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Energy shock, industrial transformation and macroeconomic fluctuations

Chenyang Yu, Changluan Fu, Piaoyang Xu *

School of Economics, Hangzhou Normal University, Hangzhou 311121, China

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ABSTRACT

This paper analyzes the impact of coal shock and oil shock on China's macro economy by constructing SVAR model, and clarifies the impact mechanism of the two shocks and corresponding countermeasures by constructing a small open DSGE model. We find that: 1) The impact of exogenous coal impact mainly affects the total output by influencing thermal power generation. Due to the incomplete release of power price in China, under the impact of exogenous coal, the rise of thermal power generation cost will lead to the decline of thermal power generation, which will lead to the shortage of power supply for industrial production and the decline of output. 2) Exogenous oil shock mainly affects total output by influencing monetary policy. Different from coal, oil is widely used and its price rise has a significant impact on industrial product prices, which will lead to a certain degree of monetary policy contraction and total output decline. 3) According to the counterfactual analysis and welfare analysis, we find that the exogenous coal shock can be mitigated by reducing the external dependence of coal and industrial green transformation. At the same time, the exogenous oil shock can be mitigated by establishing strategic cooperation and industrial green transformation with oil-rich countries. This paper has certain policy implications for Chinese government departments to promote industrial green transformation and improve energy security.

1. Introduction

At the beginning of 2022, the sudden conflict between Russia and Ukraine had a huge impact on energy supply, and the global price of fossil energy such as coal and oil rose significantly. Since the reform and opening up, the proportion of China's energy imports in total energy consumption has been rising, and the growth rate of energy demand is far higher than that of developed economies and other emerging economies. In 2012, China's energy consumption per 10,000 US dollars of GDP has reached 4.75 tons of standard coal, more than twice the world average, and far higher than the energy consumption per unit GDP of developed economies, leading to the escalation of China's energy problem.The National Development and Reform Commission and the National Energy Administration pointed out in the "Fourteenth Five Year" Modern Energy System Plan that in, on the one hand, the security and stability of China's energy supply chain should be enhanced; on the other hand, the security and stability of China's energy supply chain should be enhanced to promote high-quality energy development.

Energy security has always been the focus of government departments (Yu, Moslehpour, Tran, et al., 2023).At the meeting of the Central Finance and Economic Leading Group in June 2014, Xi stressed that energy security was an overall and strategic issue related to the country's economic and social development, and was crucial to the country's prosperity and development, the improvement of people's lives, and long-term social stability. We should accelerate the energy supply revolution, establish a diversified supply system, and form a multi wheel energy supply system driven by coal, oil, gas, nuclear, new energy, and renewable energy. We should vigorously promote the energy technology revolution. On the basis of China's national conditions, we should promote technological innovation in the energy industry by category and promote industrial upgrading in the direction of green and low-carbon. In fact, China's current energy security problem is not very optimistic, Yao and Chang (2014) analyzed China's energy security problems from 1981 to 2010, and found that China's energy security problems were the best in the sixth five-year plan period (1981–1985), and have been declining since then. The 30 year energy policy reform did not improve energy security. Yao and Chang (2015) further analyzed and found that China's energy problem was mainly due to the fact that China's previous energy policy reform was not intended to improve energy security, but to passively cooperate with economic reform and promote economic growth. In this context, vigorously developing renewable energy and reducing carbon emissions play a vital role in

* Corresponding author.
E-mail address: xupiaoyang@yeah.net (P. Xu).

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China's energy security (Yao and Chang, 2014). *The 2014 Research Report on China's Energy System Reform* also pointed out that China has now encountered an energy bottleneck in economic development, and China's energy development will be restricted by the total amount, structure and environment for a long time. Under this background, this paper aims to study the impact of exogenous coal and oil shocks on China's macro-economy and its impact mechanism, discuss the effectiveness of industrial green transformation in improving energy security and residents' welfare, and provide useful reference for promoting high-quality energy development.

The innovation of this paper is mainly reflected in the following aspects: First, the macroeconomic impacts of coal shocks and oil shocks are analyzed from an empirical perspective, and relevant typical facts are obtained; Second, this chapter constructs a general equilibrium model suitable for coal shocks and oil shocks, which better describes the impact mechanism of the two energy shocks; Thirdly, based on the established DSGE model, this chapter further conducts counterfactual analysis and welfare analysis, analyzes the role and effectiveness of industrial green transformation in mitigating energy shocks, and provides a corresponding theoretical basis for better evaluating the benefits of industrial green transformation.

The structure of this paper is as follows: The second part is literature review; The third part analyzes the coal shock and oil shock by constructing SVAR model; The fourth part constructs a DSGE model that can better describe the coal shock, and carries out corresponding parameter calibration and numerical simulation, analyzes the impact mechanism of coal shock and the impact of industrial green transformation on coal shock; The fifth part constructs a DSGE model that can better describe the oil shock, and carries out corresponding parameter calibration and numerical simulation, analyzes the impact mechanism of oil shock and the impact of industrial green transformation on oil shock; The sixth part is welfare analysis; The seventh part is the summary of this chapter.

2. literature review

The emergence of the oil crisis in the 1870s aroused extensive concern among economists around the world about the macroeconomic effects of energy shocks. Hamilton (2003) and Blanchard & Gali (2007) analyzed the asymmetry of oil shocks, and found that the impact of rising oil prices on the macro-economy was significantly higher than the impact of falling oil prices on the macro-economy, which was mainly due to the poor predictability of oil price increases, especially when the rise in oil prices was mainly due to the correction of early oil price declines and changes in exogenous oil supply. On this basis, Hamilton (2009) further analyzed the causes of the oil shocks from 2007 to 2008, and found that the rise in oil prices from 2007 to 2008 was mainly due to the excessive rise in total oil demand. The higher oil price shocks also became one of the factors influencing the 2008 financial crisis in the United States. Kilian (2009) and Caldara, Cavallo, & Iacoviello (2019) realized that oil price is often determined by both supply and demand, and traditional research on oil shock often regards oil price as an exogenous variable, which will lead to unclear causal relationship between oil price and economic growth. Therefore, it decomposed oil shock into oil supply shock, oil demand shock caused by industrial production and oil demand shock caused by preventive motivation, It is further found that compared with the impact of oil demand, the impact of oil supply is relatively weak and the impact time is relatively short, which further better explains that in the early 20th century, the sharp rise in oil prices did not cause a large-scale recession of the global economy, which is mainly because the rise in oil prices was mainly caused by the sharp rise in industrial production. Van de ven and Fouquet (2017) found that in the past 300 years, although the economic level has made great breakthroughs, the vulnerability and elasticity of the economy to energy shocks have not been effectively improved, but only in the process of energy supply gradually changing from coal to oil, the energy supply shock gradually turned into energy demand shock. They also pointed out that only the development of renewable energy in the future can truly reduce the economic vulnerability under energy shocks. Caldara et al., When the oil price is allowed to change with the current oil production and global total demand, it is found that the change of oil price mainly depends on the oil demand. Punzi (2019) analyzed the impact of energy price uncertainty on the macro-economy through transnational panel and nonlinear DSGE model, and found that energy price uncertainty will lead to an increase in total output in the short term, but will lead to a decline in total output in the long term. At the same time, the uncertainty of supply and demand in the economy will also amplify the negative impact of the impact of energy price uncertainty on the macro-economy to a certain extent, Expanding the scale of renewable energy in the energy market can effectively mitigate the negative impact of the impact of energy price uncertainty. Guo, Zheng, and Chen (2016) and Chen, Liu, Shi, et al., (2022) studied that the impact of coal price will have a significant asymmetric impact on the inflation rate. The increase in inflation caused by the rise of coal price is smaller than the decrease in inflation caused by the decline of coal price.

In the research on the impact mechanism of energy shocks on the macro-economy, Bernanke, Gertler, Watson, et al. (1997) said that monetary policy and other non monetary factors played a crucial role in the economic recession related to oil shocks, and the output decline caused by the tight monetary policy to deal with inflation caused by rising oil prices was one to two times greater than the direct economic impact caused by the impact of rising oil prices. Cologni and Manera (2008) conducted a cross-border analysis of G7 countries through the structural cointegration VAR model, and also found that oil shocks will affect macroeconomic fluctuations through monetary policies. That is, the oil shock leads to the rise of inflation, which in turn leads to the tightening of monetary policy, which in turn has a negative impact on the macro-economy. In different countries, due to the different reaction functions of monetary policy, the negative impact of the oil shock is also different. For Canada, France and Italy, the loose monetary policy can offset the negative impact of the oil shock to a certain extent. Balke and Brown (2018) built a DSGE model containing exogenous oil supply shocks and exogenous oil demand shocks, and found that exogenous oil supply shocks will lead to an increase in oil prices and a decrease in total output, while oil demand shocks will lead to an increase in oil prices and total output at the same time, while the increase in oil production efficiency can lead to a decrease in oil prices and an increase in output. In recent years, the United States has greatly reduced the negative impact of exogenous oil shocks on the macro-economy by reducing the oil consumption per unit GDP. In contrast, the effect of the United States on preventing oil shocks by increasing domestic oil production is weak. Liu, Margaritis, and Zhang (2013) said that there is a weak positive correlation between China's electricity price and coal price in the long term, while in the short term, the adjustment of electricity price is slower than that of coal price. This is mainly because the government is worried about the significant impact of the price change of coal and other raw materials on the production cost of enterprises and the living cost of residents, so it has regulated the adjustment of electricity price. They also said that this kind of regulation has increased the dependence of residents and enterprises on electric energy, thus increasing the dependence of the economy on energy such as coal, which is not conducive to sustainable economic development in the long run.

Yu and Yin (2005) used linear and nonlinear methods to empirically study the impact of oil shocks on China's macro-economy. They found that the negative impact of rising oil prices is higher than the economic growth caused by falling oil prices, and the negative impact of rising oil prices has a certain lag and continuity, while the impact of falling oil prices is relatively short. Wei, Gao, and Peng (2012) found through historical variance decomposition that energy shock is the main reason for China's macroeconomic fluctuations, and said that interest rate monetary policy rules help mitigate the impact of energy shock on the macro-economy, and government departments should speed up the market-oriented reform of interest rates. Wang (2014) studied the impact of energy price shocks on China's macro-economy by building a DSGE model, and found that the rise in energy prices led to a decline in output and an increase in inflation, while energy technology progress and price stickiness can weaken energy price shocks to a certain extent, and the strength of monetary policy's response to inflation will directly affect the strength of the impact of energy shocks on the macro-economy. Based on the computable general equilibrium model, Lin and Mou (2008) simulated that the negative impact of coal shocks on the macro-economy was as high as two to three times that of oil shocks.

Through sorting out the previous literature, we found that the deficiencies of the existing literature are mainly reflected in the following aspects: First, there are few literature on the impact of oil shocks on China's macro-economy, and the analysis of the impact mechanism is not perfect. Secondly, some literatures focus on the energy crisis mainly on the oil shock, but less on the coal shock, and do not take into account the unique characteristics of China's electricity market. Third, the existing literature does not evaluate the benefits of industrial green transformation from the perspective of energy security. In view of this, this paper studies the impact of energy shocks on China's macro-economy and its impact mechanism from the perspective of coal shocks and oil shocks, and calculates the benefits of green transformation of industries facing exogenous energy shocks through welfare analysis, filling the gap in existing literature.

