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Optimal CO_2 abatement pathway with induced technological progress for chinese coal-fired power industry

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ABSTRACT

This study attempts to analyze the integrated effects of carbon pricing in Chinese coal-fired power industry in two studied cases: with and without induced technological progress. Then several CO_2 abatement pathways with different levels of carbon pricing are synthetically assessed for Chinese coal-fired power industry by extending a hybrid energy-economic model. Two types of autonomous technological progress such as industrial technology upgrading and autonomous energy efficiency improvement have been exogenously set for all economic sectors. One type of induced technological progress such as direct carbon removals is assumed to be introduced in coal-fired power industry, and its market share is endogenously calculated. Especially, oxy-fuel CCS technology is considered as a potential commercialized option for direct carbon removals. Then with different levels of carbon price setting for the newly increased CO_2 emissions from coal-fired power industry, energy-economic indicators such as electricity cost, generation efficiency, economic growth, and CO_2 emissions are comparatively analyzed for the choice of CO_2 abatement pathway. Simulated results reveal that the upward trend of CO_2 emissions cannot be changed within midterm if without induced technological progress. However, if with induced technological progress when carbon pricing is high enough, CO_2 emissions could stop the upward trend, and even become decreasing accompanied by certain macroeconomic losses. When oxy-fuel CCS technology is introduced by charging for the newly increased CO_2 emissions at 100 RMB_{2002} Yuan/t CO_2, the induced CO_2 abatement pathway of Chinese coal-fired power industry could be regard as optimal.

1. Introduction

Due to extensive coal resource, coal still takes dominance to the structure of Chinese energy production and consumption. China's coal consumption, which grew by 1120 Mtce over the last 8 years, accounted for more than three-quarters of global coal demand growth in the period of 2000–2008 (OECD/IEA, 2010). Since coal belongs to high carbon energy, coal combustion contributed over 85% of the total carbon dioxide emissions in 2008 China (CDIAC, 2011). Especially, about 50% of coal consumption in 2010 China was used by coal-fired power industry (Huang et al., 2014), who is the largest CO_2 emitter among Chinese industrial sectors. Besides, ambitious economic expanding program has been planned by Chinese government, which formulated that GDP per capital should be quadruped in 2020 than that in 2002 (Xinhua Net, 2007). Economic growth keeps mid-high speed, industry moves toward mid-high levels and the goal of well-off society should be reached in 2020 (Wangyi News, 2015). For such urgent requirement of economic growth, coal-fired power industry will still be continuously expanded to satisfy electricity demand. And the development of low-carbon coal-fired power technology has become a crucial task for sustainable development of China. Among current available low-carbon coal-fired power technologies in China, highly efficient coal combustion technology has always been treated as a convenient and cheap method of indirect CO_2 emissions mitigation. However, the abatement of CO_2 emissions only through energy efficiency improvement seems not enough. From a long-term view, direct carbon removals and renewable energy also should be considered to be introduced into electricity generation sector in China (Fu et al., 2010). As an important technique of direct carbon removals, carbon capture and storage (i.e., CCS) particularly has potential developing advantage (IEA Clean Coal Center, 2002). Moreover, oxy-coal systems are an obvious candidate for consideration of co-disposal options and there will be a need for continuing feedback from studies of CO_2 transport and especially storage compatibility issues to the suite of technologies to be considered for the capture plant (IEA Clean Coal Center, 2005). Hence, oxy-fuel CCS technology is considered as a potential commercialized option in this study. However, the introduction of oxy-fuel CCS technology will unavoidably affect electricity cost, generation efficiency, economic growth, and CO_2 emissions. In this study, all these factors are considered by extending a hybrid energy-economic model, which is combined a top–down computable general equilibrium model (i.e., CGE model) with two bottom–up

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engineering sub-models (i.e., an energy balance sub-model and a coal-fired power sub-model).

