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Macroeconomic effect of energy transition to carbon neutrality : Evidence from China's coal capacity cut policy

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Abstract:

While the retirement of fossil fuel capacity is an inevitable consequence of the energy transition to carbon neutrality, policymakers face challenges in setting the pace in order that the energy transition policies do not significantly damage the economy. This paper designs a dynamic stochastic general equilibrium (DSGE) model to examine the macroeconomic effects of coal capacity cut policy (CCP) shocks on the Chinese economy. The results show that: firstly, an energy policy shock can distort the transmission effect of coal supply and demand and other factors on coal prices. Secondly, the impact of different policy tools is significantly different on the macroeconomic system, in which the economic effect of advanced capacity replacement is the weakest. Thirdly, in the short term, no matter which policy tool is adopted, the CCP will inevitably lead to a reduction in social welfare levels. The study suggests that in the short term, the Chinese government can further release more replacement quotas of capacity with advanced production efficiency, and innovate other policy tools for coal industrial structural optimization and synergistic effects with environmental regulation. In addition, the results highlight the need for market mechanisms to further accelerate the energy transition over the long run.

Key words: Coal capacity cut; Coal price; DSGE model; Energy transition; carbon neutrality;

JEL Code: D5; E3; Q4

1 Introduction

Countries around the world are devoting considerable efforts towards transitioning from fossil fuels to renewable energy as a mean to reduce emisisons and achieve carbon neutrality. As the world's largest energy consumption country, China has announced strengthening its nationally determined contributions (NDCs) by achieving carbon neutrality by 2060 (Huaxia, 2020). This process can lead to the creation of redundant capacity in the fossil fuel sectors directly, especially the coal sector, and thus capacity cuts are needed. The regulation of coal overcapacity will continue to be the basic task of China's supply-side reforms during the 14th Five-Year Plan period due to the importance of the coal industry in the Chinese economy (Li and Yao, 2020).

As coal is one of the most basic intermediate inputs, coal capacity cuts would inevitably lead to fluctuations in coal supply and prices. These fluctuations above will potentially shock the economy. However, the implementation of the coal capacity cut policy (CCP) in China remains uncertain and its impact on macroeconomic variables is still controversial. For example, the radical price hike in 2016 forced the Chinese government to abandon its restrictions on working hours and relax its restrictions on new coal mine projects (Zhang et al., 2017; Shi et al., 2018, 2021). In order to reduce the resistance of energy transition, it is necessary to explore the macroeconomic effects of the CCP, especially its impact on coal prices, economic development and social welfare level.

Although the Chinese government liberalized its coal market in 2005, coal industry has been frequently subjected to closing mines policy, and coal production capacity becomes permanent excess due to the energy transition and China's low growth model (Shi et al., 2018). Given this, a series of CCP as shown in Table 1 were implemented to optimize the industrial structure, which may generate strong and exogenous intervention in coal price fluctuations. During the period of 2010-2017, an overheating in capacity investment took place, causing coal prices to fall sharply (Zhang et al., 2017). In order to boost the persistently low coal price, the Chinese government tried to significantly eliminate outdated coal capacity (see Table 1) and a key guiding opinion (P07) was issued in 2016 by the State Council to reduce the annual working days in coal mines from 330 to 276 (State Council, 2016).

Table 1 Key policies on capacity cut in China's coal industry

Code	Agency	Issued time	Main content
P01	State Council	2010-4-6	By the end of 2010, it is planned to close 8,000 small coal mines and eliminate 200 million tons of production capacity.
P02	NEA	2011-12-3	By the end of 2012, it is planned to eliminate 625 outdated coal mines and eliminate outdated production capacity of 23.47 million tons.
P03	NEA and CMS	2013-3-18	By the end of 2013, 1256 coal mines are planned to be eliminated, and 64.18 million tons of outdated production capacity will be eliminated.
P04	State Council	2013-10-6	Formulating the guiding opinions for resolving serious overcapacity contradictions.
P05	NEA and CMS	2014-3-27	In 2014, 1,725 outdated coal mines will be eliminated, with an outdated coal production capacity of 117.48 million tons.

P06	NEA and CMS	2015-3-26	In 2015, 1254 outdated coal mines will be eliminated, with an outdated coal production capacity of 77.79 million tons.
P07	State Council	2016-2-5	Within three to five years, it is planned to withdraw coal capacity by about 500 million tons; Since 2016, the annual working days of coal mines changes from 330 to 276 (276 working days).
P08	NDRC, NEA and CMS	2016-7-23	The capacity of newly built advanced coal mines should be reduced and replaced with those of closed coal mines.
P09	NDRC	2017-4-5	Establishing a long-term mechanism for advanced coal capacity replacement.
P10	NDRC	2017-4-25	Beginning in 2017, the policy of 276 working days will no longer be implemented, and the policy of 330 working days will be resumed.
P11	NDRC and NEA	2017-11-28	Establishing a minimum and maximum inventory system on the coal supply side.
P12	NDRC	2018-11-23	Disposing of the debt problems of "zombie companies" and de-capacity companies in coal industry.
P13	NDRC, MIIT and NEA	2019-4-30	Before the end of 2020, completing the regional and central coal capacity reduction tasks, as well as the disposal of "zombie enterprises"; Broadening the channels for employee resettlement.
P14	NEA	2020-7-14	Formulating the task and decomposition plans of the coal power industry to eliminate outdated coal capacity in 2020.

Note: 1) NEA, CMS, NDRC and MIIT refer to National Energy Administration, State Administration of Coal Mine Safety, National Development and Reform Commission, and Ministry of Industry and Information Technology of the People's Republic of China, respectively.

2) P01 refers to "Notice on further strengthening the elimination of backward production capacity"; P02 denotes "Notice on the deployment of the 2012 coal industry to eliminate outdated production capacity"; P03 represents "Notice on the deployment of the elimination of backward production capacity in the coal industry in 2013"; P04 refers to "Guiding opinions on resolving the contradiction of serious overcapacity"; P05 denotes "Notice on the deployment of the 2014 coal industry to eliminate backward production capacity"; P06 refers to "Notice on the deployment of the 2015 coal industry to eliminate backward production capacity"; P07 represents "Guiding opinions to resolve overcapacity problem of coal industry"; P08 refers to "Notice on implementing reduction and replacement to strictly control new coal production capacity"; P10 denotes "Video and telephone conference held by the National Development and Reform Commission"; P11 denotes "Notice on guiding opinions and assessment methods for establishing and improving the minimum and maximum coal inventory system"; P12 refers to "Notice on further completing the debt disposal of 'Zombie Enterprises' and de-capacity enterprises"; P13 refers to "Notice on completing the work of resolving excess capacity in key areas in 2019"; P14 represents "Notice on the goal of eliminating outdated production capacity in the coal power industry in 2020".

Source: Authors' compilation based on policies listed at State Council (http://www.gov.cn/) and NRDC (http://www.ndrc.gov.cn/).

Under this dramatic policy, the coal prices skyrocketed to levels beyond the government's expectations in 2017 and could not be eased by a gradual release of production capacity (Shi et al., 2018). As coal prices fall, the number of workers in coal mining in 2018 dropped significantly by 28% compared to that in 2015, while the consumer price index (1978=100) increased from 615% in 2015 to 670% in 2019 (NBS, 2020). This indicates that the associated coal price fluctuations may have had a significantly negative impact on China's macro-economy after the implementation of the CCP. Given this, a great deal of investigation remains to be done into the impact of the CCP on coal prices and the macro economy.

Many scholars argued that from a long-term perspective, the regulation of coal capacity above might hinder the marketization of coal prices and lead to energy price distortions (Cui and Wei, 2017; Ju et al., 2017; Shi et al., 2020). And there are many recent studies on China's CCP, such as its price impact (Shi et al., 2018; Zhang et al. 2018), allocation of capacity among provinces (Wang et al., 2020, 2018), and capacity permit trading as an alternative to mandatory closure of mines (Shi et al., 2020, 2021). Regarding the macroeconomic effects of the CCP, the relevant literature mainly focuses on environmental regulation, not as much as expected. Several scholars investigated the effects of the CCP on air pollution and emission reduction, but simply regarded the CCP as a reduction in coal production, which weakens the reliability of their empirical results (Li and

Yao, 2020; Xiao et al., 2020).

To fill the literature gap, this paper adopts a dynamic stochastic general equilibrium (DSGE) model to simulate the macroeconomic effects of the CCP shocks. Its contributions are threefold. Firstly, this paper establishes a DSGE model with the exogenous shock of the CCP, providing a unique case to evaluate energy transition policy from the perspective of the energy supply-side. Secondly, a coal goods-producing sector is introduced in the intermediate goods-producing process to explore the impact of the CCP shock on coal production and pricing decisions. This assumption is closer to the economic reality. Thirdly, the measured effectiveness and persistence of different policy tools on coal prices, economic development and social welfareprovides valuable references for the ongoing energy transition in China and other countries.

The remainder of this paper is organized as follows: Section 2 describes the related literature. Section 3 introduces the models and its symmetric equilibrium conditions, and then the calibration and Bayesian method are used to estimate the model parameters in section 4. Next, the macroeconomic effects of the CCP in different scenarios are identified through impulse response. Section 6 concludes the paper and provides some policy implications.

2 Literature review

Along with the marketization of energy prices, the impact of energy policy on energy prices and the macro economy has received increasing amounts of attention from academics, practitioners and politicians in recent decades (Bernanke et al., 1997; Wang and Tian, 2015; Wang et al., 2020).

In terms of the causes of energy price fluctuations, most of the studies have focused on market supply and demand, and only few studies have been carried out on policy factors (Zhao et al., 2010; Oikonomou et al., 2012; Zhang et al., 2019). Regarding the CCP and coal prices, Shi et al. (2020) proposed that policy intervention, especially the command and control approach, may lead to unexpected coal price fluctuations, which will force governments to cancel and even reverse their policies from time to time. For example, the 276 working days mechanism was cancelled after only one year (Shi et al., 2018). Wang et al. (2020) adopted the difference-in-differences model to conclude that the CCP would contribute to increases in coal prices without consideration of the impact of coal supply and demand.

However, these studies divided the CCP into the 2013 policy and the 2016 policy (measured by the 276 working days mechanism), ignoring the diversity of policy tools in the same period. By contrast, other scholars empirically concluded that the pricing mechanism, tax instrument and other energy policies could generate energy price distortions, which in turn would affect China's economic development and social welfare (Sun et al., 2016; Ju et al., 2017; Shi and Sun, 2017). Overall, these studies provide valuable references of energy policies in regulating price fluctuations.

With regards of the macroeconomic effects, most scholars have concluded that energy policy shocks can affect economic activities through energy price fluctuations (Kilian and Vigfusson, 2011; Zhang et al., 2018; Guo et al., 2019). Pindyck (1980) claimed that an increase in energy prices results in direct losses and indirect policy costs for actual national income, which are supported by Finn (2000). Speaking of coal prices, Lin and Mou (2008) found that with the same proportion increases, coal prices have significantly negative impact on economic growth, two to three times larger than that of oil prices. Further, Guo et al. (2016) proposed that inflation responds very abruptly to China's coal price shock in the short run, but that the impact regresses rapidly with time.

