and use fossil energy and labor to produce energy, facing financing constraints based on corporate value; the representative final product sector uses energy, capital and labor to produce final products. The production of energy comes with the generation of emissions, which accumulate pollution and reduce productivity. This article focuses on the impact of the bursting of the “carbon bubble” on economic production and efficiency in the context of policy regulations. Specifically, fossil energy reserves are an important asset for energy companies that supports their company value. The implementation of policy emission reduction targets will lead to a decline in the market's expected value of fossil energy reserves, which will then affect their current prices and the financing capabilities of energy companies, and ultimately affect the operation of the overall economy. This article defines the decline in the value of fossil energy reserves caused by emission reduction policies as the bursting of the "carbon bubble", and analyzes the size of the "carbon bubble" corresponding to different policies and the welfare losses caused by the bursting of the "carbon bubble".

In the theoretical analysis part, we find that when there is heterogeneity in energy companies, lending between companies will produce an endogenous investment efficiency threshold. Only companies with higher investment efficiency will choose to invest, and the threshold reflects the degree of misallocation between companies within the department. It can be proved that the adoption of financial policies and industrial policies will lead to an increase in the misallocation within the energy sector and a decrease in the average investment efficiency; while the adoption of price policies such as taxation will not aggravate the misallocation so the efficiency loss will be relatively small. In the quantitative analysis part, we parameterize the model based on China and the United States energy consumption data, and analyze the emission reduction effects, transition paths, and welfare effects under different policy scenarios. Our simulation shows that the resource investment tax and financial policy have small emission reduction space, and can only achieve less than 15% emission reduction (in the case of $\mu \geq 0$ and $\tau \leq 0.6$); the industrial policy has the largest policy space. By increasing δ_m from 0.3 to 0.7 we can reduce carbon emissions by more than 25%. Energy tax can also reduce emissions by more than 25% through tax increases, but it requires an additional tax rate of more than 40% on the existing basis, which is not consistent with reality. From the perspective of steady-state welfare, the use of financial policies and industrial policies to reduce emissions will lead to a decline in steady-state consumption and welfare losses.

Among them, the welfare losses caused by the use of industrial policies are greater; in comparison, the steady-state consumption losses caused by using tax emissions reductions smaller. From the perspective of dynamic welfare effects, the use of financial policies and industrial policies to reduce emissions will lead to long-term welfare decline. In contrast, the use of tax policies to reduce emissions may increase welfare in the long term since taxes can correct externality. In terms of "carbon bubble", the "carbon bubble" corresponding to the use of energy tax or energy enterprise tax to reduce emissions is the smallest, that is, the total value of fossil energy reserves $P^M M$ decreases the least when the same emission reduction effect is achieved; the use of financial policies and industrial policies to reduce emissions will generate large "carbon bubble", among which the "carbon bubble" corresponding to the adoption of financial policies is even larger; the "carbon bubble" corresponding to the adoption of resource investment tax for emission reduction is the largest, because the existence of resource investment tax directly reduces the price of fossil energy。

Based on a dynamic general equilibrium model including heterogeneous enterprises, this paper discusses the impact of policy emission reductions on asset values and the welfare effects it brings when there is heterogeneity in the energy sector, in order to analyze the policy choices for achieving given emission reduction goals. We find that due to the heterogeneity of energy firms, using unified financial constraints or industrial policy regulations to reduce emissions may worsen the misallocation of resources within the energy sector and bring unnecessary losses in efficiency and welfare. In contrast, the adoption of price policies such as taxation will not worsen resource misallocation and the efficiency loss will be relatively small. However, it should be noted that for the convenience of analysis, this article simplifies some important features of the economy, such as the development of green and non-green technologies, exogenously given policy emission reduction targets, etc. If we want to analyze the endogenous emission reduction path of the economy in the context of technological development, we may need to introduce different technologies as Acemoglu et al. (2012) and analyze the economic transition path when policies guide different technologies. At the same time, this article currently only considers the comparison of the effects of emission reduction under a single policy, and does not consider the synergistic superposition effect between policies. If we want to more systematically analyze the impact of the emission reduction policy system on the economy, we need to analyze and discuss the interactions between different policies in a model environment with multiple policies, and try to find the optimal policy combination under a given emission reduction goal.

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Appendix

(A) Proofs of Propositions

1. Proof of Proposition 1

Assume that the value function of an energy firm is given by $V_t\big(m_t(i), b_t(i), \epsilon_t(i)\big) = v_m\big(\epsilon_t(i)\big)m_t(i) - v_b\big(\epsilon_t(i)\big)b_t(i)$. Plug the assumption back into the Bellman equation we get:

$$v_m(\epsilon_t)m_t - v_b(\epsilon_t)b_t = max\left\{d_t + \beta E_t \frac{\Lambda_{t+1}}{\Lambda_t}[v_m(\epsilon_{t+1})m_{t+1} - v_b(\epsilon_{t+1})b_{t+1}]\right\}$$