3. Macroeconomic impact of energy shocks: an empirical analysis based on structural VAR model

3.1. Construction and estimation of SVAR

Before the empirical analysis, we first briefly introduce the SVAR model we have built. Consider the following structural VAR model:

$$X_t = C + \phi_1 X_{t-1} + \phi_2 X_{t-2} + \ldots + \phi_p X_{t-p} + B\varepsilon_t \tag{1}$$

Where, X_t is the observation matrix of all variables selected in the empirical study of this chapter, C is the intercept term of the model, ϕ and B are the coefficient matrix of the model, and ε_t is the white noise process with the mean value of 0. The key of structural VAR estimation is to estimate the coefficient matrix B in Eq. (1). Before estimating coefficient matrix B, we first need to estimate the reduced model corresponding to SVAR model. The reduced VAR model is as follows:

$$X_t = C + \phi_1 X_{t-1} + \phi_2 X_{t-2} + \ldots + \phi_p X_{t-p} + u_t \tag{2}$$

By estimating formula (2), we can get the covariance matrix Σ_u of u_t, but since Σ_u is a symmetric matrix, and B is a matrix of $n \times n$, n is the number of variables entering the model, which makes it necessary to add $n(n-1)/2$ additional restrictions to estimate the coefficient matrix B. The commonly used methods of imposing constraints in SVAR model are: short-term constraints (Cholesky decomposition is a kind of short-term constraints), long-term constraints, symbolic constraints and tool variable methods. This chapter adopts the Cholesky decomposition in short-term constraints, that is, the coefficient matrix B is assumed to be a lower triangular matrix.

3.2. The impact of coal shock on macro economy

We selected coal import price (PC), year-on-year growth rate of thermal power generation (EF), real GDP growth rate, year-on-year growth rate of CPI and 7-day interbank lending rate (R) in the interbank market to analyze the impact of coal shocks on macroeconomic variables. The time interval is Q1 in 1996 to Q4 in 2021. The coal import price is obtained by dividing the amount of coal imports by the amount of coal imports, and the data are all from the CEIC database. Before conducting structural VAR analysis, we first tested the stability of the time series we selected. The year-on-year growth of thermal power generation, CPI and 7-day interbank lending rate in the interbank market are all stable series. Both the coal price and the real GDP growth rate are stationary series after the first order difference, so we further conducted a cointegration test. The cointegration test shows that there is at least one cointegration relationship between the selected series. For the lag order of variables, we select the first order lag to model according to AIC, SC and HQ tests.

Fig. 1 shows the impulse response of major macroeconomic variables to a positive coal price impact of a standard deviation. It can be seen from Fig. 1 that a 0.6% increase in coal prices will lead to a significant decrease of thermal power generation by about 1%, and then gradually return to steady state. At the same time, it will also lead to a short-term decline of about 0.04 percentage points in real GDP growth. CPI will also decline to a certain extent, but it is not significant in the short term, and it is significant in the medium term. At the same time, interest rates will also decline to a certain extent, but not significant. This is mainly because the price of China's electricity market has not been fully liberalized, and most of the demand for coal comes from thermal power generation. When the price of electricity is subject to administrative constraints, the rise in the price of coal will lead to a decline in power generation to a certain extent. As one of the necessities of production and life, the decline in the output of electricity will have a certain negative impact on production activities, leading to a decline in output. The impact on CPI in the short term is not significant, which also indicates that due to the regulation of electricity prices (as shown in Fig. 2), the transmission of coal prices to the cost of living has been hindered to some extent, while the significant decline in CPI in the medium term may be caused by the depression of economic activities. The policy interest rate is not significant, which indicates that our country adopts more administrative means than conventional monetary policy when facing exogenous coal shocks. In order to further support our above views, we further simulated the impact of thermal power generation with a standard deviation on the macro-economy in Fig. 3. It can be seen that the increase of thermal power generation can significantly drive the increase of output, inflation, interest rate and coal price, which has a significant positive correlation with the prosperity of the macro-economy. Therefore, we propose the first typical fact of this chapter: the rise of coal price will have a significant negative impact on the total output. In the case of power price regulation, it will have a negative impact on the real economy mainly by affecting power generation.

3.3. The impact of oil shock on macro economy

For the analysis of the impact of oil shocks on the macro-economy, we selected the global economic activity index (Igrea), Keqiang index (LI), imported oil price (OP), consumer price index (CPI), and 7-day interbank lending rate (R) in the inter-bank market built by Kilian (2009). The time interval is Q4 in 2000 to Q4 in 2021. The global economic activity index constructed by Kilian (2009) is mainly used to exclude the impact of the increase in oil demand caused by economic growth, which leads to the rise in oil prices. Before the structural VAR analysis, we first conducted a stationarity test on the time series we selected. The Keqiang index, consumer price index and imported oil price are all stationary series, and the global economic activity index and the 7-day interbank offered rate are all stationary series after the first difference. Therefore, we further conducted cointegration test, and the results of cointegration test show that there is at least one cointegration relationship between the selected sequences. For the lag order of variables, we select the second order lag to model according to AIC, SC and HQ tests.

Fig. 4 shows the impulse response of major macroeconomic variables to a standard deviation positive oil price shock. It can be seen from Fig. 4 that the rise of oil prices will significantly affect monetary policy and the degree of world economic prosperity, leading to the tightening of domestic monetary policy and the decline of the world economy. For this reason, we further simulated the impact of monetary policy shocks on

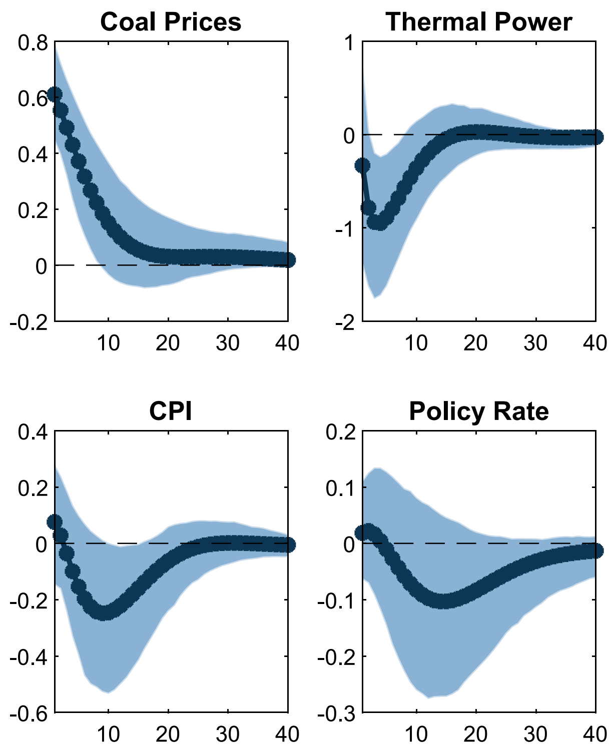

Fig. 1. Pulse response diagram of coal price shock.

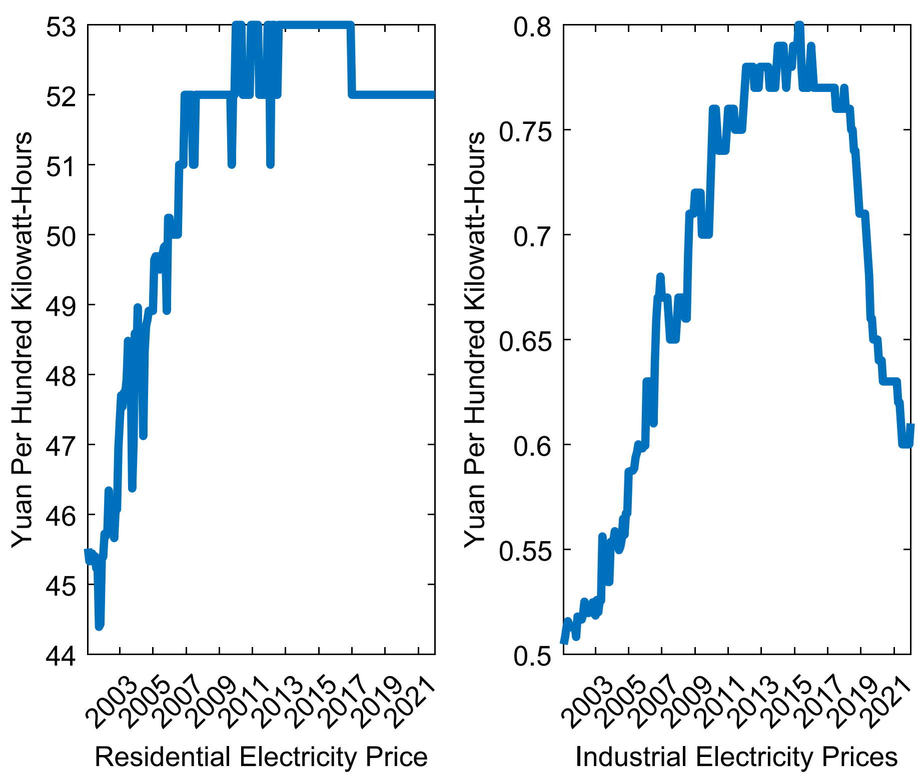

Fig. 2. Electricity price change.

major macroeconomic variables in Fig. 5, and found that there is a significant negative correlation between policy interest rates and Keqiang index, indicating that oil shocks will affect China's economy by influencing monetary policies. On this basis, we propose the second typical fact of this chapter: the oil shock will lead to the tightening of domestic monetary policy, which will have a negative impact on the macro-economy.

4. Theoretical mechanism analysis of coal shock: based on small open DSGE model

4.1. Construction of a small open DSGE model containing coal shocks

The models in this section mainly include the residential sector, the final product production sector, the power production sector and the