When focusing on the impact of the CCP, several scholars proposed that a path exists to affect the macro economy through coal supply. Zhang et al. (2013) deduced that the coal supply gap follows a similar trend as GDP gap from the coal supply side. Then they used coal capacity utilization as the proxy variable of the CCP and concluded that coal capacity utilization has a long-term coupling relationship with economic growth (Zhang et al.,2018). After that, Shi et al. (2020) proposed that the current CCP was found to be technically infeasible since it leads to a significant increase in coal prices and economic costs. The above studies mainly explore the long-term relationship between coal prices, the CCP and economic growth, but lack in-depth analyses of the dynamic interaction between energy policy and macroeconomic system.

Among these studies, the mainstream models include the CGE model (Tang et al., 2017; Li and Yao, 2020; Xiao et al., 2020) and the DSGE model (Balke and

Brown, 2018; Aminu, 2019) based on general equilibrium theory. Generally, the CGE model has great advantages in analyzing the sectoral economic linkages, but it is difficult to cope with the dynamics and uncertainties of the macroeconomic system (Zhang and Zhang, 2020). Due to the lack of microeconomic basis, the CGE model also has a deficiency to avoid the "Lucas Critique" [1](Lucas, 1976). Therefore, the DSGE model has been introduced to explore the economic effects of energy transition policy in recent years. Specifically, Punzi (2019) adopted an open DSGE model to examine the impact of energy price uncertainty on macroeconomic variables. Meanwhile, other scholars establish the DSGE model to compare the economic and environmental effects of different energy policies (Argentiero et al., 2018; Xiao et al., 2018; Zhang and Zhang, 2020). To this end, we employed a DSGE model to analyze the impact of the CCP on macroeconomic variables.

In addition, several scholars found that price fluctuations are sticky due to the added menu cost, and that this cost plays an important role in the impact of price shocks on total output (Angeloni et al., 2006). On this basis, this paper also attempts to examine the stickiness of goods prices in order to improve the rationality of the simulation of China's real macroeconomic activities in a closed DSGE model.

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[1] Lucas (1976) proposed the policy non-invariance argument, i.e. the "Lucas Critique", to interpret econometric policy using deep rational expectations. Lucas pointed out that when making expectations about future events, the economic agents not only consider the past, but also estimate the impacts of current events on the future, which indicates that the economic agents can change their current decision-making behaviors based on the expected influence of current economic policies. The changes in behavior make it difficult to evaluate economic policy since the traditional economic models are almost incapable to identify changes in behavioral parameters.

3 Methodology and data

3.1 Overview of the economic system

This paper argues that the implementation of the overcapacity policy can be disturbed by exogenous random activities in the short term, and coal companies will adjust their optimal production and investment behaviors according to policy expectations, while the optimal consumption behavior of downstream coal-consuming companies will also be adjusted. As mentioned in Section 2, both CGE model and DSGE model can describe a whole economy via a set of equations. Among them, CGE model is the mainstream tool for economic simulation of long-term equilibrium relations, usually starts with an empirical SAM and interprets it as the equilibrium of some economy, then builds an Arrow-Debreu economy that replicates the SAM as its equilibrium solution (Gräbner, 2014). Differently, DSGE model is often used for economic simulation of short-term random shocks. All the behavior is microfounded in the sense that it is derived from clearly specified utility or production functions which makes the model immune, at least in theory, to the “Lucas Critique” (Lucas, 1976). According to the characteristics of the above two models, DSGE model has more advantages in examining the macroeconomic effects of this policy.

The specific DSGE model used here takes the basic features of those developed by Ireland (2003, 2004, 2011) and its modeling strategy follows Canova’s (2009) by using a small-scale model. The model economy, as shown in Fig.1, consists of a representative household, a representative finished-goods-producing firm, a continuum of intermediate-goods-producing firms indexed by $i \in (0,1)$, a continuum of coal-goods-producing firms indexed by $j \in (0,1)$, and the government by implementing monetary policy and the CCP. Compared with Ireland (2011), our model has three improvements that are reflected in three main equations: 1) constructing a new utility function without considering the effect of currency holdings; 2) introducing the capital and coal inputs into the production function of the intermediate firms; 3) adding coal firms which sell all coal goods competitively to the intermediate firms.

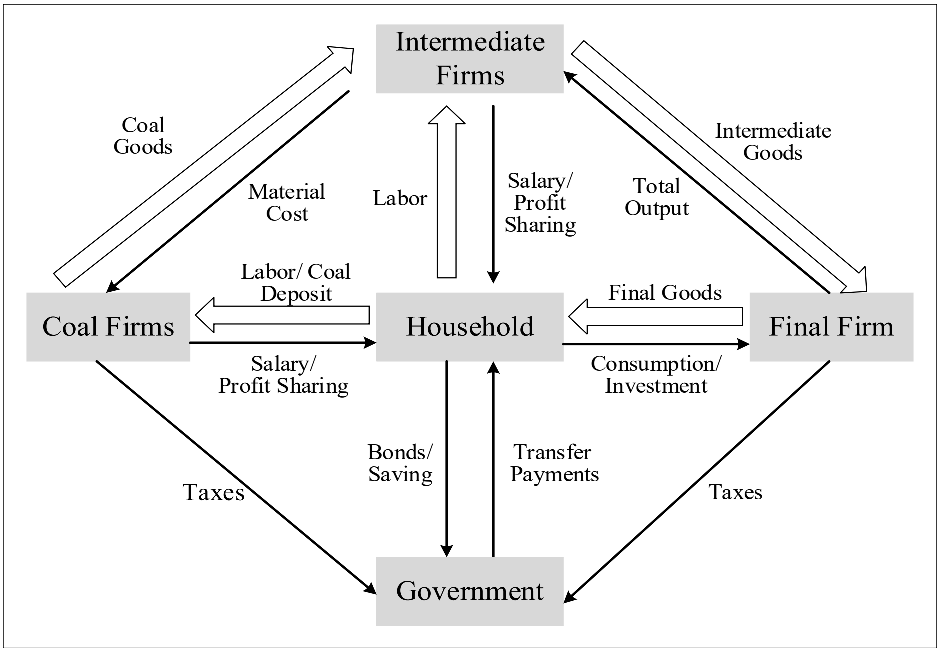

Fig.1 Frame of the macro-economic system

Without loss of generality, this paper proposes not considering the international coal market because imports, on average, have accounted for only less than 7% of China’s total coal demand over the past five years (NBS, 2020). In this closed economic system, the transmission mechanism of the CCP is as follows: with the implementation of the CCP, a random shock is assumed to affect the coal firms’ optimal production and pricing decisions through the stock of coal reserves, acting as a policy-push shock. During each period $\mathrm{t} = 0,1,2,\ldots,$ each intermediate firm uses coal goods to produce distinct, perishable intermediate goods for finished goods production. Under budget constraints, the expenditures of the representative household and the government will also be adjusted to bring dynamic changes in final output, the inflation rate, investment and other economic variables under the fixed interest rate.

Based on these features, we proposed that in this system, each economic agent chooses its optimal strategy according to the principle of maximizing revenue, while the representative household aims to maximize its utility. Thus, the CCP can trigger resource redistribution among all economic agents.

3.2 DSGE model setting

(1) The representative household

All households are homogenous in pursuing their maximum utility. Hence, it is feasible to analyze the behavior of a representative household. In the system, the representative household carries M_{t-1} units of money, B_{t-1} bonds, k_{t-1} units of physical capital and the ownership of amounts stock of coal deposit[2] S_{t-1} into period t.

During the period t, the household provides h_t^y and h_t^c units of labor and k_t^y and k_t^c units of capital for various intermediate firms and coal firms, respectively. Hence, the labor distribution is $h_t = h_t^y + h_t^c$. Meanwhile, the household provides amounts of coal deposit stocks S_{t-1} for coal firms and

[2] Coal deposits refer to the proven coal reserves that have not yet been mined and which cannot be directly consumed by the representative household.

purchases the final goods at the nominal price P_t from the representative final firms and its expenditure consists of c_t, i_t^y and i_t^c to be consumed and invested. Hence, capital accumulation is $k_t = k_t^y + k_t^c$, where

$$k_t^y = (1-\delta)k_{t-1}^y + i_t^y \tag{1}$$

$$k_t^c = (1-\delta^c)k_{t-1}^c + i_t^c \tag{2}$$

In these capital accumulation constraints, δ and δ^c represent the depreciation rate of intermediate firms and coal firms respectively, satisfying $1 > \delta > 0,\ 1 > \delta^c > 0$. Moreover, in this period, the household also receives a lump-sum nominal transfer T_t from the government and purchases B_t new bonds at the cost of $1/r_t$ units of money per bond, where r_t denotes the gross nominal interest rate between *t* and *t+1*.

At the end of the period *t*, the household receives D_t units of money in the form of dividend payments from the various intermediate goods-producing firms, as well as D_t^c units of money from coal firms. Thus, the budget constraint of the representative household is as follows.

$$c_t + i_t^y + i_t^c + \frac{M_t}{P_t} + \frac{B_t}{P_t r_t} \leq \frac{M_{t-1} + B_{t-1} + w_t^y h_t^y + w_t^c h_t^c + r_t^k k_t^y + R_t^k k_t^c + f_t S_{t-1} + D_t + D_t^c + T_t}{P_t} \tag{3}$$

where, w_t^y and w_t^c denote the nominal wage of intermediate firms and coal firms respectively, r_t^k and R_t^k denote the nominal rental rate for capital k_t^y and k_t^c, and f_t is the cost for exploitation of the coal stock S_{t-1}.

Drawing on the classic form of the utility function, this paper assumes that the representative household obtains positive utility from consumption and negative utility from supplying labor. Endowed with one unit of time per period, the household aims to maximize the expected utility function:

$$max\, E_t[\sum_{t=0}^{\infty} \beta^t u(C_t, h_t^y, h_t^c)] \tag{4}$$

$$u(C_t, h_t^y, h_t^c) = a_t\left[ln(c_t - b_c c_{t-1}) - \frac{(h_t^y)^{1+\eta^y}}{1+\eta^y} - \frac{(h_t^c)^{1+\eta^c}}{1+\eta^c}\right] \tag{5}$$

where, both the discount factor β and the habit formation parameter b_c (Christiano et al., 2005) are $0 < \beta < 1$ and $0 \leq b_c < 1$; the supply elasticities of h_t^y and h_t^c satisfies $\eta^y > 0$ and $\eta^c > 0$; the preference shock a_t (Ireland, 2011) follows the stationary autoregressive process:

$$ln(a_t) = \rho_a ln(a_{t-1}) + \varepsilon_t^a \tag{6}$$

for all *t* = 0, 1, 2, …, with the estimated parameter ρ_a meets $0 \leq \rho_a < 1$. ε_t^a is defined as an irrelevant random variable ($\varepsilon_t^a \sim N(0,\ \sigma^a)$). By rationally choosing consumption, labor supply, coal deposit supply, investment and bonds holding, the representative household maximizes its utility (Eq.4) while meeting the budget constraint (Eq. 3), the first order conditions (FOC) are as follows.