In fact, the initial version of this hybrid energy-economic model has been constructed to analyze Chinese industrial energy-saving potential in our previous research (Li, 2010a). Since coal-fired power units will still dominate electricity generation in China within a long term, coal consumption and its related SO_2, NO_x and CO_2 emissions from Chinese coal-fired power industry by 2030 have been forecasted as further research (Li, 2010b). The integrated effects of technological progress for coal utilization in China during rapid urbanization period from 2002 to 2030 have also been analyzed (Li and Li, 2012). In this study, by extending the above hybrid energy-economic model, this study will focus on analyzing the satisfied speed and optimal pathway of induced CO_2 abatement with oxy-fuel CCS technology introduction for Chinese coal-fired power industry by 2030. The simulation is differentiated in two cases, which are without induced technological progress (i.e., indirect CO_2 emissions reduction by energy-saving) and with induced technological progress (i.e., direct CO_2 emissions removals by CCS technology). Finally, suitable level of carbon pricing in Chinese coal-fired power industry is also suggested.

2. Model construction

The basic framework of this hybrid energy-economic model is shown as Fig. 1, which mainly includes an energy balance sub-model, a coal-fired power engineering sub-model and an intertemporal dynamic CGE model. And these two bottom–up engineering sub-models are softly linked with the dynamic CGE model. Energy related indicators which are estimated by CGE are all expressed in monetary unit. By the energy balance sub-model, energy consumption and energy production during each energy utilization process can be transformed to physical unit. Especially, coal consumption by coal-fired power industry is used as a key variable in this study. With exogenously given carbon price, the charging fee for newly increased CO_2 emissions can be estimated by the coal-fired power engineering sub-model. Then macroeconomic impact, electricity generation efficiency and CO_2 emissions can be simulated for Chinese coal-fired power industry in two cases: with and without induced technological progress.

2.1. Assumptions

Production is assumed to be fully competitive, and no excess profits are reaped. It implicates that the maximum profit conditions diminish to cost minimization conditions for production processes. Each economic sector works as a producer, and each producer only produce one type of commodity by specific technology pattern. There are two kinds of household such as the rural and the urban, who consume these commodities so as to maximize its utility. The household earns income by providing its endowments of labor and capital for these firms. Markets of commodity, labor and capital are perfectly competitive. That is, they are assumed to be price-takers, who do not have any economic power to determine market prices. In all the commodity and factor markets, prices are flexibly adjusted to achieve demand–supply equilibrium. Their demand and supply are equilibrated in markets by price adjustment. With CGE models, quantities and prices in various equilibria can be computed to simulate what will happen if (or if not) a low-carbon energy policy is introduced. Then quantity change of CO_2 emissions, SO_2 and NO_x emissions in each sector by energy price adjustment can be computed to show economic activities in detail. And quantitative analyses are performed by computing its equilibria to evaluate effects of policies and/or exogenous shocks. Thus, the theoretical basis of this model lies in general equilibrium models developed by K. Arrow and G. Debreu (Armington, 1969), where the competitive equilibrium is determined by optimization of consumers and producers. Economic sectors are assumed to have perfect foresight, which means economic sectors are able to anticipate future changes when making consumption, savings, and investment decisions. Households are assumed to maximize welfares through the intertemporal allocation of income across consumption in different periods with saving rate endogenously calculated. Particularly, intertemporal borrowing of funds is assumed possible. Thus, savings and investments are determined by utility optimization which is based on future welfare, but not on the current state of the economy (Babiker et al., 2009; Cheng and Dinopoulos, 1996).

The simulation period is 28 years interval of year 2002 to 2030. Chinese economy is divided into 22 industries, which are shown in Table 1. The sector classification is based on 42 sectors China 2002 input–output table. Especially, non-energy intensive and low energy consumption sectors in secondary industry and tertiary industry are combined as other secondary industry and other tertiary industry. There are five energy sectors in this model, which are sector 2 (mining and washing of coal), sector 3 (extraction of petroleum and natural gas), sector 5 (processing of petroleum and nuclear fuel, coking), sector 6 (production and supply of electricity and heat) and sector 7 (production and supply of gas). Accordingly, there are five energy sorts in the model, which are coal (energy sort 1), petroleum and natural gas (energy sort 2), petro-chemical products, nuclear fuel and coking (energy sort 3), electricity and heat (energy sort 4) and gas (energy sort 5).