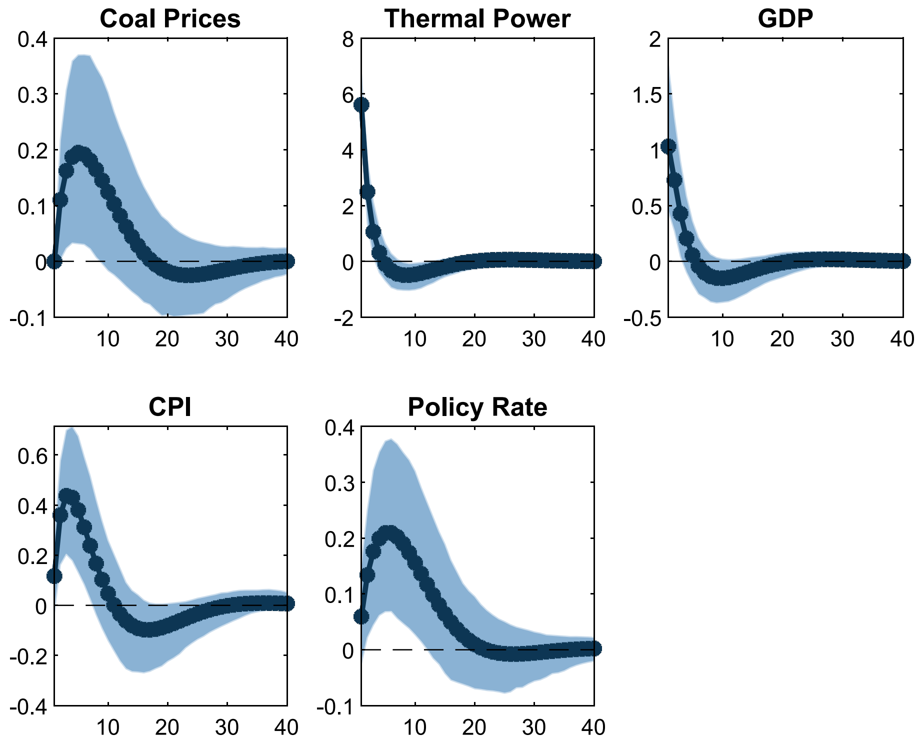

Fig. 3. Impulse response diagram of thermal power generation shock

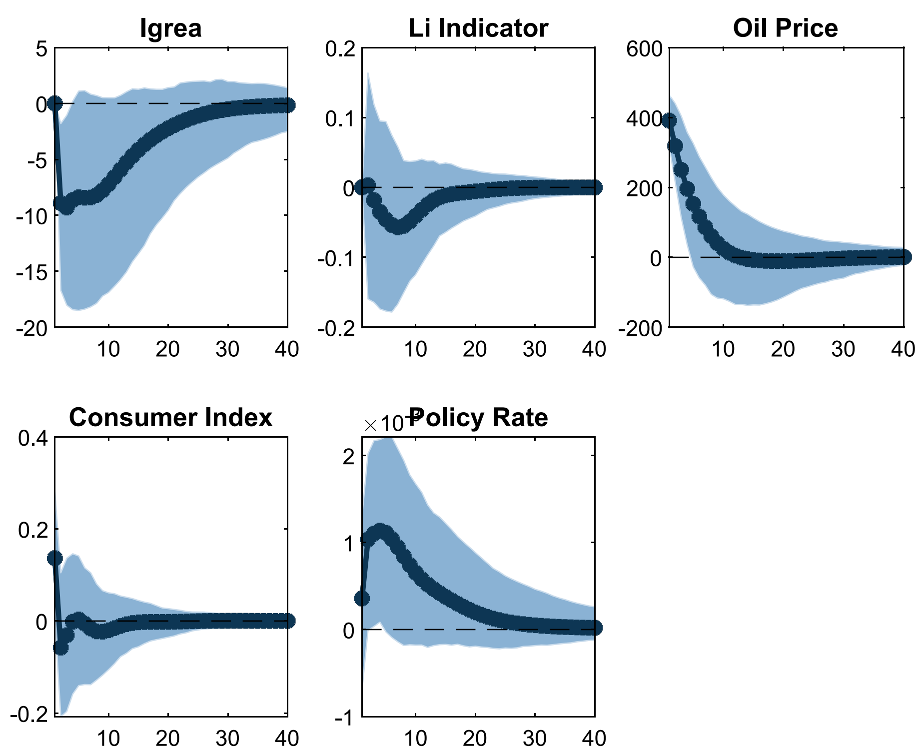

Fig. 4. Impulse response diagram of oil price shock.

government sector. The final product producers need to rely on electricity for production, among which the power production needs the corresponding coal supply, and the coal supply sources include domestic and foreign sectors. The specific settings of the model are as follows.

4.1.1. Residential sector

This section assumes that residents need to provide labor to the final product production sector and the power production sector at the same time, and residents maximize their lifetime utility by adjusting the labor and consumption provided to the two sectors. The utility function of representative residents is:

$$E_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{\left(C_t - h_c \overline{C}_{t-1}\right)^{1-\varkappa_C}}{1-\varkappa_C} - \sum_{\mathscr{I}} \Psi_{\mathscr{I}} \frac{N_{\mathscr{I},t}^{1+\varkappa_{\mathscr{I}}}}{1+\varkappa_{\mathscr{I}}} \right] \tag{3}$$

Where, β is the subjective discount factor of residents, $\varkappa_C$ is the risk

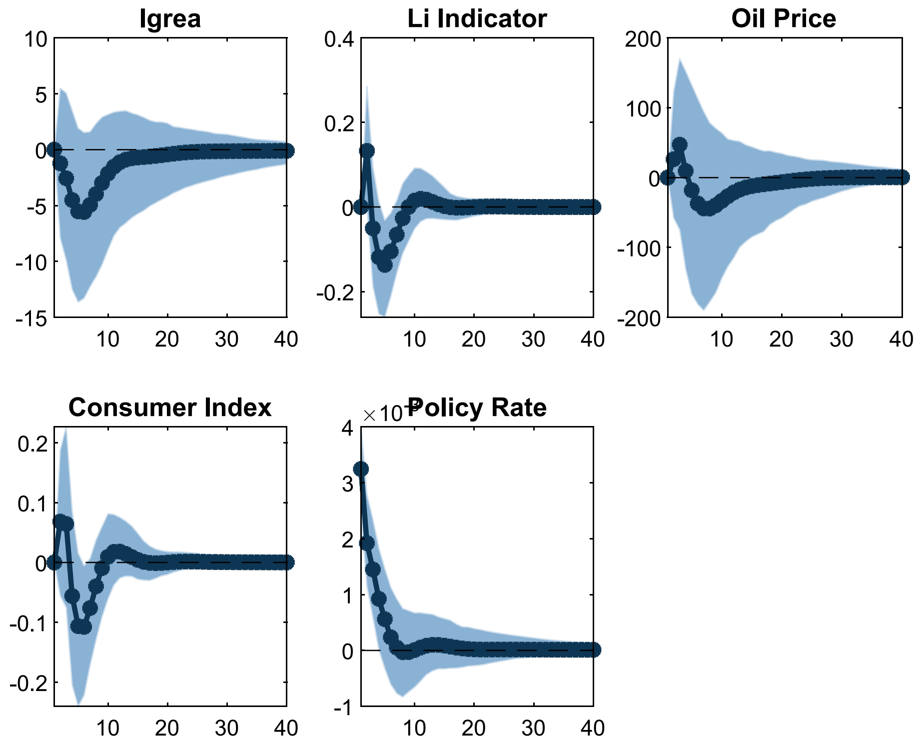

Fig. 5. Impulse response diagram of monetary policy shocks

aversion coefficient of residents, $h_c$is the consumption habit coefficient, $\varkappa_{\mathscr{S}}$is the inverse Frisch elasticity coefficient of labor supply, and $\Psi_{\mathscr{S}}$ is the degree of residents' aversion to labor. C_t is the consumption of residents, $\overline{C}_{t-1}$ is the average consumption of representative residents, $\mathscr{S} \in (Y, F)$ is the final product production sector and power production sector respectively, $N_{Y,t}$ and $N_{F,t}$ are the labor provided to the final product production sector and power production sector respectively. Constraints on residents' consumption budget are:

$$C_t + \sum_{\mathscr{S}} \left[1 + \frac{\phi_{\mathscr{S},t}}{2}\left(\frac{I_{\mathscr{S},t}}{I_{\mathscr{S},t-1}} - 1\right)^2\right] I_{\mathscr{S},t} + B_{t+1} = \sum_{\mathscr{S}} \left(W_{\mathscr{S},t} N_{\mathscr{S},t} + R_{\mathscr{S},t} K_{\mathscr{S},t-1}\right) + \frac{R_t}{\pi_t} B_t + \Pi_t + T_t \tag{4}$$

Among them, $W_{Y,t}$ and $W_{Y,t}$ are the wages of workers in the final product sector and the power production sector, B_t is the risk-free assets purchased by residents, R_t is the return on assets of risk-free assets, π_t is the inflation rate, Π_t is the corporate dividend, and Π_t is the government's one-time tax and transfer payment. $K_{Y,t-1}$ and $K_{F,t-1}$ are physical assets held by residents that can be used for the production of the final product sector and the power sector, respectively, and $I_{Y,t}$ and $I_{Y,t}$ are new investments in these two assets. The evolution equation of physical assets held by residents is:

$$K_{\mathscr{S},t} = \left(1 - \delta_{\mathscr{S},t}\right) K_{\mathscr{S},t-1} + I_{\mathscr{S},t} \tag{5}$$

$$\delta_{\mathscr{S},t} = \delta_{\mathscr{S},0} + \frac{\delta_{\mathscr{S},1}}{1 + \delta_{\mathscr{S},2}} U_{\mathscr{S},t}^{1+\delta_{\mathscr{S},2}} \tag{6}$$

Where, $\delta_{\mathscr{S},t}$ is the depreciation rate of the asset. According to the first-order condition of residents' utility maximization, the random discount factor of residents can be obtained as follows:

$$\Lambda_{t,t+1} = \beta \frac{\left(C_{t+1} - h_c \overline{C}_t\right)^{-\varkappa_C}}{\left(C_t - h_c \overline{C}_{t-1}\right)^{-\varkappa_C}} \tag{7}$$

4.1.2. Retailer

Retailers process intermediate products into final products through fixed elasticity of substitution. The production function of retail products is:

$$Y_t = \left(\int_0^1 Y_t(i)^{\frac{\varepsilon-1}{\varepsilon}} di\right)^{\frac{\varepsilon}{\varepsilon-1}} \tag{8}$$

Among them, $Y_t(i)$is the intermediate product produced by the final product manufacturer i, which is the substitution elasticity between different final products ε. According to the profit maximization problem of retailers, the demand function of a single final product can be obtained as follows:

$$Y_t(i) = \left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon} Y_t \tag{9}$$

Among them, $P_t(i)$is the price of a single final product and $P_t$is the price of retail products. According to the zero profit conditions of retailers, the retail price index can be obtained as follows:

$$P_t = \left(\int_0^1 P_t(i)^{1-\varepsilon} di\right)^{\frac{1}{1-\varepsilon}} \tag{10}$$

4.1.3. Final product production sector

Suppose that the final product manufacturers are continuously distributed on the interval [0,1], and the final product manufacturers are in a perfectly competitive market, producing different final products. The production function of the final product is:

$$Y_t = \left[(1 - \varpi_E)^{\frac{1}{\varepsilon_Y}} \left(VA_{Y,t}\right)^{\frac{\varepsilon_Y - 1}{\varepsilon_Y}} + \varpi_E^{\frac{1}{\varepsilon_Y}} (E_t)^{\frac{\varepsilon_Y - 1}{\varepsilon_Y}}\right]^{\frac{\varepsilon_Y}{\varepsilon_Y - 1}} \tag{11}$$

$$VA_{Y,t} = A_{Y,t}\left(U_{Y,t} K_{Y,t}\right)^{\alpha_Y} N_{Y,t}^{1-\alpha_Y} \tag{12}$$

Among them, $VA_{Y,t}$is the intermediate product produced by the final product manufacturer, $E_t$is the total power input, $K_{Y,t}$is the physical asset input, $\varpi_E$is the share of power output, $\varepsilon_Y$is the substitution elasticity between the intermediate product produced by the final product manufacturer and power, $\alpha_Y$is the share of capital output of the final product department, and $U_{Y,t}$is the capital utilization rate. $A_{Y,t}$is the total factor productivity, which follows the logarithmic AR(1) process, $lnA_{Y,t} = \rho_{AY}lnA_{Y,t-1} + \varepsilon_{AY,t}$,$lnA_{Y,t} = \rho_{AY}lnA_{Y,t-1} + \varepsilon_{AY,t}$. According to the profit maximization conditions of the final product manufacturer, under the condition that the power price can be adjusted freely, the power demand is equal to the power supply:

$$E_t = \varpi_E\left(\frac{P_{E,t}}{P_{Y,t}}\right)^{-\varepsilon_Y}Y_t \tag{13}$$

When the power price cannot be fully adjusted, the power demand is equal to or greater than the power supply:

$$E_t \le \varpi_E\left(\frac{\overline{P}_{E,t}}{P_{Y,t}}\right)^{-\varepsilon_Y}Y_t \tag{14}$$

Among them, $P_{E,t}$refers to the electricity price when the electricity price can be adjusted freely, and $\overline{P}_{E,t}$refers to the electricity price which cannot be adjusted freely. Electric power mainly consists of thermal power generation and new energy power generation. $E_t = E_{L,t} + E_{F,t}$, $E_{F,t}$refers to thermal power generation and $E_{L,t}$refers to new energy power generation. We assume that new energy power generation follows the logarithmic AR (1) process, $ln(E_{L,t}) = (1-\rho_{EL})ln(E_L) + \rho_{EL}ln(E_{L,t-1}) + \varepsilon_{EL,t}$, $\varepsilon_{EL,t} \sim N(0, \sigma_{EL}^2)$.