(a) the Euler equation of consumption:

$$\lambda_t = a_t(c_t - b_c c_{t-1})^{-1} - \beta b^C E_t[a_{t+1}(c_{t+1} - b_c c_t)^{-1}] \tag{7}$$

(b) the equations of labor supply:

$$(h_t^y)^{\eta^y} = \frac{\lambda_t w_t^y}{a_t P_t} \tag{8}$$

$$(h_t^c)^{\eta^c} = \frac{\lambda_t w_t^c}{a_t P_t} \tag{9}$$

(c) the equation of bonds holding:

$$\lambda_t = \beta r_t E_t\left({}^{\lambda_{t+1}}/_{\pi_{t+1}}\right) \tag{10}$$

(d) the equations of capital:

$$\lambda_t = \beta E_t \left[{\lambda_{t+1} r_{t+1}^k}/{P_{t+1}} + \lambda_{t+1}(1-\delta_t) \right] \tag{11}$$

$$\lambda_t = \beta E_t \left[{\lambda_{t+1} R_{t+1}^k}/{P_{t+1}} + \lambda_{t+1}(1-\delta_t^c) \right] \tag{12}$$

in which, λ_t is the nonnegative Lagrange multiplier on the budget constraint for period t and $\pi_t = P_t / P_{t-1}$ refers to the gross inflation rate between t and t + 1.

(2) The representative final firm

According to Ireland's model (Ireland, 2011) and the classic setting in the DSGE model, this paper proposed that the final goods are produced by a representative finished-goods-producing firm with constant return technology in a perfectly competitive environment. And the final goods y_t are packaged by a certain number of intermediate goods $y_t(i)$ ($i \in [0,1]$) at nominal price $P_t(i)$, and all the intermediate goods satisfy the Dixit-Stiglitz technology of the constant-scale return (Dixit and Stiglitz, 1977). Hence, the final goods y_t are as follows:

$$y_t = \left[\int_0^1 y_t(i)^{\frac{\theta-1}{\theta}} di \right]^{\frac{\theta}{\theta-1}} \tag{13}$$

where, θ represents the substitution elasticity of intermediate goods and $\theta > 1$. In the perfectly competitive market, the final firm aims to maximize its profits: the FOC for this problem is:

$$y_t(i) = [P_t(i)/P_t]^{-\theta} y_t \tag{14}$$

for all $i \in [0,1]$, $-\theta$ measures the constant price elasticity of demand for each intermediate good. Since the representative final firm is the recipient of price so that the price of final goods is equal to the marginal cost. As a result, the following relationship between the prices of final goods P_t and intermediate goods $P_t(i)$ is obtained:

$$P_t = \left[\int_0^1 P_t(i)^{1-\theta} di\right]^{\frac{1}{1-\theta}} \tag{15}$$

(3) Intermediate firms

Based on Ireland's model, the capital and coal inputs are introduced in the production process of intermediate goods. In other words, the intermediate goods-producing firm i hires $h_t^y(i)$ units of labor, $k_{t-1}^y(i)$ units of capital from the representative household, and $ec(i)$ units of coal goods from the coal firms in order to produce $y_t(i)$ units of intermediate good i according to the constant-returns-to-scale technology described by:

$$y_t(i) = (z_t h_t^y(i))^{\alpha_1} (k_{t-1}^y(i))^{\alpha_2} (ec_t(i))^{\alpha_3} \tag{16}$$

where, $ec_t(i)$ denotes the coal goods; α_1, α_2 and α_3 represent the output elasticities of labor, capital and coal inputs, respectively while $\alpha_1 + \alpha_2 + \alpha_3 = 1$. The aggregate technology follows a random walk with drift:

$$\ln(z_t) = \rho_z \ln(z_{t-1}) + \varepsilon_t^z \tag{17}$$

in which, the estimated ρ_z meets $0 \le \rho_z < 1$ and an irrelevant random variable ε_t^z meets $\varepsilon_t^z \sim N(0, \sigma^z)$. According to Ireland (2011), the price stickiness is taken into account, which means that the intermediate firms are in a monopolistic competitive market while each intermediate firm faces a quadratic cost of adjusting its nominal price between periods, measured in terms of the finished good: $\frac{\phi}{2}[P_t(i)/\pi P_{t-1}(i) - 1]^2 y_t$, where $\phi > 0$ governs the size of the price adjustment cost and π measures the gross steady-state inflation rate.

At the end of period t, the intermediate firm i seeks to maximize its market value by optimizing $P_t(\mathrm{i})$ (see Eq. 18). $\beta^t \lambda_t$ is the representative household's marginal utility of consumption and $D_t(i)/P_t$ denotes the real value of the firm's profits and dividend payments during period t, which is given by Eq. 19.

$$max\, E_t[\sum_{t=0}^{\infty} \beta^t \lambda_t ({}^{D_t(i)}/_{P_t})] \tag{18}$$

$$\frac{D_t(i)}{P_t} = \frac{P_t(i) y_t(i) - w_t^y h_t^y(i) - r_t^k k_{t-1}^y(i) - cp_t ec_t(i)}{P_t} - \frac{\phi}{2} [\frac{P_t(i)}{\pi P_{t-1}(i)} - 1]^2 y_t \tag{19}$$

where, cp_t denotes the nominal price of coal goods. To solve this problem, the FOC is derived as follows, reflecting the New Keynesian Phillips curve: the inflation rate depends on the expected future inflation and the actual marginal cost. For any intermediate goods, the actual marginal cost ($mc_t(i)/P_t$) represents the incremental cost created by each unit of extra output, which is related to the technical level and prices of the input factors.

$$\frac{mc_t(i)}{P_t} = \frac{(w_t^y)^{\alpha_1} (r_t^k)^{\alpha_2} (cp_t)^{\alpha_3}}{(z_t)^{\alpha_1} {\alpha_1}^{\alpha_1} {\alpha_2}^{\alpha_2} {\alpha_3}^{\alpha_3}} \tag{20}$$

$$(\theta - 1) \left[\frac{P_t(i)}{P_t}\right]^{-\theta} = \theta \left[\frac{P_t(i)}{P_t}\right]^{-\theta-1} \frac{mc_t(i)}{P_t} - \phi \frac{\pi_t}{\pi} \left[\frac{\pi_t}{\pi} - 1\right] + \beta\phi E_t \left\{\frac{\lambda_{t+1}}{\lambda_t} \left[\frac{\pi_{t+1}}{\pi} - 1\right] \frac{\pi_{t+1}}{\pi} \frac{y_{t+1}}{y_t}\right\} \tag{21}$$

(4) Coal goods-producing firms

This paper assumes that all coal resources are homogeneous production factors in the intermediate goods-producing process, regardless of the final consumption of the coal in bulk. Similarly, coal goods are indexed by $j \in [0,1]$, where coal firm j produces coal good j. And the coal goods-producing firm j hires $h_t^c(j)$ units of labor, $k_{t-1}^c(j)$ units of capital and $S_{t-1}(j)$ units of coal deposits from the representative household in order to produce $ec_t(j)$ units of coal good j according to the constant-returns-to-scale technology described by

$$ec_t(j) = (z'_t h_t^c(j))^{\beta_1}(k_{t-1}^c(i))^{\beta_2}(S_{t-1}(j))^{\beta_3} \tag{22}$$

where, β_1, β_2 and β_3 represent the output elasticities of labor, capital and the coal deposit stocks, respectively while $\beta_1 + \beta_2 + \beta_3 = 1$. The aggregate technology z'_t follows a random walk with drift:

$$\ln(z'_t) = \rho_{z'} \ln(z'_{t-1}) + \varepsilon_t^{z'} \tag{23}$$

in which, the estimated $\rho_{z'}$ meets $0 \leq \rho_{z'} < 1$ and an irrelevant random variable $\varepsilon_t^{z'}$ meets $\varepsilon_t^{z'} \sim N(0, \sigma^{z'})$. Note that for all $j \in [0,1]$, the cost of the exploitation, f_t, has no differences and the stock $S_{t-1}(j)$ is a very large value. Following Argentiero et al. (2018), the coal firm j exploits $S_{t-1}(j)$ coal deposit units in period t, while the depreciation rate of the coal deposits satisfies $1 > \delta^s > 0$. The coal mining constraint is given by:

$$ec_t = \int_0^1 ec\,(j)dj = \int_0^1 ec\,(i)di = \int_0^1 [(1-\delta^s)S_{t-1}(j) - S_t(j)]dj \tag{24}$$

At the end of period t, the coal firm j seeks to maximize its total market value, seeing Eq.25. $\beta^t \rho_t$ measures the representative household's marginal utility of consumption and $D_t^c(j)/P_t$ denotes the real value of the coal firm's profits and dividend payments during period t, which is given by Eq.26.

$$max\, E_t \left\{ \sum_{t=0}^{\infty} \beta^t \rho_t [{D_t^c(j)}/{P_t} + \lambda'_t((1-\delta^s)S_{t-1}(j) - S_t(j) - ec(j))] \right\} \tag{25}$$

$$\frac{D_t^c(j)}{P_t} = \frac{cp_t ec_t(j)}{P_t} - \frac{w_t^c h_t^c(j) + R_t^k k_{t-1}^c(j) + f_t S_{t-1}(j)}{P_t} \tag{26}$$

Unlike the intermediate goods, each representative coal firm produces homogeneous, non-perishable and exhaustible goods. According to the economics of exhaustible resources (Hotelling, 1931)[3], coal reserves will decrease along with coal mining and producing, and thus the expected coal price is related with the cost for exploitation and marginal productivity of capital (or labor), that is "the Hotelling rule"[4]. Among the existing literature, Argentiero et al. (2018) applied this rule to a DSGE model, assuming that the production behavior of the representative fossil fuels' producer follows "the Hotelling rule". Then they put forward the expected price function to obtain the FOC conditions of fossil fuels firms. Given that coal is the primary fossil fuel, we set the relationship between the expected coal price and the cost for the exploitation as shown in Eq.27, following the practice of Argentiero et al. (2018).

$$\beta\rho E_t(cp_{t+1}) = \frac{f_t}{1-\delta^s} + \beta\rho E_t\left(\frac{1+R_{t+1}^k-\delta^c-(1-\delta^s)}{\underbrace{\beta_2\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2-1}\left(s_{t-1}(j)\right)^{\beta_3}}_{MP\ of\ capital}}\right) - \frac{\underbrace{\beta_3\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2}\left(s_{t-1}(j)\right)^{\beta_3-1}}_{MP\ of\ coal\ deposits}}{\underbrace{\beta_2\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2-1}\left(s_{t-1}(j)\right)^{\beta_3}}_{MP\ of\ capital}}\left(\frac{R_t^k}{1-\delta^s}\right) \quad (27)$$

(5) Government

In this paper, the government primarily intervenes in the optimal behaviors of other economic agents by issuing bonds and currencies through the central bank, except for its transfer payments. This paper proposes that the behaviors

[3] Hotelling (1931) found that in a perfectly competitive market, the first to be mined is low-cost mineral resources, and then the high-cost mineral resources; the expected mineral product price in period t+1 equals the marginal mining cost and marginal use cost, while the latter refers to the present value of the opportunity cost lost at the margin, that is, the marginal opportunity cost (net present value) for current usage instead of future usage.