$$= max\left\{R_t^M m_t + \frac{b_{t+1}}{R_{ft}} - b_t - P_t^M i_t^M + Q_t^M[(1-\delta_m)m_t + \epsilon_t i_t^M] - Q_t^L b_{t+1}\right\}$$

where

$$Q_t^M = \beta E_t \frac{\Lambda_{t+1}}{\Lambda_t} v_m(\epsilon_{t+1})$$

$$Q_t^L = \beta E_t \frac{\Lambda_{t+1}}{\Lambda_t} v_b(\epsilon_{t+1})$$

$$0 \le i_t^M \le \frac{1}{P_t^M}[(R_t^M + \mu Q_t^M)m_t(i) - b_t(i)]$$

Note that the right hand side of the above equation is a linear function of i_t^M. When $\epsilon_t \ge \frac{P_t^M}{Q_t^M}$, we get $\frac{b_{t+1}}{R_{ft}} = \mu Q_t^M m_t$ and $i_t^M = \frac{1}{P_t^M}[(R_t^M + \mu Q_t^M)m_t(i) - b_t(i)]$, or the firm will make no investment. Plug the investment decision back into the equation and we get:

$$v_m(\epsilon_t) = Q_t^M(1-\delta_m) + \left(\frac{Q_t^M}{P_t^M}\epsilon_t - 1\right)(R_t^M + \mu Q_t^M) + R_t^M$$

$$v_b(\epsilon_t) = \frac{Q_t^M}{P_t^M}\epsilon_t$$

when $\epsilon_t \ge \epsilon_t^*$, and

$$v_m(\epsilon_t) = Q_t^M(1-\delta_m) + R_t^M$$
$$v_b(\epsilon_t) = 1$$

when $\epsilon_t < \epsilon_t^*$.

From the optimization of b_{t+1} we get $Q_t^L = \frac{1}{R_{ft}}$, and then we get Q_t^M and Q_t^L:

$$Q_t^M = \beta E_t \frac{\Lambda_{t+1}}{\Lambda_t}[R_{t+1}^M(1+\Gamma_{t+1}) + (1-\delta_m)Q_{t+1}^M + \mu\Gamma_{t+1}Q_{t+1}^M]$$

$$\frac{1}{R_{ft}} = \beta E_t \frac{\Lambda_{t+1}}{\Lambda_t}(1+\Gamma_{t+1})$$

where $\Gamma_t = \int max\{\epsilon_t/\epsilon_t^* - 1, 0\}\, dF(\epsilon_t)$.

2. Proof of Proposition 3

In the steady state, the FOC for the competitive equilibrium is:

$$P_C^E = Y_E = \gamma A e^{-\nu S}\left[\gamma E^{\frac{\sigma-1}{\sigma}} + (1-\gamma)(K^a N^{1-a})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{1}{\sigma-1}} E^{-\frac{1}{\sigma}}$$

while the social optimal FOC is:

$$P_S^E - \phi Y_S = \beta(1-\delta_s)(-Y_E + P^E) \Rightarrow P_S^E = \frac{\phi}{1-\beta(1-\delta_s)}Y_S - \frac{\beta(1-\delta_s)}{1-\beta(1-\delta_s)}Y_E$$

In the steady state, we have

$$Y_S = \frac{1}{\phi} Y_E - \mathcal{E}$$

where $\mathcal{E} = \nu A e^{-\nu S}\left[\gamma E^{\frac{\sigma-1}{\sigma}} + (1-\gamma)(K^a N^{1-a})^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}}$, so we immediately get:

$$P_S^E = Y_E - \frac{\phi}{1-\beta(1-\delta_s)}\mathcal{E}$$

where $\mathcal{E}$ represents the negative externality.

3. Proof of Proposition 4

Note that energy tax on the final sector will not change the optimization problem of the energy sector, thus will not change the cutoff investment efficiency.

Then consider the energy firm tax. When there is an energy firm tax τ, the resource return becomes $R_t^M = (1-\tau)\frac{\alpha P_t^E E_t}{M_t}$, and then the total resource investment is given by:

$$I_t^M = \frac{1}{P_t^M}[(1-\tau)\alpha P_t^E E_t + \mu Q_t^M M_t]\big(1 - F(\epsilon_t^*)\big),$$

The corresponding Euler equation is:

$$Q_t^M = \beta E_t \frac{u'(C_{t+1})}{u'(C_t)}\left[(1-\tau)\frac{\alpha P_t^E E_t}{M_t}(1+\Gamma_{t+1}) + (1-\delta_m)Q_{t+1}^M + \mu \Gamma_{t+1} Q_{t+1}^M\right]$$

From the above two equations, we can easily conclude that the cutoff efficiency in the steady state remains unchanged.

Then consider the resource investment tax. Assume that the tax rate is τ, then the price that an energy firm should pay for resources becomes $(1+\tau)P_t^M$, and the corresponding cutoff efficiency is given by $Q_t^M \epsilon_t^* = (1+\tau)P_t^M$. However, we have shown that cutoff efficiency is unrelated to the resource prices, so ϵ^* remains unchanged.