4.1.4. Price setting mechanism

Referencing to Rotemberg (1982), it assumed that the final product manufacturer needed to pay a certain price adjustment cost when adjusting the price $\phi_p/2(P_t(i)/P_{t-1}(i)-1)^2Y_t$. The objective function when the final product manufacturer adjusts the price is:

$$\max_{P_{t+j}(i)} E_t\sum_{j=0}^{\infty}\Lambda_{t,t+j}\left[\left(\frac{P_{t+j}(i)}{P_{t+j}} - \frac{P_{Y,t+j}}{P_{t+j}}\right)Y_{t+j}(i) - \frac{\phi_p}{2}\left(\frac{P_{t+j}(i)}{P_{t+j-1}(i)} - 1\right)^2Y_{t+j}\right] \tag{15}$$

Among them, $\phi_p$is the price adjustment cost coefficient, and $P_{Y,t+j}$is the marginal cost of each unit of final product produced by the final product manufacturer. The first order conditions for the optimal price of the final product manufacturer are:

$$\left[(1-\varepsilon)\left(\frac{P_t(i)}{P_t}\right)^{1-\varepsilon} + \varepsilon\frac{P_{Y,t}}{P_t}\left(\frac{P_t(i)}{P_t}\right)^{-\varepsilon} - \phi_p\left(\frac{P_t(i)}{P_{t-1}(i)} - 1\right)\frac{P_t(i)}{P_{t-1}(i)}\right]Y_t + \phi_pE_t\Lambda_{t,t+1}\left(\frac{P_{t+1}(i)}{P_t(i)} - 1\right)\frac{P_{t+1}(i)}{P_t(i)}Y_{t+1} = 0 \tag{16}$$

Since all final product manufacturers have the same objective function, they will choose the same price $P_t(i) = P_t$and produce the same quantity of product $Y_t(i) = Y_t$. Under symmetric equilibrium, the optimal price setting function is:

$$\phi_p\left(\frac{P_t}{P_{t-1}} - 1\right)\frac{P_t}{P_{t-1}} = \phi_pE_t\Lambda_{t,t+1}\left(\frac{P_{t+1}}{P_t} - 1\right)\frac{P_{t+1}}{P_t}\frac{Y_{t+1}}{Y_t} + 1 - \varepsilon + \varepsilon\frac{P_{Y,t}}{P_t} \tag{17}$$

4.1.5. Power production department

It is assumed that power producers are continuously distributed in the interval [0,1]. On the one hand, they produce electricity necessary for production activities by importing corresponding coal from abroad, and on the other hand, by mining domestic coal resources, and then combining them with labor and physical capital. Assume that the power production function is:

$$E_{F,t} = \left[(1-\varpi_X)^{\frac{1}{\varepsilon_F}}(VA_{F,t})^{\frac{\varepsilon_F-1}{\varepsilon_F}} + \varpi_X^{\frac{1}{\varepsilon_F}}(X_t)^{\frac{\varepsilon_F-1}{\varepsilon_F}}\right]^{\frac{\varepsilon_F}{\varepsilon_F-1}} \tag{18}$$

$$VA_{F,t} = A_{F,t}(U_{F,t}K_{F,t})^{\alpha_F}N_{F,t}^{1-\alpha_F} \tag{19}$$

$$X_t = X_{H,t} + X_{F,t} \tag{20}$$

Among them, $X_{H,t}$refers to the coal mined by the power producer from China, and $X_{F,t}$refers to the coal import volume. It is assumed that it follows the logarithmic AR (1) process, $lnX_{H,t} = (1-\rho_{XH})lnX_H + \rho_{XH}lnX_{H,t-1} + \varepsilon_{XH,t}$, $\varepsilon_{XH,t} \sim N(0, \sigma_X^2)$. $VA_{F,t}$refers to intermediate products produced by power production departments, $N_{F,t}$refers to labor employed by power producers, and $K_{F,t}$refers to physical assets used by power producers. $\varpi_X$is the output share of coal, $\varepsilon_F$is the substitution elasticity between coal and intermediate products, $\alpha_F$is the output share of physical capital, and $U_{F,t}$is the capital utilization rate. $A_{F,t}$is total factor productivity, subject to AR (1) process, $lnA_{F,t} = \rho_{AF}lnA_{F,t-1} + \varepsilon_{AF,t}$, $\varepsilon_{AF,t} \sim N(0, \sigma_{AF}^2)$. At the same time, we assume that the domestic coal mining cost is $\Gamma_{XH,t} = \chi_0M_t^{-\chi_1}X_{H,t}$, of which $\chi_0$and $\chi_1$are coal mining coefficients, and $M_t$is the domestic coal storage. Assume that the motion equation of coal storage is $M_{t+1} = (1-g_M)M_t - X_{H,t} + \Delta_t$, where $\Delta_t$is the newly proved coal storage in each phase and $g_M$is the loss during coal mining. Carbon emissions are assumed to be equal to coal consumption$e_t = X_t$.

4.1.6. Government departments and market clearing

We assume that the government department is mainly the People's Bank of China, which mainly uses monetary policy tools to maintain economic and price stability. The monetary policy function is:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R}\left[\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi}\left(\frac{Y_t}{Y_{t-1}}\right)^{\phi_y}\right]^{1-\rho_R}e^{\varepsilon_{R,t}} \tag{21}$$

Wherein, $R$and $\pi$are the steady-state values of risk-free return rate and inflation rate respectively. $\rho_R$is the auto-correlation coefficient of risk-free rate of return, $\phi_\pi$is the reaction coefficient of risk-free rate of return to inflation, and $\phi_y$is the reaction coefficient of risk-free rate of return to total output. $\varepsilon_{R,t} \sim N(0, \sigma_{R,t}^2)$is the exogenous impact of monetary policy.

The final product market clearing conditions are:

$$Y_t = C_t + \sum_{\mathscr{S}}\left[1 + \frac{\phi_{\mathscr{S},t}}{2}\left(\frac{I_{\mathscr{S},t}}{I_{\mathscr{S},t-1}} - 1\right)^2\right]I_{\mathscr{S},t} + \frac{\phi_p}{2}\left(\frac{\pi_t}{\pi} - 1\right)^2Y_t + X_{F,t} \tag{22}$$

4.2. Parameter calibration and numerical simulation of small Open DSGE model including coal shock

4.2.1. Parameter calibration of a small open DSGE model containing coal shocks

Parameters related to the residential sector. Referring to the settings in most literatures, we set the subjective discount factor $\beta$of residents to 0.995, which corresponds to an annualized risk-free rate of return of 2%. At the same time, we set the consumption habit $h_c$to 0.7, the intertemporal substitution elasticity $\varkappa_C$of residents to 2, and the inverse Frisch elasticity coefficient $\varkappa_{\mathscr{S}}$ of labor supply to 1. For the coefficient of labor aversion $\Psi_{\mathscr{S}}$, we set the steady state value of the total labor supply to 1/3, and then backward deduce $\Psi_{\mathscr{S}}$. The depreciation rate $\delta_{\mathscr{S}}$ of the two kinds of physical assets held by residents is calibrated to 0.025, corresponding to the annual depreciation rate of 10%, the capital adjusted cost $\phi_{\mathscr{S}}$ is set to 2, and the elasticity coefficient $\delta_{\mathscr{S},2}$ of the depreciation rate to the capacity utilization rate is set to 7.2.

Parameters related to enterprise departments. Referring to the settings in most literatures, we set the substitution elasticity between intermediate products ε to 10, making the price markup rate 10%. For the price adjustment coefficient of intermediate products ϕ_p, we set it to 60. Referring to Kalkuhl, Edenhofer, and Lessmann (2012), we set the substitution elasticity between intermediate products and energy in the final product sector $\varepsilon_Y$to 0.5, and the substitution elasticity between intermediate products and coal resources in the power production sector ε_F to 0.15. At the same time, the capital output shares of the final product sector and the power production sector $\alpha_Y$and α_F are set to 0.5, Consistent with most literatures, the share of coal output is calibrated to 0.2, the share of power output is calibrated to 0.1, the proportion of thermal power generation in total power generation is calibrated to 0.9, and the proportion of coal imports in total coal consumption is calibrated to 0.075. Refer to Van der Ploeg and Rezai (2020) to set the coal mining cost coefficient χ_1 as 1.25. According to the actual data of the net export amount of coal from 2010 to 2021, we obtained that the autocorrelation coefficient of coal imports is 0.64, and the standard deviation of coal import shocks is 0.36. At the same time, according to the actual data of thermal power generation from 2009 to 2021, we obtained that the autocorrelation number of thermal power generation shocks is 0.988, and the standard deviation of thermal power generation shocks is 0.09. Meanwhile, the autocorrelation coefficient of interest rate is set as 0.8, the reaction coefficient of interest rate to inflation is set as 1.5, and the reaction coefficient of interest rate to output is set as 0.5.

4.2.2. Analysis of the impact of coal shock on macroeconomy

In order to better clarify the impact of coal shocks on the macroeconomy and the impact mechanism, we simulated the impact of coal import shocks on the macro-economy in Fig. 6 under the conditions of fully flexible electricity prices, stickiness of electricity prices and completely unchanged electricity prices. It can be seen from Fig. 6 that under different price setting mechanisms, the impact of coal import shocks on the macro-economy has the same direction, but the impact amplitude and transmission mechanism are quite different. Under the condition that the electricity price remains unchanged, the exogenous coal supply shock will, on the one hand, lead to an increase in the coal price, on the other hand, lead to a sharp decline in the total power generation, which to some extent will alleviate the rise in the coal price, but the sharp decline in power generation will have a greater negative impact on downstream production activities, leading to a sharp decline in output and inflation, It is much higher than the decline of total output and inflation under sticky power price and flexible power price. When electricity price stickiness and electricity price can be adjusted freely and flexibly, but at the beginning of coal shock, electricity price adjustment under stickiness price is slow, which will cause relatively more decline in total output compared with flexible adjustment of price. When the price adjustment is sufficient, the impact of coal shock on the whole macro-economy is almost the same in both cases.

In Fig. 7, we further simulated the impact of the negative thermal power generation production impact of one standard deviation on the main macroeconomic variables. It can be seen from the figure that the decline in power supply will lead to a significant decline in output, investment and consumption, that is, the decline in power supply will have a significant negative impact on the economy. It can also be seen from the figure that when the electricity price can be adjusted accordingly, the inflation rate will rise first and then fall. On the one hand, the short-term inflation rise is due to the rise of electricity price, on the other hand, because the output of the final product declines due to the lack of electricity supply, and the supply does not meet the demand. It can also be seen from Fig. 7 that the short-term inflation caused by the mismatch between supply and demand will rise more rapidly, but the duration is also short. The long-term decline of inflation is caused by insufficient effective demand. This further proves that exogenous energy shocks will affect the overall macroeconomic fluctuations by affecting the power

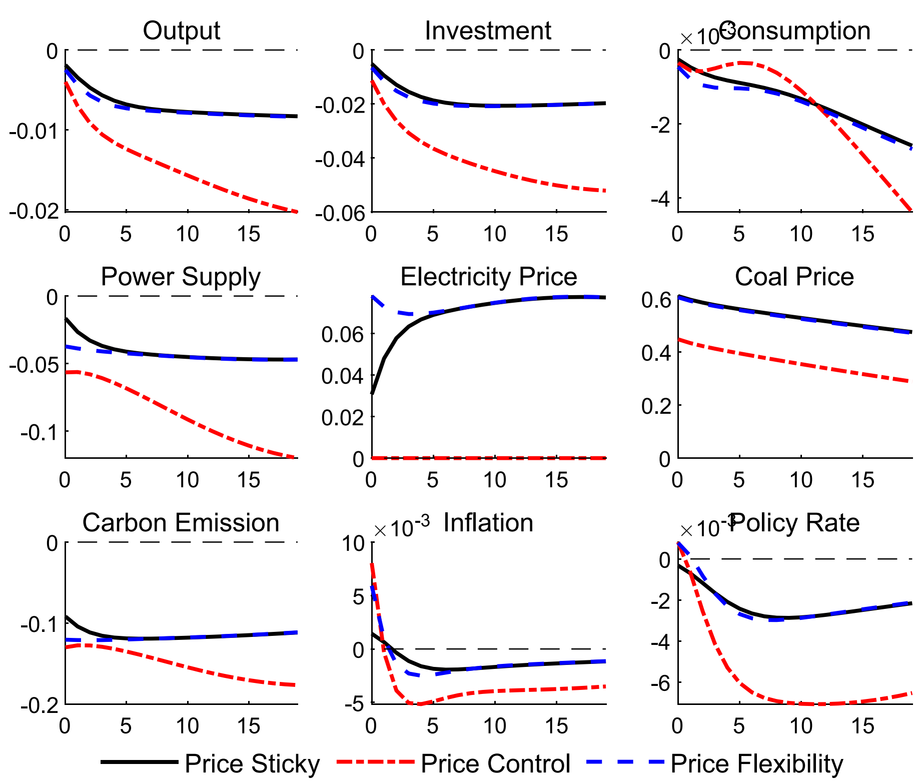

Fig. 6. Impact of coal import shocks on major macroeconomic variables under different price restrictions.