[4] "The Hotelling rule" is defining the net price path as a function of time while maximizing rent in the time of fully exploiting a non-renewable natural resource (Livernois, 2009). The maximum rent is known as Hotelling rent or scarcity rent and is the maximum rent that could be obtained while emptying the stock resource. Hotelling's rule can be expressed by the equilibrium situation representing the optimal solution, which is that the rent equals the shadow value of the natural resource and natural capital.

of the government have a significant effect on the optimal decisions of the representative households and firms. Firstly, according to the budget constraint, the representative household can buy bonds issued by the government, and the government monetary transfer payments are also part of every household's income. Secondly, the government controls the entire money supply in the macroeconomic system and maintains the stability of the money supply by adjusting the interest rate. Thirdly, the government has the right to formulate and implement macro-policies, especially the CCP.

(a) The monetary policy

Following Ireland (2011) and Xu et al. (2015), the government conducts its monetary policy according to a variant of the Taylor (1993) rule, given as:

$$\ln(r_t) = \ln(r_{t-1}) + \rho_\pi \ln\left({\pi_t}/{\pi}\right) + \rho_y \ln\left({y_t}/{y}\right) + \varepsilon_t^e \tag{28}$$

where, y denotes the steady-state value of y_t; ρ_π and ρ_y represent the response to deviations of inflation and final output, respectively; ε_t^r is the irrelevant random variable with $\varepsilon_t^r \sim N(0, \sigma^r)$.

(b) The fiscal policy

Thus, the budget constraint is as follows.

$$M_{t-1} + B_{t-1} + T_t = \frac{B_t}{r_t} + M_t \tag{29}$$

To simplify the conditions for clearing the money and bond markets, the impact of bonds is assumed not to be considered on the revenues and expenditures of households, firms and government, i.e. $B_{t-1} = B_t = 0$ and $M_{t-1} + T_t = M_t$.

(c) The coal capacity cut policy (CCP)

Except for 276 working-day mechanism mentioned above, the policy tools of the CCP mainly include eliminating backward capacity and advanced capacity replacement. Backward capacity refers to mines with an annual production of less than 300000 tons and small coal mines that need to be eliminated according to State Council (2010); advanced capacity is recognized as mines with advanced technology, high production efficiency, high resources utilization, low environmental pollution and other standards (State Council, 2016). According to MOHRSS (2016) and NDRC (2017), the government employed the above policy tools to govern China's coal overcapacity, which has led to an improvement in energy transition and capacity utilization[5].

Based on the existing literature, coal prices can be affected by market fundamentals, policy factors and other random factors (Kilian, 2008; Sheng et al., 2014). And Zhang et al. (2017, 2018) found that capacity utilization has an actual impact on coal prices in China. Given this, we proposed that the implementation of the CCP will bring changes in the coal deposit scale and capacity utilization directly under coal mining constraint. For example, coal deposit scale can be simplified to a substantial shrink if coal mines' working days are reduced from 330 to 276. Then the above changes will cause coal price to fluctuate under "the Hotelling rule".

Given the three tools of the CCP currently being used by China's government, this paper sets three different policy mechanisms as shown in Table 2.

[5] Coal capacity utilization is defined as the ratio of coal production to coal capacity, i.e., the available coal deposits (Zhang et al., 2018).

Mechanism I: In S1, an exogenous change of working days caused by the CCP brings a reduction in coal deposit scale. Drawing on the experience of cost-push shock (Clarida et, al. 1999), we proposed that at the beginning of period t, coal deposit scale is affected by a policy-push shock (ϑ_t), referring to the CCP shock. And it follows a random walk with drift:

$$\ln(\vartheta_t) = \rho_\vartheta \ln(\vartheta_{t-1}) + \varepsilon_t^\vartheta \tag{30}$$

in which, the estimated ρ_ϑ meets $0 \le \rho_\vartheta < 1$ and an irrelevant random variable ε_t^ϑ meets $\varepsilon_t^\vartheta \sim N(0, \sigma^\vartheta)$. Note that a positive policy-push shock (ϑ_t) calls for a tightening of the CCP, that is, an increase in the short-term policy intensity. Combined with "the Hotelling rule", Eq. 24 and Eq. 27 are rewritten as

$$ec_t = \int_0^1 ec\,(j)dj = \int_0^1 ec\,(i)di = \int_0^1 [(1-\delta^s)\vartheta_t S_{t-1}\,(j) - S_t(j)]dj \tag{31}$$

$$\beta\rho E_t(cp_{t+1}) = \frac{f_t}{(1-\delta^s)\vartheta_t} + \beta\rho E_t\left(\frac{1+R_{t+1}^k-\delta^c-(1-\delta^s)}{\beta_2\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2-1}\left(S_{t-1}(j)\right)^{\beta_3}}\right.$$
$$\left. - \frac{\beta_3\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2}\left(S_{t-1}(j)\right)^{\beta_3-1}}{\beta_2\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2-1}\left(S_{t-1}(j)\right)^{\beta_3}}\left(\frac{R_t^k}{1-\delta^s}\right)\right) \tag{32}$$

Table 2 Classification of CCP mechanisms

CCP mechanisms	Policy character description	Main reference
Baseline: No CCP	S_{t-1} is hired into the period t and no extra shocks are carried out on f_t and δ^s	Tumen et al. (2015), Argentiero et al. (2018)
Scenario 1 (S1): Direct production reduction	By reducing the number of annual working days in coal mines from 330 to 276, $\vartheta_t S_{t-1}$ is hired into the period *t*, in which ϑ_t represents the policy-push shock.	State Council (2016), MOHRSS (2016) Zhang et al. (2019)

Scenario 2 (S2): Eliminating backward capacity	By eliminating the old, small and less efficient coal mines, S_{t-1} is hired into the period t with a new depreciation rate $\tau_t\delta^s$, in which τ_t represents the policy-push shock.	State Council (2010,2013), MIIT and NEA (2016), MOHRSS (2016)
Scenario 3 (S3): Advanced capacity replacement	By replacing the written-off existing capacity in a certain proportion[a] with new higher efficient capacity, S_{t-1} is hired into the period t with a new depreciation rate $\tau'_t\delta^s$ and a new cost $\tau'_t f_t$, in which the setting of τ'_t is the same as that of τ_t.	NDRC (2017) Shi et al. (2020) Xiao et al. (2020)

[a] The capacity replacement is regressive: for a unit of capacity that is written off, less than one unit of quota for replacement will be generated.

Mechanism II: In S2, eliminating backward capacity means that most small coal mines with low production efficiency are forced to withdraw from the market and many traditional mining skills are also obsolete. The above policy regulation leads to an increase in exited capacity of the whole coal industry compared with the previous depreciation trend, that is to say the exogenous change of backward capacity caused by the CCP can give rise to the depreciation rate. Given this, the policy mechanism is described as a depreciation rate which is affected by a policy-push shock (τ_t). Similarly, a positive policy-push shock (τ_t) reflects an increase in the short-term policy intensity of the CCP and τ_t follows a random walk with drift:

$$\ln(\tau_t) = \rho_\tau \ln(\tau_{t-1}) + \varepsilon_t^\tau \tag{33}$$

in which the estimated ρ_τ meets $0 \le \rho_\tau < 1$ and an irrelevant random variable ε_t^τ meets $\varepsilon_t^\tau \sim N(0, \sigma^\tau)$. Then, Eq. 24 and Eq. 27 can be rewritten as

$$ec_t = \int_0^1 ec\,(j)dj = \int_0^1 ec\,(i)di = \int_0^1 [(1-\tau_t\delta^s)S_{t-1}\,(j) - S_t(j)]dj \tag{34}$$

$$\beta\rho\mathrm{E}_t(cp_{t+1}) = \frac{f_t}{1-\tau_t\delta^s} + \beta\rho\mathrm{E}_t\left(\frac{1+R_{t+1}^k-\delta^c-(1-\delta^s)}{\beta_2\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2-1}\left(S_{t-1}(j)\right)^{\beta_3}}\right.$$
$$\left.-\frac{\beta_3\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2}\left(S_{t-1}(j)\right)^{\beta_3-1}}{\beta_2\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2-1}\left(S_{t-1}(j)\right)^{\beta_3}}\left(\frac{R_t^k}{1-\tau_t\delta^s}\right)\right) \tag{35}$$

Mechanism III: Based on ***Mechanisms II***, another policy tool, using advanced capacity to replace backward ones is introduced to cut coal excess capacity, which also brings about changes in the depreciation rate by optimizing the structure of coal capacity. Meanwhile, according to the standards of advanced capacity, it is clear that alternative coal mines with advanced capacity can achieve lower exploitation cost than replaced coal mines. In view of this, an exogenous change of capacity distribution caused by the CCP is assumed to move the depreciation rate and the exploitation cost in S3. The policy mechanism is described by having both the depreciation rate and the exploitation cost affected by a policy-push shock (τ'_t), the setting of which is the same as τ_t in ***Mechanism II***. Thus, Eq. 24 and Eq. 27 can be rewritten as:

$$ec_t = \int_0^1 ec\,(j)dj = \int_0^1 ec\,(i)di = \int_0^1 [(1-\tau'_t\delta^s)S_{t-1}\,(j) - S_t(j)]dj \tag{36}$$

$$\beta\rho\mathrm{E}_t(cp_{t+1}) = \frac{\tau'_t f_t}{1-\tau'_t\delta^s} + \beta\rho\mathrm{E}_t\left(\frac{1+R_{t+1}^k-\delta^c-(1-\delta^s)}{\beta_2\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2-1}\left(S_{t-1}(j)\right)^{\beta_3}}\right.$$
$$\left.-\frac{\beta_3\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2}\left(S_{t-1}(j)\right)^{\beta_3-1}}{\beta_2\left(z'_t h_t^c(j)\right)^{\beta_1}\left(k_{t-1}^c(j)\right)^{\beta_2-1}\left(S_{t-1}(j)\right)^{\beta_3}}\left(\frac{R_t^k}{1-\tau'_t\delta^s}\right)\right) \tag{37}$$

3.3 Symmetric Equilibrium

In a symmetric equilibrium, all intermediate-goods-producing firms make identical decisions as well as all coal-goods-producing firms, so that $h_t = h_t^y +$

$h_t^c = h_t^y(i) + h_t^c(j)$, $k_t^y = k_t^y(i)$, $k_t^c = k_t^c(i)$, $P_t = P_t(i)$, $mc_t = mc_t(i)$, $y_t = y_t(i)$, $ec_t = ec_t(i) = ec_t(j)$, $D_t = D_t(i)$, $D_t^c = D_t^c(j)$, and $S_t = S_t(j)$ for all $i \in [0,1]$, $j \in [0,1]$, and $t = 0,1,2, \ldots$. In addition, combining Eq. 3,19,26 and 29, the clearing condition is given as:

$$P_t y_t - \frac{\phi}{2}\left[\frac{\pi_t}{\pi} - 1\right]^2 y_t = c_t + i_t^y + i_t^c \quad (38)$$

After imposing these equilibrium conditions and using P_t to convert all nominal variables into actual variables, we then adopted Eq. 11, 12 and 21 to solve for r_t^k, R_t^k, and mc_t. The real variables of a_t, z_t, and z'_t in this system inherit unit roots from the random walk in their respective exogenous shocks. Sixteen of the remaining equations, including Eq. 1, 2, 3, 7, 8, 9, 10, 16, 19, 20, 22, 24, 26, 27, 29, and 38 in the baseline, form a system determining the equilibrium behavior of the 16 variables, including k_t^y, k_t^c, i_t^y, i_t^c, λ_t, λ'_t, c_t, w_t^y, w_t^c, r_t, π_t, y_t, ec_t, cp_t, S_t, and f_t. In order to describe how the economy responds to the four exogenous shocks in the baseline, the above system can be log-linearized around its steady state.