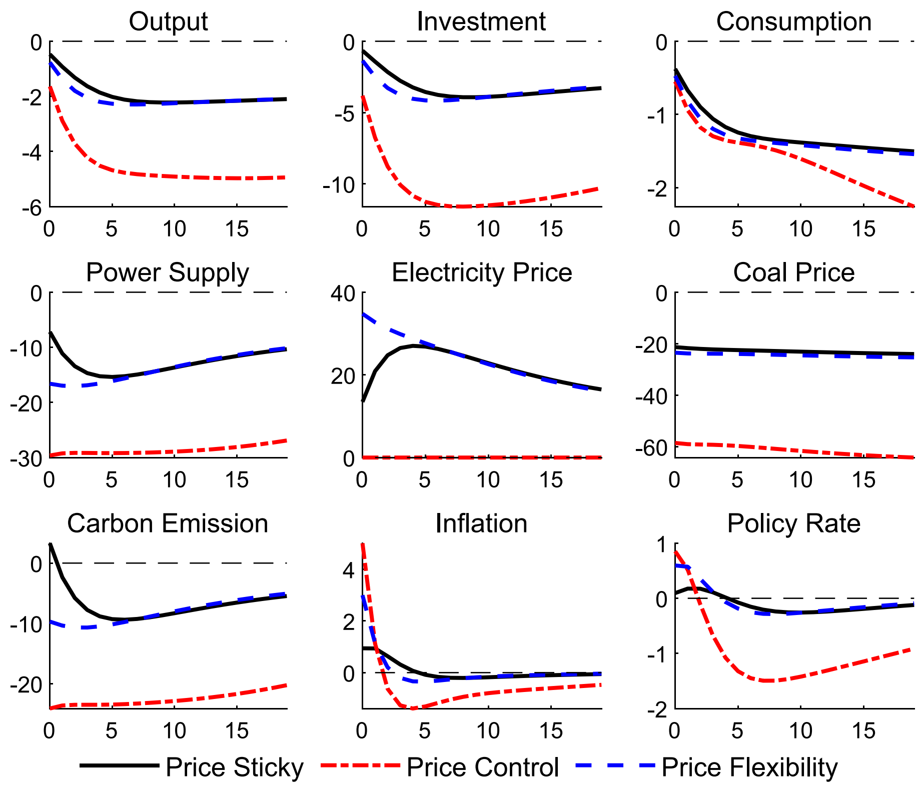

Fig. 7. Influence of electric shock on main macroeconomic variables

supply. From Fig. 7, we can also find that under the power price restriction, the impact of power production has a greater negative impact on the macro-economy. This is mainly because, under the condition that the price can be adjusted, the power production sector can increase the power supply by raising the price. However, under the price restriction, this mechanism to mitigate the economic downturn is blocked, which leads to more output decline. It can be noted that under the condition of price stickiness, the output decline is the least. This is mainly because

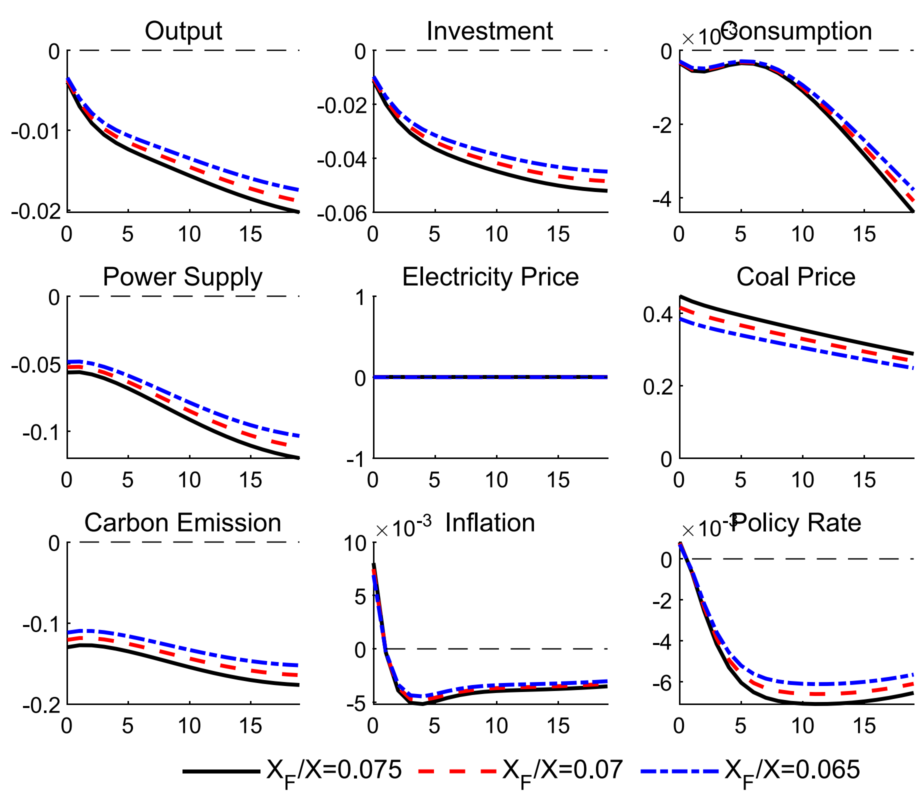

Fig. 8. The impact of coal shocks on major macroeconomic variables under different net coal imports.

the price stickiness enables the power production department and the downstream final product production department to share the cost of external shocks and risks, thereby mitigating the output decline.

4.2.3. Two reform paths to deal with coal shock

The emergence of the energy crisis in the 1970s prompted countries around the world to begin to reform their energy development strategies. There are two main reform paths, one is "open source", that is, to expand the source of fossil energy. For example, after the oil crisis, the United States continued to expand the exploitation of its own oil resources, and in recent years has gradually become a net exporter of natural gas; The other is "throttling", that is, green transformation of industries. For example, Europe and Japan, on the one hand, actively improve oil utilization efficiency and save oil consumption, on the other hand, actively develop renewable energy to replace traditional fossil energy. In terms of improving the energy crisis, China can also start from these two aspects in the future. Therefore, in Fig. 8 and Fig. 9, we simulated the impact of coal shocks on the macro-economy under different coal import dependence and different proportions of new energy power generation. It can be seen from Fig. 8 and Fig. 9 that reducing the net import of coal and increasing the proportion of new energy power generation in the total power supply can effectively mitigate the negative impact of exogenous coal supply shocks on the macro-economy. It can also be seen from the figure that the mechanisms of the two reform schemes in blocking the exogenous negative impact are not the same. After the reduction of coal imports, the increase of coal prices after the exogenous coal impact has significantly reduced, thus significantly reducing the decline of carbon emissions. However, in the green transformation of the industry, the changes of coal prices and carbon emissions are basically the same as before the reform. However, it should be noted that after the green transformation of the industry, although the decline of carbon emissions after the impact of exogenous coal is the same as before the reform, the absolute amount of carbon emissions has already declined, which is more conducive to the realization of the dual goals of carbon peak and energy security.

5. Theoretical mechanism analysis of oil shock: based on small open DSGE model

5.1. Construction of a small open DSGE model containing oil shocks

The model in this section mainly includes six parts: residential sector, final product production sector, oil producer, new energy producer, government sector and foreign sector. The final product producers need to rely on oil and new energy for production. There is a certain substitutability between oil and new energy, and the sources of oil supply include domestic and foreign sectors. The pricing mechanism of retailers and final product manufacturers in this section is the same as that in Part IV, so it will not be repeated in this section. The specific settings of the model are as follows.

5.1.1. Residential sector

This section assumes that residents need to provide labor to the final product production sector, oil production sector and new energy sector at the same time, and residents maximize their lifetime utility by adjusting the labor and consumption provided to the three sectors. The utility function of representative residents is:

$$E_0\sum_{t=0}^{\infty}\beta^t\left[\frac{(c_t-\chi_c\bar{c}_{t-1})^{1-\sigma}}{1-\sigma}-\chi_l\frac{l_t^{1+\eta}}{1+\eta}\right] \tag{23}$$

Among them, $\beta$is the subjective discount factor of residents, $\sigma$is the risk aversion coefficient of residents, $\chi_c$is the consumption smoothing coefficient, $\eta$is the inverse Frisch elasticity coefficient of labor supply, and $\chi_l$is the degree of residents' aversion to labor. c_t is the consumption of residents, $\bar{c}_t$ is the average consumption of residents, $l_t = l_{f,t} + l_{o,t} + l_{g,t}$ is the total labor supply of residents, $l_{f,t}, l_{g,t}$ and $l_{g,t}$ are the labor provided to the final product production sector, the oil production sector and the new energy production sector, respectively. Constraints on residents' consumption budget are:

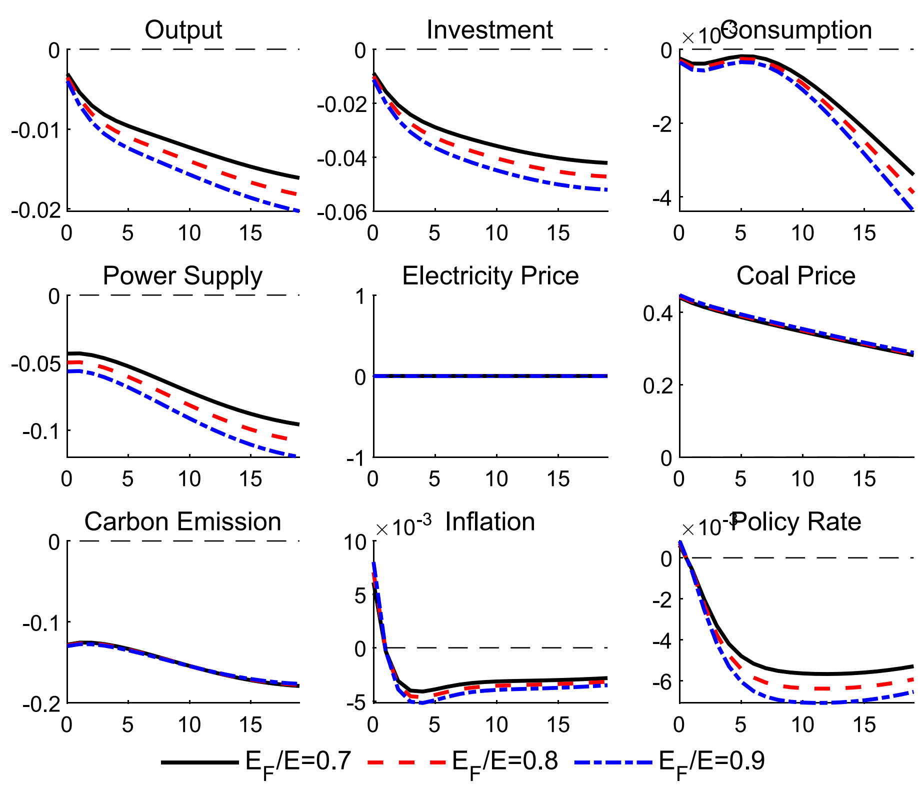

Fig. 9. Impact of coal shock on main macroeconomic variables under different thermal power dependence.

$$c_t + \sum_s \left[1 + \frac{\kappa_{s,t}}{2}\left(\frac{I_{s,t}}{I_{s,t-1}} - 1\right)^2\right] I_{s,t} + B_t \le w_t l_t + \sum_s R_{k_s,t} k_{s,t-1} + \frac{R_{t-1}}{\pi_t} B_{t-1} + \Pi_t \tag{24}$$

Where, w_t is the wages of workers, $B_t$is the risk-free assets purchased by residents, $R_t$is the rate of return on risk-free assets, $\pi_t$is the rate of inflation, and Π_t is the enterprise dividend. $k_{m,t-1}$, $k_{o,t-1}$and$k_{g,t-1}$ are physical assets held by residents that can be used for production in intermediate goods sector, domestic oil sector and new energy sector, respectively. $I_{m,t}$, $I_{o,t}$and $I_{g,t}$ are new investments in these three assets. The evolution equation of physical assets held by residents is:

$$k_{s,t} = (1-\delta)k_{s,t-1} + I_{s,t} \; s \in \{m, o, g\} \tag{25}$$

According to the first-order condition of residents' utility maximization, the random discount factor of residents can be obtained as follows:

$$\Lambda_{t,t+1} = \beta \frac{(c_{t+1} - \chi_c \overline{c}_t)^{-\sigma}}{(c_t - \chi_c \overline{c}_{t-1})^{-\sigma}} \tag{26}$$

5.1.2. Intermediate product manufacturer

Suppose that intermediate product producers are continuously distributed on the interval [0,1], and intermediate product producers are in a perfectly competitive market, producing differentiated intermediate products. The production function of intermediate products is:

$$y_t(i) = z_{m,t}\left[\psi_{m,l}^{\frac{1}{\rho_m}}\left(l_{m,t}(i)\right)^{\frac{\rho_m-1}{\rho_m}} + \left(1-\psi_{m,l}\right)^{\frac{1}{\rho_m}}\left(ks_{m,t}(i)\right)^{\frac{\rho_m-1}{\rho_m}}\right]^{\frac{\rho_m}{\rho_m-1}} \tag{27}$$

$$ks_{m,t}(i) = \left[\psi_{m,e}^{\frac{1}{\rho_{ksm}}}\left(e_{m,t}(i)\right)^{\frac{\rho_{ksm}-1}{\rho_{ksm}}} + \left(1-\psi_{m,e}\right)^{\frac{1}{\rho_{ksm}}}\left(k_{m,t-1}(i)\right)^{\frac{\rho_{ksm}-1}{\rho_{ksm}}}\right]^{\frac{\rho_{ksm}}{\rho_{ksm}-1}} \tag{28}$$

$$e_{m,t}(i) = \left[\psi_{m,o}^{\frac{1}{\rho_{em}}}\left(o_{m,t}(i)\right)^{\frac{\rho_{em}-1}{\rho_{em}}} + \left(1-\psi_{m,o}\right)^{\frac{1}{\rho_{em}}}\left(g_{m,t}(i)\right)^{\frac{\rho_{em}-1}{\rho_{em}}}\right]^{\frac{\rho_{em}}{\rho_{em}-1}} \tag{29}$$

Among them, $ks_{m,t}$refers to total capital investment, $e_{m,t}$refers to total energy investment, $k_{m,t}$ refers to physical assets investment, $o_{m,t}$refers to oil investment, and $g_{m,t}$refers to new energy investment. $\psi_{m,l}$is the share of labor output, ρ_m is the substitution elasticity between labor and capital, $\psi_{m,e}$is the proportion of energy in total capital input, $\rho_{ksm}$is the substitution elasticity between energy and physical capital, $\psi_{m,o}$ is the proportion of oil in total energy input, and $\rho_{em}$is the substitution elasticity between oil and new energy. $z_{m,t}$ is the total factor productivity, $z_{m,t}$ follows the logarithmic AR (1) process, $lnz_{m,t} = \rho_{z_m} lnz_{m,t-1} + \varepsilon_{m,t}$, $\varepsilon_{m,t} \sim N\left(0, \sigma^2_{z_m,t}\right)$.

5.1.3. Oil production sector

Assume that oil producers are continuously distributed in the interval [0,1]. On the one hand, they import corresponding oil from abroad, and on the other hand, they exploit domestic oil resources, and then package and sell them to intermediate producers. Assume that the production function of oil is:

$$o_{m,t}(i) = \left[\psi_o^{\frac{1}{\rho_o}}\left(o_{H,t}(i)\right)^{\frac{\rho_o-1}{\rho_o}} + (1-\psi_o)^{\frac{1}{\rho_o}}\left(o_{F,t}(i)\right)^{\frac{\rho_o-1}{\rho_o}}\right]^{\frac{\rho_o}{\rho_o-1}} \tag{30}$$

$$o_{H,t}(i) = z_{o,t}\left[\psi_{o,l}^{\frac{1}{\rho_{o,l}}}\left(l_{o,t}(i)\right)^{\frac{\rho_{o,l}-1}{\rho_{o,l}}} + \left(1-\psi_{o,l}\right)^{\frac{1}{\rho_{o,l}}}\left(k_{o,t-1}(i)\right)^{\frac{\rho_{o,l}-1}{\rho_{o,l}}}\right]^{\frac{\rho_{o,l}}{\rho_{o,l}-1}} \tag{31}$$

Among them, $o_{H,t}(i)$ refers to the oil produced by the oil producer from China and $o_{F,t}(i)$ refers to the imported oil, which follows the logarithmic AR (1) process. $lno_{F,t} = (1-\rho_{oF})lno_F + \rho_{oF} lno_{F,t-1} + \varepsilon_{oF,t}$. $k_{o,t}(i)$ is the labor employed by oil producers, $k_{o,t}(i)$ is the physical assets used by oil producers to exploit oil.ψ_o is the proportion of domestic oil production in total domestic oil demand, $\rho_o$is the substitution elasticity between domestic oil and foreign oil, $\psi_{o,l}$is the output share of labor in the oil production process, and $\rho_{o,l}$ is the substitution elasticity between labor and physical assets. $z_{o,t}$is the total factor productivity of domestic oil production, subject to the logarithmic AR (1) process, $lnz_{o,t} = \rho_{z_o} ln\, z_{o,t-1} + \varepsilon_{o,t}$, $\varepsilon_{o,t} \sim N\left(0, \sigma^2_{z_o,t}\right)$.

5.1.4. New energy production sector

Assuming that new energy producers are continuously distributed in the interval [0,1], they mainly produce new energy by employing labor and leasing capital. Assume that the new energy production function is:

$$g_{m,t}(i) = z_{g,t}\left[\psi_g^{\frac{1}{\rho_g}}\left(l_{g,t}(i)\right)^{\frac{\rho_g-1}{\rho_g}} + \left(1-\psi_g\right)^{\frac{1}{\rho_g}}\left(k_{g,t-1}(i)\right)^{\frac{\rho_g-1}{\rho_g}}\right]^{\frac{\rho_g}{\rho_g-1}} \tag{32}$$

Among them, $l_{g,t}(i)$refers to the labor employed by new energy producers and $k_{g,t}(i)$ refers to the physical assets required by new energy producers. ψ_g is the output share of labor in the new energy production process, and ρ_g is the substitution elasticity between labor and physical assets. $z_{g,t}$ is the total factor productivity of new energy production, which follows the logarithmic AR (1) process, $lnz_{g,t} = \rho_{z_g} lnz_{g,t-1} + \varepsilon_{g,t}$, $\varepsilon_{g,t} \sim N\left(0, \sigma^2_{z_g,t}\right)$.

5.1.5. Government departments and market clearing

We assume that the government department is mainly the People's Bank of China, which mainly uses monetary policy tools to maintain economic and price stability. The monetary policy function is:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R}\left[\left(\frac{\pi_t}{\pi}\right)^{\phi_\pi}\left(\frac{y_t}{y}\right)^{\phi_y}\right]^{1-\rho_R} e^{\varepsilon_{R,t}} \tag{33}$$

Among them, R, π and y are the steady-state values of risk-free rate of return, inflation rate and output respectively. ρ_R is the autocorrelation coefficient of risk-free rate of return, ϕ_π is the reaction coefficient of risk-free rate of return to inflation, and ϕ_y is the reaction coefficient of risk-free rate of return to total output. $\varepsilon_{R,t} \sim N\left(0, \sigma^2_{R,t}\right)$ is the exogenous impact of monetary policy.

The final product market clearing conditions are:

$$y_t = c_t + \sum_s \left[1 + \frac{\kappa_{s,t}}{2}\left(\frac{I_{s,t}}{I_{s,t-1}} - 1\right)^2\right] I_{s,t} + \frac{\phi_p}{2}\left(\frac{p_t}{p_{t-1}} - 1\right)^2 Y_t + nx_{f,t} \tag{34}$$

Among them,$nx_{f,t}$ is the net export of final products, and the terms of trade balance are:

$$nx_t = nx_{f,t} - \frac{p_{o_H,t}}{p_t} o_{F,t} \tag{35}$$

Wherein,nx_t is the total net export, subject to the logarithmic AR (1) process, $lnnx_t = (1-\rho_{nx})lnnx + \rho_{nx} lnnx_{t-1} + \varepsilon_{nx,t}$, $\varepsilon_{nx,t} \sim N\left(0, \sigma^2_{nx,t}\right)$.

5.2. Parameter calibration and numerical simulation of a small open DSGE model containing oil shocks

5.2.1. Parameter calibration of small open DSGE models containing oil shocks

Parameters related to the residential sector. Referencing to the settings in most literature, we set the subjective discount factor of residents β to 0.9925, which corresponds to an annualized risk-free rate of return of 2%. At the same time, we set the consumption habit χ_c to 0.7, the intertemporal substitution elasticity of residents σ to 2, and the inverse Frisch elasticity coefficient of labor supply η to 1. For the coefficient of labor aversion χ_l, we set the steady-state value of the total labor supply to 1/3, and then backward deduce χ_l. The depreciation rate of the three kinds of physical assets held by residents is set as 0.025.