3.4 Data

According to the model settings of our DSGE model, there are five exogenous shocks, i.e. a_t, z_t, z'_t, r_t and the policy-push shock. Hence, part of the parameters may be estimated via calibration and maximum likelihood, with data on as many as five variables. Based on the availability of data, this paper selected quarterly data from the first quarter of 2005 to the fourth quarter of

2019 as a sample[6], for a total of 60 sets of data. The five series used here were those for final output, consumption, investment in coal firms, inflation, and coal production.

As explained above, final output and consumption were measured by gross domestic product and total retail sales of social consumer goods, while inflation was calculated as changes in the GDP deflator (NBS, 2020). Investment in coal firms was represented by investment in fixed assets in the coal mining and washing industry, while coal production was measured by the production of raw coal from the CEIC database. Note that all the nominal data was converted into real values according to the CPI (1995=100). And all of these data were seasonally adjusted by census X-13. The simulation and calculations were performed by Dynare software.

4 Parameters calibration and estimation

4.1 Parameters calibration

To calibrate the parameters, we referred to the abundant literature as well as long-term statistics. The results are shown in Table 3.

Table 3 Results of calibrated parameters

Parameter	Calibrated value	Parametric description
β	0.985	The discount factor
η	1.97	The reciprocal of labor supply elasticity
η^c	1.97	The reciprocal of labor supply elasticity in coal firms
ψ	0.10	Phillips Curve parameter, i.e. $(\theta - 1)/\ \phi$
α_1	0.79	The labor output elasticity

[6] Note that since 2005, the Chinese government replaced the guidance pricing mechanism for coal prices to market-based pricing.

$\boldsymbol{\alpha_2}$	0.13	The capital output elasticity
$\boldsymbol{\alpha_3}$	0.08	The output elasticity of coal goods
$\bar{\boldsymbol{\lambda}}$	1	The Lagrange multiplier in the household sector
$\bar{\boldsymbol{\lambda}}'$	1	The Lagrange multiplier in the coal-producing sector
$\bar{\boldsymbol{f}}$	1	The cost of the exploitation

As for the fixed parameters, this paper firstly calibrated β at 0.985 in view of China's current one-year deposit rate of 1.5% and the two reciprocals of the labor supply elasticities were set to 1.97. Secondly, following the practice in Ireland (2011), $\boldsymbol{\psi} = 0.10$, is accompanied by a substantial cost in the nominal price adjustment. Thirdly, based on China's input-output table for 2002-2017 (NBS, 2020), the average proportion of stable capital income[7] was 0.13, i.e. $\alpha_2 = 0.13$. And referring to Ireland (2003), we calibrated α_1 as 0.79. Finally, the calibration value of α_3 was estimated to be 0.08 based on $\alpha_1 + \alpha_2 + \alpha_3 = 1$. In addition, the steady-state values of λ_t, λ'_t, and f_t were set to 1.

4.2 Dynamic parameters estimation

For the dynamic parameters to be estimated, this paper used prior distributions referring to Smets and Wouters (2007), Ireland (2011) and Argentiero et al. (2018) through the Bayesian method (see Table 4). Due to space limitations, the Bayesian estimated results in S1-S3 are shown in Table A.1-A.3 of the Appendix.

Table 4 Estimated results of parameters in baseline scenario

Parameters	Prior			Posterior		
	Type	Mean	Standard	Mean	10%	90%

[7] According to the income law, GDP was decomposed into depreciation of fixed assets (G1), operating surplus (G2), labor remuneration and net production tax in China. Among them, the first two represent capital income, so the output elasticities of capital (α_1) could be estimated as: $\alpha_1 = \frac{G1+G2-CV}{GDP-CV}$, where CV denotes the industrial value added of the coal sector. The data was obtained from the National Bureau of Statistics of China (NBS) database.

			deviation		interval	interval
$\boldsymbol{b_c}$	Beta	0.5	0.01	0.5120	0.4949	0.5282
$\boldsymbol{\delta}$	Beta	0.05	0.01	0.0784	0.0534	0.1038
$\boldsymbol{\delta^c}$	Beta	0.06	0.005	0.0590	0.0526	0.0676
$\boldsymbol{\delta^s}$	Beta	0.05	0.01	0.0519	0.0341	0.0677
$\boldsymbol{\beta_1}$	Beta	0.2	0.01	0.1709	0.1563	0.1825
$\boldsymbol{\beta_2}$	Beta	0.5	0.01	0.5336	0.5201	0.5492
$\boldsymbol{\beta_3}$	Beta	0.3	0.01	0.2990	0.2839	0.3196
$\boldsymbol{\rho_a}$	Beta	0.85	0.005	0.8499	0.8433	0.8562
$\boldsymbol{\rho_z}$	Beta	0.9	0.01	0.8363	0.8252	0.8468
$\boldsymbol{\rho_{z'}}$	Beta	0.55	0.01	0.5518	0.5388	0.5672
$\boldsymbol{\rho_\pi}$	Normal	1.0	0.05	1.0650	0.9848	1.1478
$\boldsymbol{\rho_y}$	Normal	-0.05	0.01	-0.0412	-0.0542	-0.0252
$\boldsymbol{\varepsilon_t^a}$	Inv gamma	0.01	inf	0.0048	0.0040	0.0062
$\boldsymbol{\varepsilon_t^z}$	Inv gamma	0.01	inf	0.0038	0.0032	0.0044
$\boldsymbol{\varepsilon_t^{z'}}$	Inv gamma	0.01	inf	0.0061	0.0030	0.0096
$\boldsymbol{\varepsilon_t^r}$	Inv gamma	0.01	inf	0.0772	0.0652	0.0908

Note: inf denotes infinity.

Firstly, all the standard deviations of four shocks, including preference shock ε_t^a, technical shock ε_t^z and $\varepsilon_t^{z'}$, and interest rate shock (ε_t^r), were assumed to be distributed as an inverse gamma distribution. And all the estimated parameters of shocks were imposed with a Beta distribution, including ρ_a, ρ_z, and $\rho_{z'}$. Secondly, a normal distribution was imposed on the response parameters of ρ_y and ρ_π. Thirdly, we imposed a Beta distribution on the output elasticity in the coal goods-producing sector, including β_1, β_2, and β_3, as well as the consumption habit b_c and the depreciation rate δ, δ^c and δ^s.

From Table 4, b_c=0.5118 indicates that for the 2005-2019 sample, China's data prefer a version of the model with a considerable amount of backward-looking behavior in consumption. And $\beta_1 + \beta_2 + \beta_3$=1.0035≈1, which is close to the reality of China's economy. Moreover, the policy response of ρ_y and ρ_π indicate that the government adjusts the short-term nominal interest rate in response to deviations in inflation instead of final output since the estimate of ρ_y is -0.0412 (Ireland, 2003).

5 Empirical results

In order to evaluate the model's overall goodness of fit, this paper compares the actual and predicted values of the observed variables, as shown in Fig. A.1 in the Appendix. It is obvious that the model does a good job in replicating all the observed variables in China's economic system since in the long term, all predicted values of the real final output, consumption, investment in coal firms and coal production are basically consistent with the actual values.

5.1 Model dynamics in the baseline scenario

In this section, this paper discusses the dynamic response of the main variables of interest when the economy is hit by stochastic shocks in terms of preference, technology and interest rate, i.e. impulse responses function (IRF) (Pesaran and Shin, 1998). Note that the measures of the response can be read as elasticities since the variables in Fig.2 are expressed in logs. Moreover, because the issue hereby is concentrated on the macroeconomic effects of an energy policy shock, the main variables of interest are coal price, coal production, inflation, and the final output (GDP).

From Fig.2, the positive shocks of preference and technology on final output generate an increase in coal production along with a decrease in coal price through the shift of the final goods' production curve and cost curve. However, the fluctuations in the above variables gradually return to the equilibrium state again after the 30th period. This indicates that in the baseline scenario, the fluctuations of preference and technology will bring forth short-term effects on the macro economy.

Specifically, first of all, after being hit with positive shocks, all the above variables significantly deviate from the equilibrium state in the current period. This indicates that final output, coal price and coal production are relatively sensitive to these shocks. Secondly, according to the magnitude of the deviation, the effect of the exogenous shocks is in order of: technology shock> preference shock> coal production technology shock. Thirdly, contrary to the mechanism of the above two shocks, the technology shock generates an increase in coal production, thus inducing growth in final output in the current period. However, unlike the slowing convergence response of final output, a rebound effect in coal production appears in the 10th period when hit with preference and technology shocks. As a result, the changes in coal production have brought about an opposite fluctuation in coal prices. This finding implies that coal production will regulate to a new equilibrium state through the spontaneous adjustment of the market.

Besides, in the baseline scenario, the interest rate shock acts like demand-side disturbances, moving final output and inflation in the same direction. These responses above of the key macroeconomic variables are consistent with

Ireland’s (2011) economic intuitions. That is, after an increase in the current period, final output and inflation will eventually show a rapid and slight decline in the short term.