Parameters related to enterprise departments. Referring to the settings in most literatures, we set the substitution elasticity between intermediate products ε to 6, making the price markup rate 10%. For the price adjustment coefficient of intermediate products ϕ_p, we set it to 100. Set the substitution elasticity between labor and capital in the intermediate product sector ρ_m as 1, making the form of intermediate product production function as Cobb Douglas form, and set the labor output share $\psi_{m,l}$ as 0.5, which is consistent with most literatures. With reference to Wei et al. (2012), we set the alternative elasticity between energy and physical capital ρ_{ksm} as 0.09. For the proportion of energy in total capital investment$\psi_{m,e}$, we calibrate it to 0.086 according to the proportion of China's total energy consumption and fixed asset investment from 2006 to 2020. Referring to Diluiso, Annicchiarico, Kalkuhl, et al. (2021), we set the substitution elasticity between traditional energy and new energy ρ_{em} as 5. According to the proportion of new energy in total energy consumption from 2000 to 2009, we calibrated the proportion of traditional energy in total energy input $\psi_{m,o}$ to 0.9. Referring to Fan Maoqing et al.'s (Fan, Ren, & Chen, 2010) estimate of the substitution elasticity between energy and capital in various industries, we set the substitution elasticity between domestic energy supply and foreign energy import ρ_o as 2. For the proportion of domestic produced energy in total domestic energy demand ψ_o, we set it as 0.85 according to the share of domestic energy production in total energy consumption. Similarly, we set the substitution elasticity between labor and physical assets in the domestic traditional energy production sector $\rho_{o,l}$ to 1, making it Cobb Douglas, and set the output share of labor in the domestic energy production process$\psi_{o,l}$ to 0.5. For the new energy production sector, we set the substitution elasticity between labor and physical assetsρ_g as 1, and the output share of labor in the new energy production process ψ_g as 0.5.

For the parameters related to monetary policy and exogenous shocks. We set the autocorrelation coefficient of interest rate as 0.7, the reaction coefficient of interest rate to inflation as 1.5, the reaction coefficient of interest rate to output as 0.5, and the monetary policy shock as 0.12, referring to the setting of most literatures. For oil import shocks, we set the autocorrelation coefficient of exogenous oil shocks to 0.95 and the standard deviation of first-order moment shocks to 0.18 according to the data of oil imports.

5.2.2. Analysis of the impact of oil shock on macroeconomy

In order to better understand the impact of oil shocks on the macroeconomy and the impact mechanism, we simulated the impact of exogenous oil supply shocks on the macro-economy in Fig. 10. It can be seen from Fig. 10 that the impact of exogenous oil supply will lead to a significant increase in the price of oil imports, and a significant decline in total output, total investment and total consumption. The rise in the price of imported oil will make more oil demand turn to domestic oil, and domestic oil output and new energy output will rise significantly. The direct effect and substitution effect of the rise in oil prices will make the quantity of oil imports drop significantly. At the same time, consistent with our empirical results, inflation will decline after a short rise, and interest rates will rise significantly, which to some extent exacerbated the decline in domestic gross output.

In order to further support the typical fact 2 of this paper, we further simulated the impact of monetary policy shocks on the macro-economy in Fig. 11. It can be seen from Fig. 11 that the negative monetary policy impact (interest rate rise) of a standard deviation will lead to a significant decline in total output, total investment, total consumption and inflation rate. The decline in total demand will also lead to a decline in enterprises' demand for energy, which in turn will lead to a decline in the demand for new energy and oil, and the oil price, domestic oil output and new energy output will also decline. This further proves that exogenous oil supply shocks can affect the real economy by affecting the degree of monetary policy easing.

5.2.3. Reform path to deal with oil shock

Different from coal, China's oil resources are relatively scarce. The existing oil resources are difficult to exploit, and the oil quality is poor. It is difficult to mitigate the impact of oil supply through open source. Therefore, in response to the oil shock, China can only mitigate the negative impact of the oil shock on the macro-economy in two ways: first, reduce the dependence on oil through the green transformation of the industry; second, establish strategic cooperation with major oil resource countries to ensure the stability of oil supply and reduce the oil

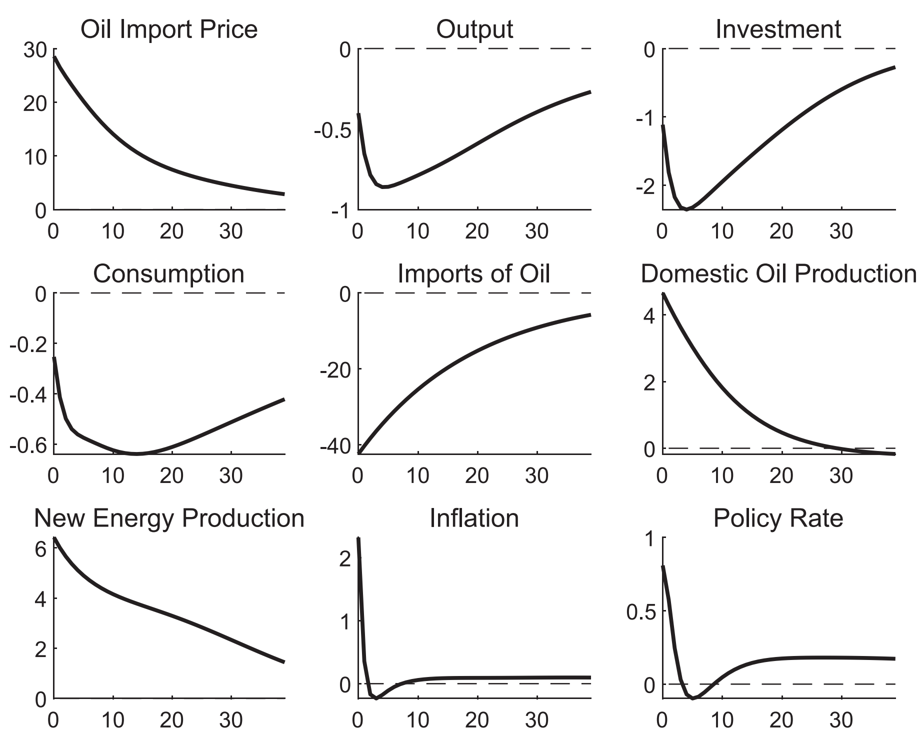

Fig. 10. The Impact of Oil Supply Shock on Macro-economy.

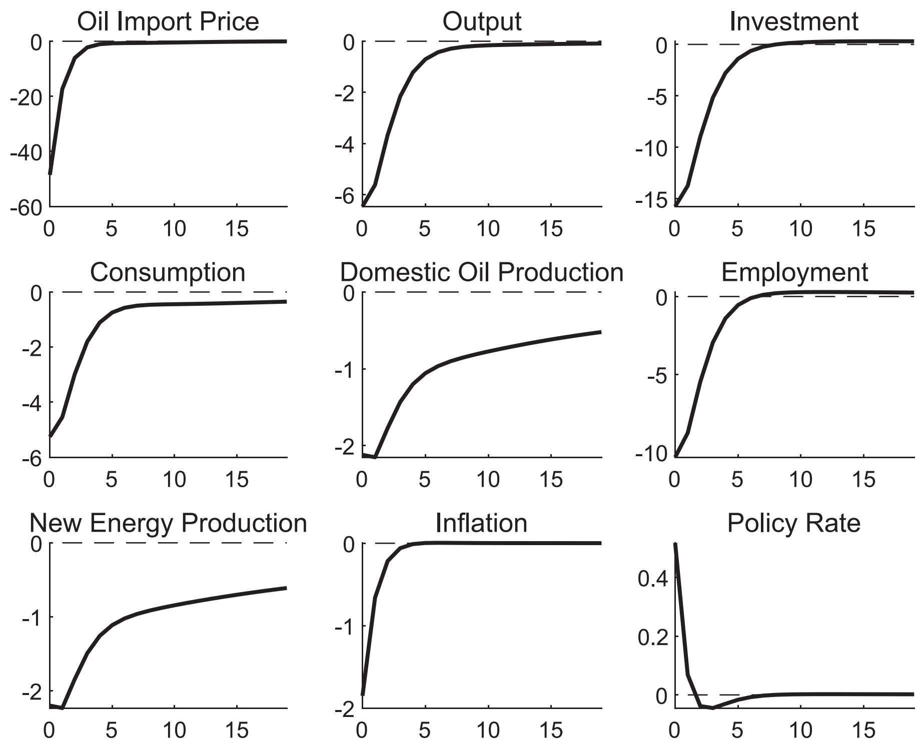

Fig. 11. The Impact of Monetary Policy Shock on Macro-economy

supply shock. Therefore, we first simulated the impact of exogenous oil supply shocks on the macro-economy in the case of different new energy market shares in the 12th Central Committee. It can be seen from Fig. 12 that the higher the market share of new energy, the smaller the impact of exogenous oil supply shocks on total output, total investment and total consumption. On the one hand, the higher the market share of new energy, the stronger the energy security, and thus the stronger the endogenous stability of the economy. On the other hand, the higher the market share of new energy, the less the impact of exogenous oil shocks on the volatility of total prices, At this time, the stability of monetary policy is also strong, and the impact mechanism of energy shocks on the real economy through monetary policy is weakened.

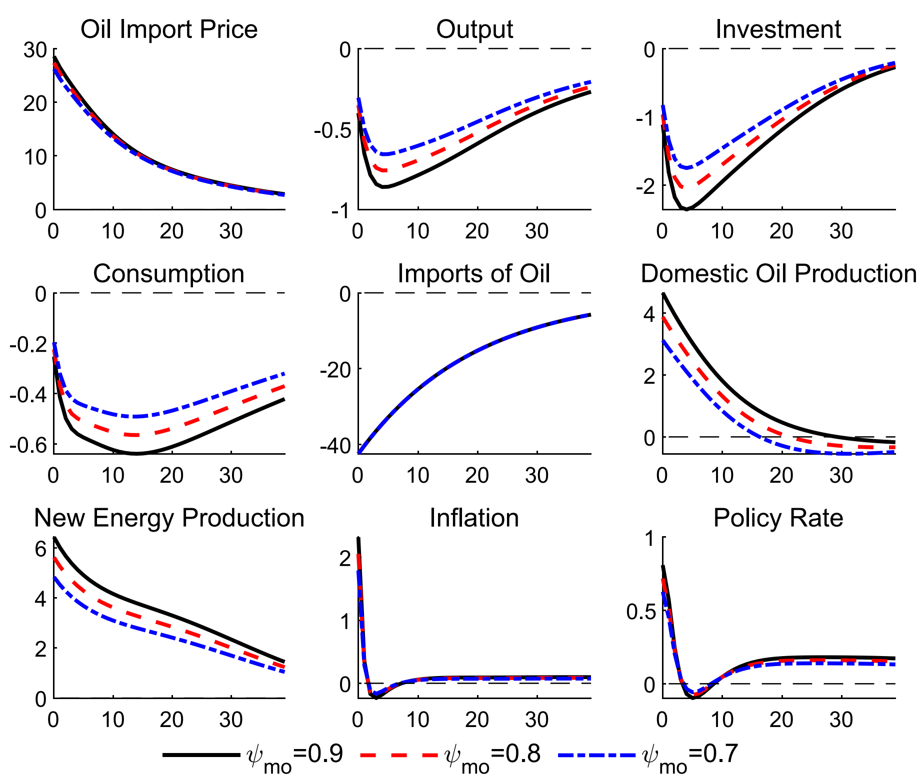

Fig. 12. The impact of exogenous oil supply shocks on the macro-economy under different market shares of new energy.

In addition to industrial upgrading, establishing corresponding energy strategic cooperation with resource rich countries will also help reduce the impact of exogenous energy shocks on the macro-economy. Therefore, we simulated the impact of different exogenous shocks on the main macroeconomic variables and the impact of exogenous energy supply uncertainty shocks on the macroeconomic in Fig. 13. It can be seen from Fig. 13 that the greater the impact of exogenous oil supply, the higher the response of inflation and interest rate, and the greater the decline in output, investment and consumption.

6. Welfare analysis

In the previous article, we analyzed the role of green adjustment of industrial structure in mitigating exogenous energy shocks from the perspective of numerical simulation. On this basis, this section will further analyze the benefits of green adjustment of industrial structure through welfare analysis. In order to better evaluate the importance of industrial structure adjustment to residents and government authorities, we will use both unconditional welfare analysis and loss function method to evaluate the changes in social welfare under the impact of exogenous energy under different industrial structures. Refer to Elekda ğ And Tchakarov (Elekdağ & Tchakarov, 2007), we use the relative ratio of the unconditional mean value of the spot utility function to the steady-state utility to describe the change of the unconditional consumption compensation:

$$E(U(C_t, N_t)) = U((1-\lambda)C, N) \tag{36}$$

λ is the change of unconditional consumption compensation. With reference to Woodford (Woodford, 2012), Ma Yong and Fu Li (Ma & Fu, 2020), the loss function of social welfare from the perspective of the government is set as:

$$W_G = \frac{1}{2}E_0\sum_{t=0}^{\infty}\beta^t\left(\lambda_\pi\pi_t^2 + \lambda_y y_t^2\right) \tag{37}$$

Among them, the subjective discount factor of the government sectorβ is consistent with that of the residential sector. $\lambda_\pi$and $\lambda_y$are respectively the preference parameters of the policy authorities for inflation and output, which are used to measure the loss of social welfare under different economic development levels and economic structure preferences. Referring to Ma Yong and Fu Li (Ma & Fu, 2020), we choose three representative weight ratios Ω_1, Ω_2 and Ω_3 to reflect the different preferences of the policy authorities: (1)$\Omega_1 = \{\lambda_\pi = 1, \lambda_y = 1\}$, indicating that the policy authorities have the same preferences for inflation and output; (2)$\Omega_2 = \{\lambda_\pi = 2, \lambda_y = 1\}$, indicating that the policy authorities are more concerned about price stability; (3)$\Omega_3 = \{\lambda_\pi = 1, \lambda_y = 2\}$, indicating that the policy authorities are more concerned about economic growth.The three industrial structures are as follows: (1) Industrial structure I Industrial structure consistent with the benchmark model, that is, in the model containing coal, thermal power generation accounts for 90% of the total power generation, and in the model containing oil, fossil energy accounts for 90% of the total energy; (2) The second industrial structure is that thermal power generation accounts for 80% of the total power generation in the model including coal, and fossil energy accounts for 80% of the total energy in the model including oil; (3) The third industrial structure is that in the model including coal, thermal power generation accounts for 70% of the total power generation, and in the model including oil, fossil energy accounts for 70% of the total energy.Based on the above two social welfare functions and the setting of relevant parameters, we have shown the loss of social welfare in the face of exogenous coal shocks and oil shocks under different industrial structures in Table 1. The greater the change x of unconditional consumption compensation, the more welfare loss, the

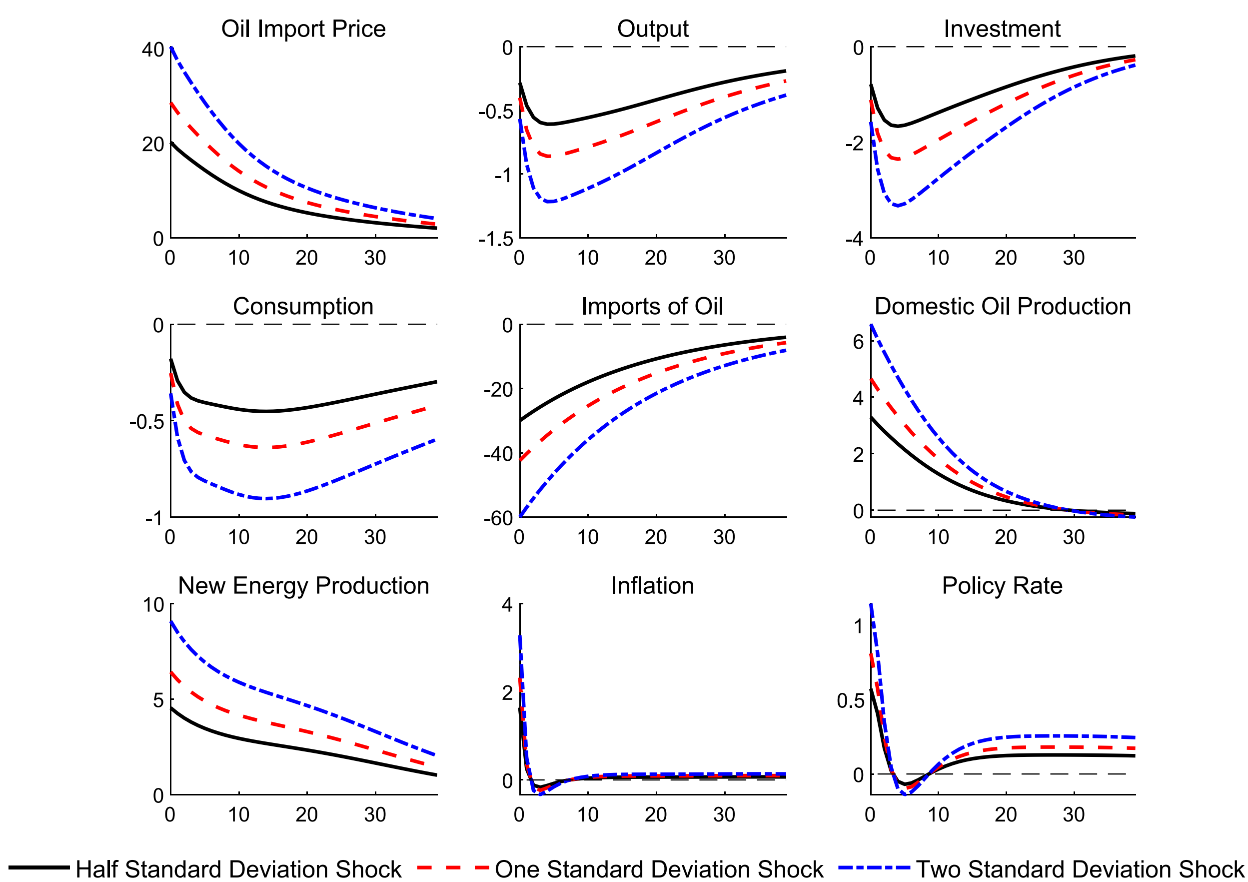

Fig. 13. Changes of major macroeconomic variables under exogenous shocks of different sizes

Table 1
Welfare loss caused by exogenous energy shocks under different industrial structures.

Coal shock							
Industrial structure	Change in unconditional consumption compensation	Welfare loss W_G			Percentage of welfare loss W_G in welfare loss W_G under the benchmark model (%)		
		Ω_1	Ω_2	Ω_3	Ω_1	Ω_2	Ω_3
Industrial Structure I	0.5478	35.8256	35.8697	71.6072	100	100	100
Industrial Structure 2	0.5363	29.1821	29.2173	58.3291	81.4560	81.4540	81.4570
Industrial Structure 3	0.5251	23.0461	23.0733	46.0649	64.3284	64.3253	64.3300

Oil shock							
Industrial structure	Change in unconditional consumption compensation	Welfare loss W_G			Percentage of welfare loss W_G in welfare loss W_G under the current industrial structure (%)		
		Ω_1	Ω_2	Ω_3	Ω_1	Ω_2	Ω_3
Industrial Structure I	0.1024	44.6522	45.0354	88.9212	100	100	100
Industrial Structure 2	0.0820	34.5547	34.8546	68.8094	77.3863	77.3939	77.3825
Industrial Structure 3	0.0620	25.9303	26.1579	51.6331	58.0718	58.0831	58.0661

smaller the welfare loss, and the higher the level of social welfare from the perspective of the government. It can be seen from Table 1 that in the change of unconditional consumption compensation, whether faced with exogenous coal shocks or exogenous oil shocks, the higher the proportion of green industries, the smaller the losses caused by exogenous energy shocks to the residential sector, which further supports our view that industrial green transformation not only helps to achieve carbon peaking and carbon neutralization, but also helps to improve China's energy security. As for the welfare analysis from the perspective of the government, as with the resident sector, when the proportion of green industry is higher, the welfare loss is smaller. At the same time, when we compare the welfare loss under different government objectives, we can find that under the impact of coal, when the government sector is more concerned about price stability, the more welfare gains from the transformation of green industry. Under the impact of oil, when government departments pay more attention to stable growth, the more welfare improvements brought by the green transformation of the industry. This is mainly because, under the impact of oil, the inflation caused by oil shocks is short-term and structural, and the impact on welfare is relatively small. Under the impact of coal, the government departments often guarantee the residents' electricity consumption by limiting the industrial power consumption, which often leads to the decline of industrial enterprises' income, thus leading to the decline of residents' total income and total demand, which leads to deflation. At this time, it is more important for the government departments to stabilize prices and increase total demand.

7. Conclusion and enlightenment

This chapter first analyzes the impact of coal shocks and oil shocks on China's macro-economy by building SVAR models, and then further analyzes the impact mechanism of the two shocks by building a small open DSGE model that includes coal shocks and oil shocks, which provides a corresponding theoretical basis for empirical research. Then, according to the reserves of China's coal resources and oil resources, we analyzed the policies to mitigate exogenous coal shocks from the perspective of industrial green transformation and reducing coal imports, analyzed the policies to mitigate exogenous oil shocks from the perspective of industrial green transformation and transnational cooperation, and finally studied the impact of industrial green transformation on China's energy security through welfare analysis. The research findings of this paper are as follows: First, both exogenous coal shocks and exogenous oil shocks will bring significant negative impacts on China's macro-economy. As the power price in China is controlled by the government, the coal shock mainly affects the power supply and then affects the production of enterprises, leading to a decline in total output. As petroleum products are widely distributed in the production chain, the oil shock mainly affects the total output by affecting the cost of industrial production and then monetary policy. Secondly, through numerical simulation, it is found that changing the industrial structure and reducing the coal import can reduce the negative impact of exogenous coal shocks on the macro-economy. However, due to the scarcity of oil resources in China, in addition to the green transformation of the industry, we can also reduce the impact of exogenous energy by establishing strategic cooperation with major oil countries. Third, through welfare analysis, this chapter finds that industrial green transformation can effectively mitigate the negative impact of exogenous energy shocks and improve China's energy security.

The policy implications of this paper mainly include the following two aspects: First, government departments should fully consider the impact of energy security while maintaining steady growth, and recognize the importance of strengthening energy security. Since the reform and opening up, China's energy policy has been mainly to support economic growth, but with the economic growth, China's energy dependence on foreign countries has been rising. At the same time, with the increasing number of black swan events in the world, energy security has begun to become one of the important factors affecting economic growth. China should change from energy reform to supporting economic growth to energy security and economic growth in parallel. This requires a green transformation of the industrial structure and a higher proportion of green clean energy and renewable energy in China's energy consumption. When formulating policies to promote the green transformation of industries, policy departments need to consider not only the benefits of carbon emission reduction, but also the benefits of energy security, so as to formulate reasonable reform policies.

Second, for the macroeconomic fluctuations caused by coal shocks, China should, on the one hand, speed up the reform of electricity price marketization to reduce the economic losses caused by power price restrictions, and on the other hand, reduce the dependence on coal by reducing the proportion of thermal power generation in the total power generation. Due to the important role of oil in industrial production, for macroeconomic fluctuations caused by oil shocks, government departments should, on the one hand, improve strategic cooperation with energy producing countries, and on the other hand, increase strategic reserves of oil, so that when oil shocks occur, oil reserves can be used to mitigate oil price fluctuations, thereby improving the stability and independence of monetary policy and reducing the negative impact of oil shocks.

CRediT authorship contribution statement

Chenyang Yu: Methodology, Conceptualization, Data curation, Writing - review & editing. **Piaoyang Xu:** Formal analysis, Investigation. **Piaoyang Xu:** Writing – review & editing, Data curation, Methodology, Writing - original draft.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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