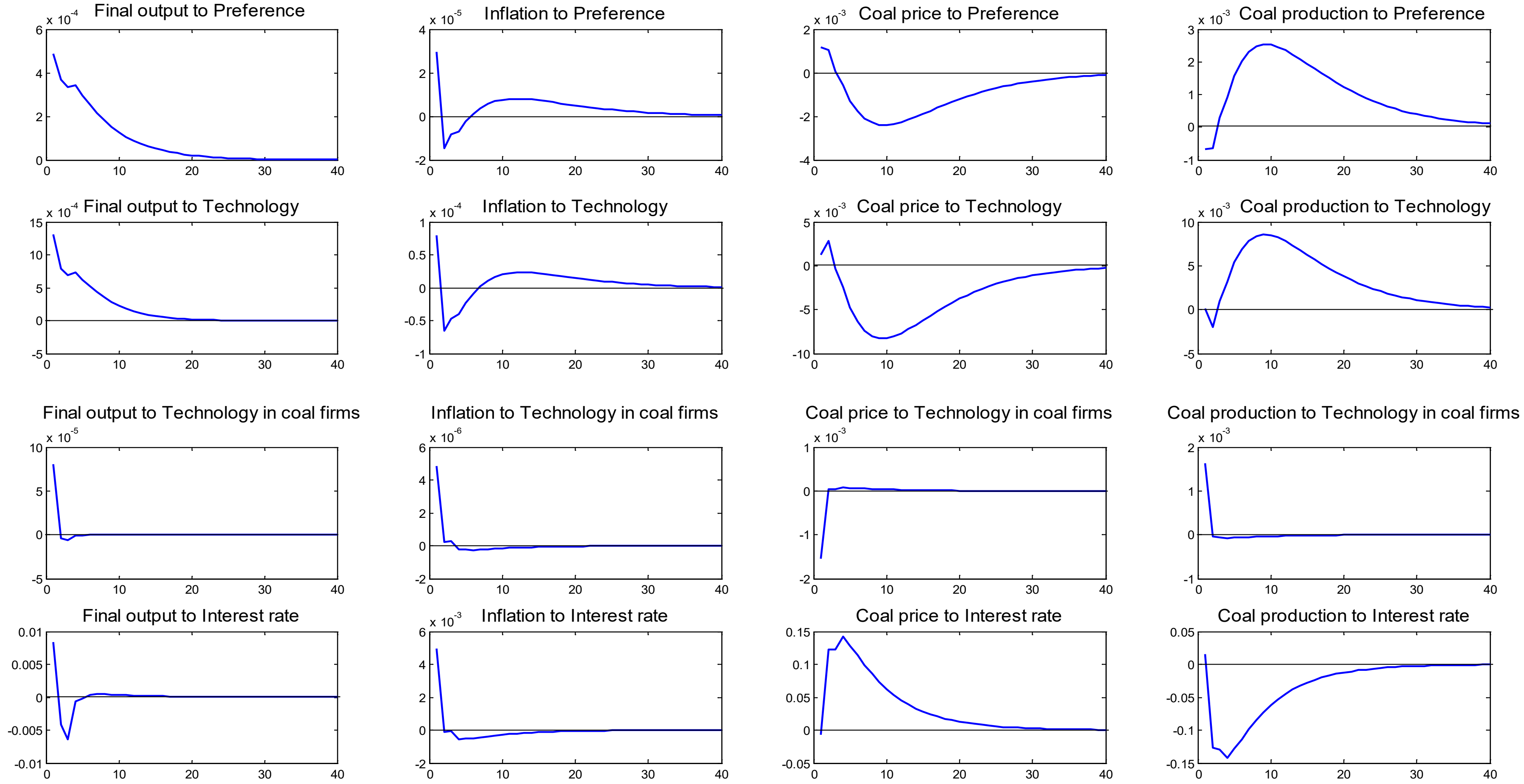

Fig. 2 Impulse response results

Note: In each panel, y-axis shows the percentage-point response in one of the model's endogenous variables to one-standard-deviation of one of the model's exogenous shocks. Periods along the horizontal axes correspond to quarter years.

5.2 Effects of the CCP shock on China’s economic system

(1) Coal price fluctuations

This section only examines the impact of the policy-push shock (the CCP shock) on coal prices to explore whether the steady fluctuation of coal prices in China at this stage is due to the implementation of the CCP (see Fig.3). Generally, with one-positive-standard-deviation shock, the CCP will get tighter in the current period, reflecting how coal price reacts to more radical targets of cutting coal capacity.

As shown in Fig.3, under “the Hotelling rule”, the enhanced CCP will cause the magnitude of the coal deposits to decline and is expected to affect coal supply directly, leading to an increase in the short-term coal prices. This is consistent with the findings of Wang et al. (2020). Combined with the effects of other exogenous shocks (see Fig.2), we concluded that fluctuations in China’s coal prices are driven primarily by changes in market fundamentals and technological progress, with energy policy playing a smaller but not negligible role. In the short run, the spontaneous regulation of China's coal market is relatively sensitive to policy interventions that distort the transmission effect of coal supply and demand and other factors on coal prices.

An interesting finding is that the impact of the three policy tools is completely different. Specifically, with a positive CCP shock, 1) the government forcibly reduces the working time of coal firms to decrease coal production directly in S1, resulting in an increase in coal price (about 0.004%); 2) in S2, eliminating the outdated coal capacity causes changes in the depreciation rate of coal capacity, thereby driving down coal production and rising coal price, but the changes' magnitude is still lower than that in S1; 3) capacity upgrades are emphasized in S3, thus the government simultaneously exerts regulations on coal deposits and the depreciation rate. This causes slight growth in the logarithmic coal price (about 2.5E-05%). In summary, the impact of direct production reduction on coal price is nearly 100 times that of eliminating backward capacity, while the impact of advanced capacity replacement is minimal. This finding proves that the selected policy tools will, to some extent, determine the policy effectiveness. Hence, it may be necessary to set reasonable priorities for the policy tools of the CCP to moderate coal prices fluctuations for promoting China's energy transition.

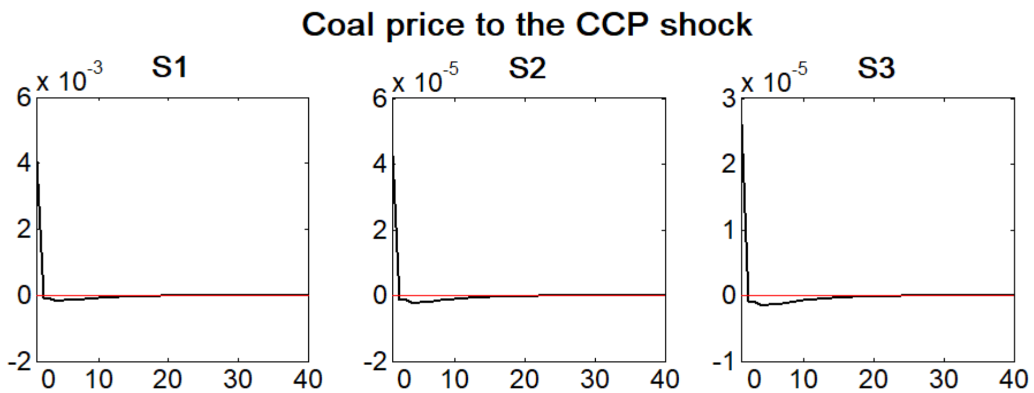

Fig. 3 Impulse response results of coal price in S1, S2 and S3

Note: S1, S2 and S3 refer to the three policy scenarios in Table 2, respectively. In each panel, y-axis shows the percentage-point response of coal price to the CCP shock; x-axis refers to the periods and each period corresponds to a quarter of a year.

(2) Production behavior of coal firms

In this section, we explore the production behavior of coal firms. With one-standard-deviation policy-push shock, the impulse response of coal production, labor input and exploitation costs are shown in Fig.4.

In both S1 and S2, a positive policy-push shock, namely a tight CCP in the short-term, generates a slight decline in coal production through a negative shift in the productive factor's supply curves. But the effects are obviously different in these two scenarios. In particular, the CCP causes decrease in marginal productivity, and hence a shrink in the current labor input in S1 and S2. Meanwhile, the decline in coal production (about 4E-03%) in S1 is significantly higher than that in S2 (about 4.5E-05%), which is consistent with the actual situation in China's coal industry. The reason is that compared with cancelling 276 working day mechanism, the eliminated capacity is generally at the inefficient and small coal mines, or even zombie coal firms. Their production behavior has almost no impact on the overall coal production due to the ongoing capacity expansion of the leading coal firms.

Moreover, opponents of the CCP hold the view that it will cause large numbers of coal mines to shut down, and render thousands of coal workers jobless (Hao et al., 2015). They claimed that the reemployment of coal miners is the largest obstacle to the implementation of the CCP in China. As shown in Fig. 4, a positive CCP shock has a significant short-term effect on labor inputs in S1 (about 2.5E-05%). However, when the government shuts down backward coal mines and replaces them with advanced ones, the subsequent labor migration from the closed coal mines to the new ones greatly eases the negative impact of the CCP on labor inputs in S2 and S3. It indicates that the implementation of the CCP would put pressure on the labor relocation, but with acceptable unemployment level, which provides strong support for continues application of the CCP during the 14th Five-Year Plan period.

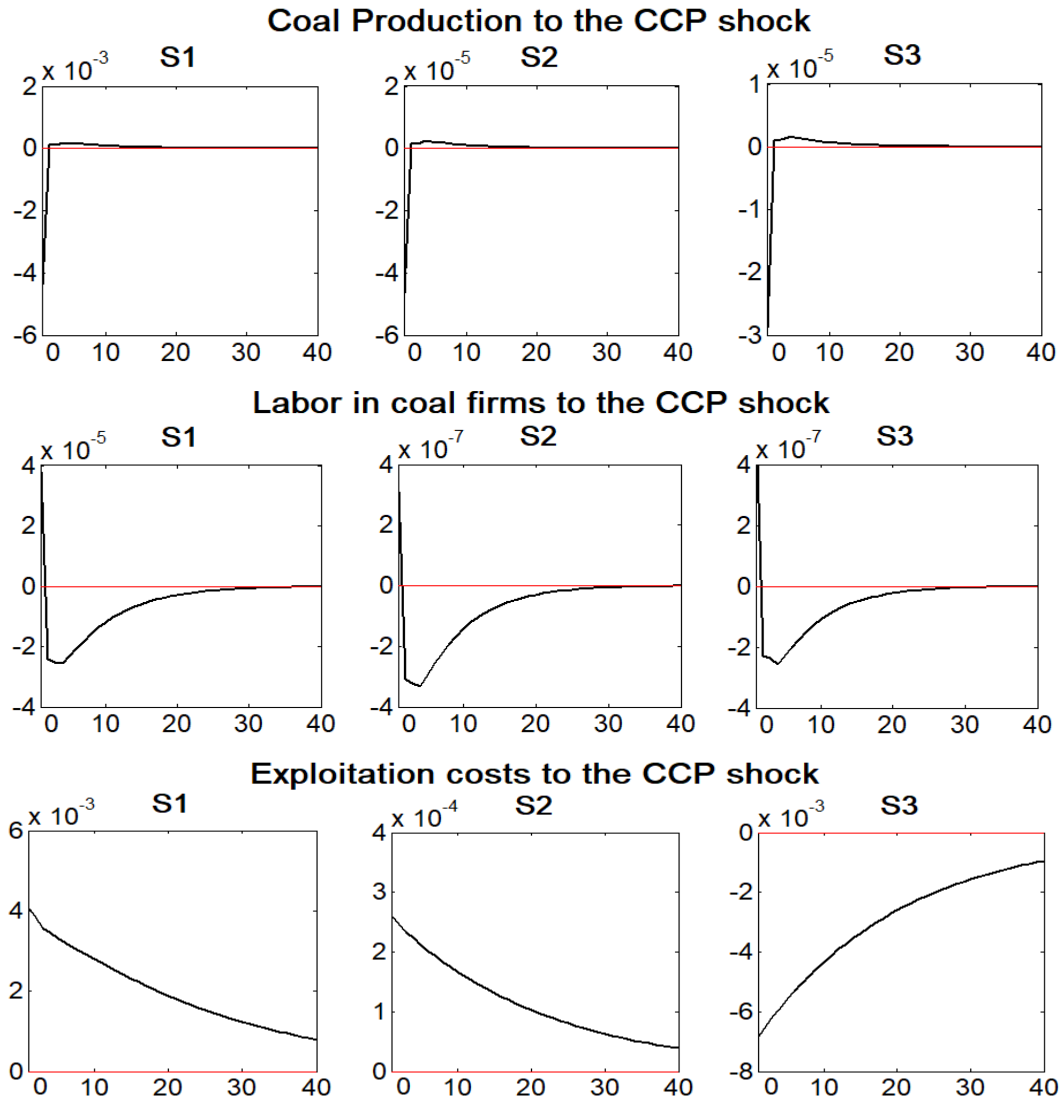

Fig. 4 Impulse response results of coal production, labor input and exploitation costs in S1, S2 and S3

Another crucial finding is that the CCP shock brings about dramatic changes in the exploitation cost due to the different policy tools. A tight CCP causes an increase in the exploitation cost in S1 and S2 due to the reduction in the amount of coal reserves available to coal firms. Note that the exploitation cost in S1 still maintains a small positive deviation (about 8E-04%) from the equilibrium state until the 40th period. This implies that the spontaneous regulation of the economic system cannot eliminate the impact of the CCP on the exploitation cost, and there will ultimately be a reduction in social welfare. Differently, the CCP shock in S3 can bring about a persistent decline (about 0.001%) in the exploitation cost during the 0-40th periods. This is in line with our expectations. In S3, the CCP depends on the optimization of coal capacity structure, and its above effect is actually driven by the shrinking of the coal deposits, as well as the efficiency improvements in capacity allocation.

To sum up, it is obvious from the results of the three scenarios that the policy tool, namely advanced capacity replacement, has a competitive advantage in cutting capacity due to its economic effect on exploitation costs. It is worth noting that as the targets of cutting coal capacity increase, the above positive effect may be offset owing to the reduction in coal production or even the final total output in the long run.

5.3 Discussion on the impulse response of output gap

Based on the above analysis, after the implementation of the CCP, the fluctuations in coal prices and coal production trigger a chain reaction in other economic variables. To depict the macroeconomic effects of the CCP, following the practice in Ireland (2011), we employed the gap[8], to measure the theoretical

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[8] In the DSGE model, we assumed that a planner can choose the efficient level of output ey_t and the efficient amounts of labor $eh_t^y(i)$ to allocate to the production of each intermediate good $i \in [0,1]$ to maximize a social welfare function, $E_t[\sum_{t=0}^{\infty} \beta^t a_t \left[ln(ey_t - b_c ey_{t-1}) - \left(eh_t^y\right)^{1+\eta^y}/(1+\eta^y) - (h_t^c)^{1+\eta^c}/(1+\eta^c)\right]$. And the output ey_t and labor $eh_t^y(i)$ meet the same preference ordering over

social welfare level. This paper assumed that coal firms are the price receivers without the consumer preference for coal goods. Hence, the ratio of final output and efficient output can be used as the gap in which efficient output is chosen by a social planner who can overcome the frictions associated with sluggish nominal price adjustment. By model simulation, the impulse response result of the gap and final output in S1 are shown in Fig.5. Due to space limitations, the impulse response results in the other two are shown in the Appendix.

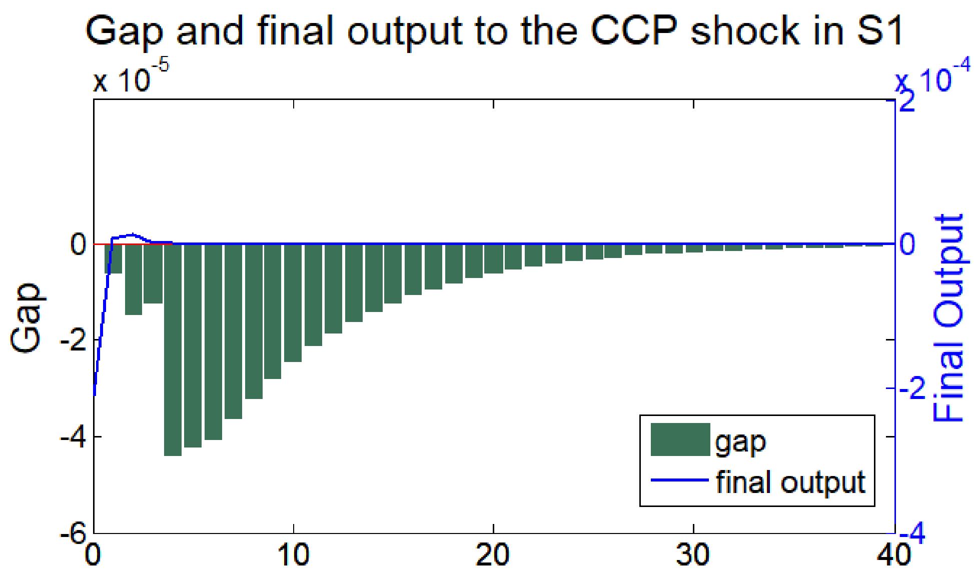

Fig. 5 Impulse response results of gap and final output in S1

Note:Axes y show the percentage-point response in the gap and final output to a one-positive-standard-deviation policy-push shock in S1, respectively; x-axis refers to the periods and each period corresponds to a quarter of a year.

In detail, according to the blue curve in Fig.5, a positive policy-push shock sets off a decrease in coal production, and further causes the current final output to decline (about 3E-05%), but there is a quick return to the steady state in the 3th

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consumption and leisure embedded into the representative household's utility function. Besides, the efficient output also satisfies the aggregate feasibility constraint, $ey_t \leq z_t^{\alpha_1}\left\{\int_0^1[(eh_t^y(i))^{\alpha_1}(k_{t-1}^y(i))^{\alpha_2}(ec_t(i))^{\alpha_3}]^{\theta-1/\theta}di\right\}^{\theta/\theta-1}$.

period, which is also verified in S2 and S3. This finding indicates that after the implementation of the CCP, the GDP will be reduced slightly in the short term, which is consistent with Li and Yao (2020).

A surprising finding is that the gap, i.e. the social welfare level, is not as sensitive to the policy-push shock as we believe, according to the green bars in Fig.5. Generally, the output gap has undergone the same changes as output, that is, a certain degree of decrease in the short term in S1. However, the dynamic movements of these two are completely different. Following a tightening CCP, efficient output does not respond fast enough since there are no dramatic fluctuations in the gap in the current period. As a result, the movements in the output gap lag behind final output, accompanied by a slight negative deviation (about 4.4E-05%) in the 5th period. Similarly, we found that the gap falls as final output decreases following a favorable intervention of the CCP in S2 and S3 (see Fig.A.2 in the Appendix). Such is the fact that no matter which policy tool of the CCP is adopted, increasing policy intensity will inevitably lead to losses in the social welfare levels in the short term.

Note that difference in response amplitude existed in the above loss caused by different policy tools of the CCP. This is basically the same as the response of coal price (see Fig.3). Based on Fig.A.2 in the Appendix, the CCP shock brings about 6E-07% and 4E-07% declines in the gap in S2 and S3, respectively, which are much smaller than that in S1. Combined with Fig.3-5, we concluded that the impact of the policy tools in S2 and S3 on the macroeconomic system is far less than that from reducing the working days in S1. We also found that the effects of a policy-push shock in S3 on final output and the social welfare level are the weakest in the short term. It suggests the Chinese government applies different short-term strategies to promote energy transition.

6 Conclusion and policy implications

When facing inevitable decline in the production capacity of fossil fuels, policymakers face a challenge in deciding the pace of the reduction. The implementation of the CCP in China provides a unique case to investigate the impact of energy policy shocks on energy prices and the macro economy. This paper regarded coal resources as an intermediate input and established a closed DSGE model. Three policy scenarios were formulated to discuss the macroeconomic effects of different policy tools to cut coal capacity.

Some interesting findings include: Firstly, regardless of the impact of the CCP, the economic system has experienced a dynamic movement driven by the preference, technology, and interest rate shocks in the short run. Secondly, the CCP shock plays a smaller but still non-negligible role in generating the increase in coal prices, which is consistent with both economic theory and empirical evidence from China. Thirdly, the impact of three policy tools on the macroeconomic system is: direct production cut > eliminating outdated capacity > advanced capacity replacement. Lastly, no matter which policy tool is adopted, the CCP will inevitably lead to a reduction in social welfare levels in the short term.

Based on these findings, several policy implications can be generated. First, in the short term, the high resilience of the Chinese economy to suit more radical targets of the CCP implies that the government could consider to accelerate the CCP process further releasing many more replacement quotas for advanced capacity in order to reduce the economic costs of the CCP. However, in view of the external costs of energy conservation and employment, the Chinese government should adopt market mechanisms to accelerate the energy transition. It should further liberalize the market to mitigate the negative impact of this capacity control policy on the final output and social welfare, for example a capacity permit trading scheme, similar to the well-known emissions trading scheme (Shi et al., 2020, 2021).

Second, for the application of the CCP during the 14th Five-Year Plan period, the government should further develop policy tools to regulate the excess capacity in the traditional energy industries. One way is the structural adjustment of coal capacity. For example, establishing large coal mining groups and integrating downstream industrial chains to relocate capital and labor can encourage coal firms to initiate closure of their mines and work towards developing alternative forms of energy. The other way is to strengthen the synergistic effect of coal capacity cut and other policies, such as carbon emissions control. The government can adopt a series of measures of employee resettlement, debt management and financial support to achieve a positive economic and environmental effect.

Several interesting issues deserve further study. Firstly, other utility preferences, especially carbon emissions, can be further engaged to discuss the synergism of coal capacity cut policy. Secondly, the carrying out of studies on open economic systems, i.e., introducing coal imports and exports, can further contribute to China's energy transition.

Acknowledgements

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Appendix

A Additional Tables

Table A.1 Results of estimated parameters in S1

Parameters	Prior			Posterior		
	Type	Mean	Standard deviation	Mean	10% interval	90% interval
$\mathbf{b}^{\mathrm{C}}$	Beta	0.5	0.01	0.4964	0.4926	0.4992
$\boldsymbol{\delta}$	Beta	0.05	0.01	0.0493	0.0434	0.0546
$\boldsymbol{\delta}^{c}$	Beta	0.06	0.005	0.0627	0.0611	0.0639
$\boldsymbol{\delta}^{s}$	Beta	0.05	0.01	0.0495	0.0477	0.0507
$\boldsymbol{\beta}_1$	Beta	0.2	0.01	0.2181	0.2132	0.2259
$\boldsymbol{\beta}_2$	Beta	0.5	0.01	0.5041	0.4980	0.5096
$\boldsymbol{\beta}_3$	Beta	0.3	0.01	0.3107	0.3070	0.3143
$\boldsymbol{\rho}_a$	Beta	0.85	0.005	0.8529	0.8517	0.8542
$\boldsymbol{\rho}_z$	Beta	0.9	0.01	0.9497	0.9479	0.9513
$\boldsymbol{\rho}_{z'}$	Beta	0.55	0.01	0.5310	0.5268	0.5343
$\boldsymbol{\rho}_{\pi}$	Normal	1.0	0.05	1.1537	1.1224	1.1910
$\boldsymbol{\rho}_{v}$	Normal	-0.05	0.01	-0.0423	-0.0465	-0.0382
$\boldsymbol{\rho}_{\vartheta}$	Beta	0.95	0.01	0.9564	0.9510	0.9611
$\boldsymbol{\varepsilon}_t^{a}$	Inv gamma	0.01	inf	0.0027	0.0025	0.0029
$\boldsymbol{\varepsilon}_t^{z}$	Inv gamma	0.01	inf	0.0014	0.0013	0.0017
$\boldsymbol{\varepsilon}_t^{z'}$	Inv gamma	0.01	inf	0.0195	0.0032	0.0378
$\boldsymbol{\varepsilon}_t^{r}$	Inv gamma	0.01	inf	0.0022	0.0018	0.0027
$\boldsymbol{\varepsilon}_t^{\vartheta}$	Inv gamma	0.01	inf	0.0080	0.0023	0.0143

Note: inf denotes infinity.

Table A.2 Results of estimated parameters in S2

Parameters	Prior			Posterior		
	Type	Mean	Standard deviation	Mean	10% interval	90% interval
$\mathbf{b}^{C}$	Beta	0.5	0.01	0.5108	0.4944	0.5259
$\boldsymbol{\delta}$	Beta	0.05	0.01	0.0653	0.0451	0.0811
$\boldsymbol{\delta}^{c}$	Beta	0.06	0.005	0.0590	0.0536	0.0661
$\boldsymbol{\delta}^{s}$	Beta	0.05	0.01	0.0340	0.0231	0.0441
$\boldsymbol{\beta}_1$	Beta	0.2	0.01	0.2047	0.1872	0.2178
$\boldsymbol{\beta}_2$	Beta	0.5	0.01	0.5192	0.5037	0.5345
$\boldsymbol{\beta}_3$	Beta	0.3	0.01	0.3547	0.3464	0.3657
$\boldsymbol{\rho}_a$	Beta	0.85	0.005	0.8473	0.8412	0.8541
$\boldsymbol{\rho}_z$	Beta	0.9	0.01	0.8845	0.8739	0.8983
$\boldsymbol{\rho}_{z'}$	Beta	0.55	0.01	0.5475	0.5316	0.5651
$\boldsymbol{\rho}_\pi$	Normal	1.0	0.05	1.1185	1.0423	1.1688
$\boldsymbol{\rho}_y$	Normal	-0.05	0.01	-0.0464	-0.0600	-0.0320
$\boldsymbol{\rho}_\tau$	Beta	0.95	0.01	0.9503	0.9406	0.9653
$\boldsymbol{\varepsilon}_t^{a}$	Inv gamma	0.01	inf	0.0015	0.0013	0.0019
$\boldsymbol{\varepsilon}_t^{z}$	Inv gamma	0.01	inf	0.0013	0.0012	0.0014
$\boldsymbol{\varepsilon}_t^{z'}$	Inv gamma	0.01	inf	0.0058	0.0024	0.0094
$\boldsymbol{\varepsilon}_t^{r}$	Inv gamma	0.01	inf	0.0315	0.0271	0.0359
$\boldsymbol{\varepsilon}_t^{\tau}$	Inv gamma	0.01	inf	0.0097	0.0023	0.0151

Note: inf denotes infinity.

Table A.3 Results of estimated parameters in S3

Parameters	Prior			Posterior		
	Type	Mean	Standard deviation	Mean	10% interval	90% interval
$\mathbf{b^C}$	Beta	0.5	0.01	0.5121	0.4991	0.5274
$\boldsymbol{\delta}$	Beta	0.05	0.01	0.0735	0.0549	0.0991
$\boldsymbol{\delta^c}$	Beta	0.06	0.005	0.0592	0.0534	0.0697
$\boldsymbol{\delta^s}$	Beta	0.05	0.01	0.0457	0.0325	0.0589
$\boldsymbol{\beta_1}$	Beta	0.2	0.01	0.2041	0.1891	0.2262
$\boldsymbol{\beta_2}$	Beta	0.5	0.01	0.5187	0.5026	0.5352
$\boldsymbol{\beta_3}$	Beta	0.3	0.01	0.3127	0.2994	0.3268
$\boldsymbol{\rho_a}$	Beta	0.85	0.005	0.8479	0.8399	0.8539
$\boldsymbol{\rho_z}$	Beta	0.9	0.01	0.8812	0.8664	0.8968
$\boldsymbol{\rho_{z'}}$	Beta	0.55	0.01	0.5500	0.5374	0.5628
$\boldsymbol{\rho_\pi}$	Normal	1.0	0.05	1.1042	1.0549	1.1601
$\boldsymbol{\rho_\nu}$	Normal	-0.05	0.01	-0.0518	-0.0656	-0.0378
$\boldsymbol{\rho_\tau}$	Beta	0.95	0.01	0.9504	0.9321	0.9629
$\boldsymbol{\varepsilon_t^a}$	Inv gamma	0.01	inf	0.0016	0.0012	0.0019
$\boldsymbol{\varepsilon_t^z}$	Inv gamma	0.01	inf	0.0013	0.0012	0.0014
$\boldsymbol{\varepsilon_t^{z'}}$	Inv gamma	0.01	inf	0.0059	0.0035	0.0089
$\boldsymbol{\varepsilon_t^r}$	Inv gamma	0.01	inf	0.0102	0.0089	0.0117
$\boldsymbol{\varepsilon_t^\tau}$	Inv gamma	0.01	inf	0.0069	0.0031	0.0118

Note: inf denotes infinity.

B Additional Figures

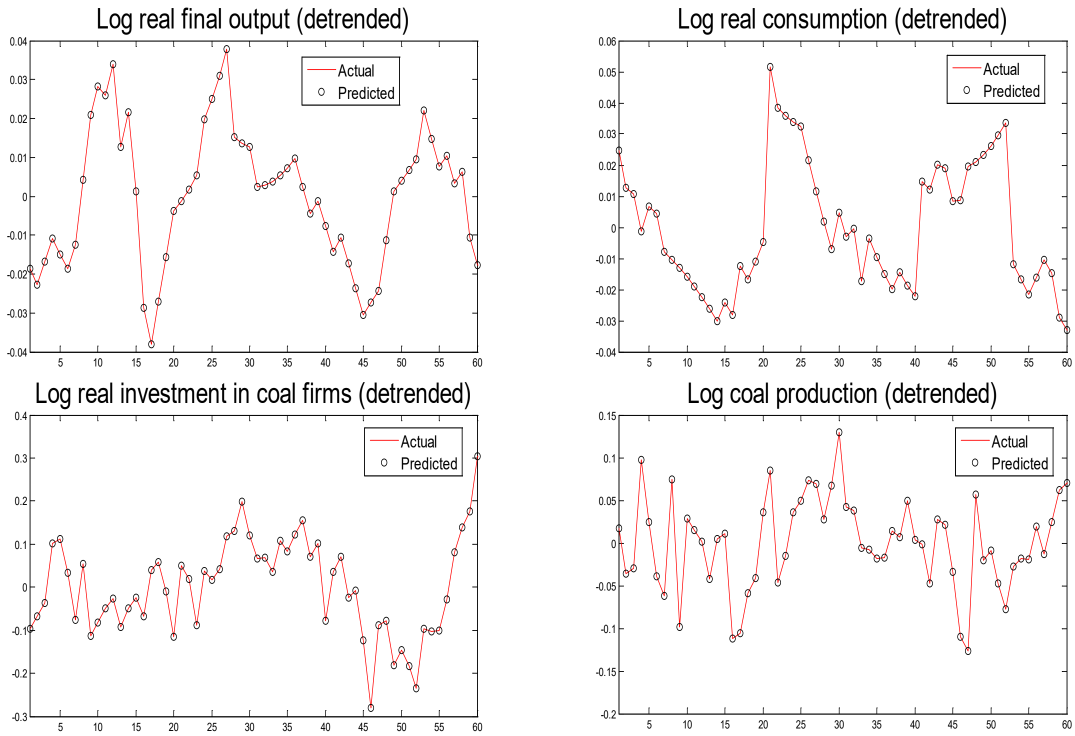
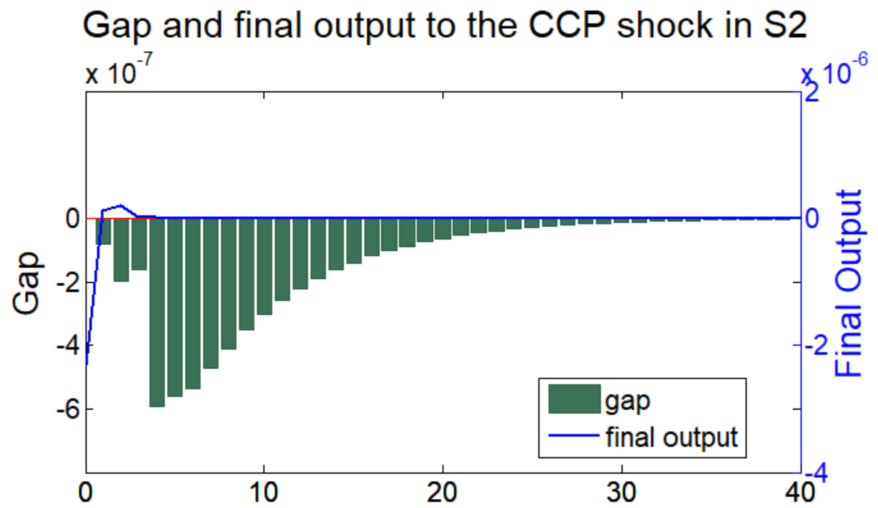


Fig. A.1 The actual and predicted values of different observed variables

Note: Axis y represents the value of a certain economic variable and x-axis denotes the time. Moreover, one-time interval means one quarter.



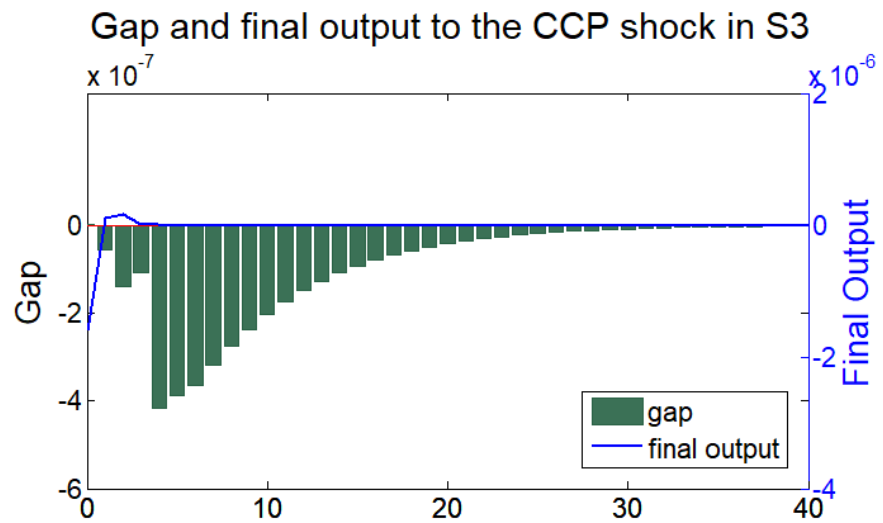


Fig. A.2 Impulse response results of gap and final output in S2 and S3

Note: Axes y show the percentage-point response in the gap and final output to a one-positive-standard-deviation policy-push shock, respectively; x-axis refers to the periods and each period corresponds to a quarter of a year.