2.2. Parameter setting

The population and the urbanization rates are exogenously given according to government predictions (Energy Research Institute of NDRC of China, 2009). The population figures in year 2010, 2020, and 2030 are estimated to be 1368 million, 1445 million and 1470 million, respectively. The urbanization rates in year 2010, 2020, and 2030 are estimated to be 49%, 58% and 63%, respectively. About modeling the uncertainty of economic growth, utility discounted rate is given as fixed value, which is 5%. And income discounted rate is set as fluctuating value, which is ranged from 9.17% to 2.68% during the entire simulation period. In 2002, energy efficiency in China was about 30% lower than international advanced level. Especially, the parameter of autonomous energy efficiency improvement (i.e., AEEI) in electricity and heat production sector in USA is assumed to be less than that in other sectors. The reason remains that its potentiality of energy efficiency improvement in this sector is very limited in USA, and no AEEI trends are also assumed in

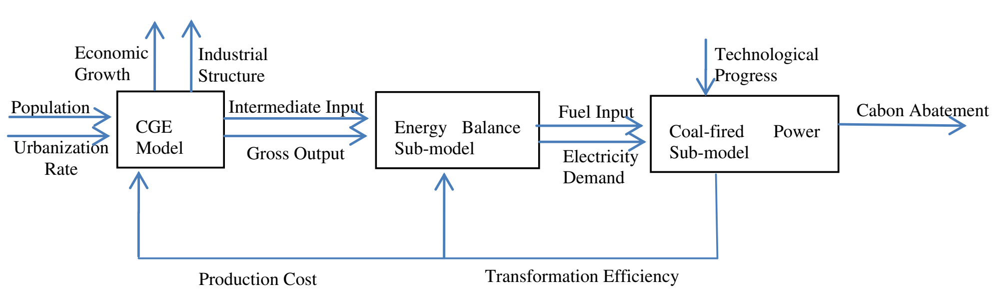

Fig. 1. The basic structure of the hybrid energy model.

Table 1
Classification of 22 industries in Chinese economy.

No	Sector	No	Sector
1	Agriculture	12	Recycling and disposal of waste
2	Mining and washing of coal	13	Manufacture of transport equipment
3	Extraction of petroleum and natural gas	14	Manufacture of electrical machinery and equipment
4	Other mining and quarrying	15	Manufacturing of paper & article printing
5	Processing of petroleum and nuclear fuel coking	16	Production and supply of water
6	Production and supply of electricity and heat	17	Chemical industry
7	Production and supply of gas	18	Construction
8	Non-metal mineral products	19	Other secondary industry
9	Smelting and pressing of metals	20	Transportation and storage
10	Metal products	21	Wholesale, retail trade, hotels and catering services
11	Manufacture of general and special purpose machinery	22	Other tertiary industry

coal, gas, crude oil, and refined oil production sectors (Webster et al., 2008; Wing and Eckaus, 2007). However, energy efficiency of all energy sectors in China still can be greatly improved, thus the extents of energy efficiency improvements for all these energy sectors are assumed to be entirely same with other energy-intensive sectors in this hybrid energy-economic model. And the extents of energy efficiency improvement in all these energy-intensive sectors are assumed to be 30%. And for agriculture sector, energy-intensive sectors and non energy-intensive sectors, the extents of energy efficiency improvement in 2030 are set as 0%, 30% and 10% respectively. On the other side, the average level of value added rate for whole Chinese economy has always been far below the level in developed countries. Among three major industries, only the primary industry (i.e., agriculture sector) in China has some advantages over developed countries, but the two other industries have contrary situation. Thus the extents of industrial technology upgrading (i.e., the increase of value-added rate) in 2030 are respectively assumed to be 0%, 10% and 5% among agriculture sector, energy-intensive industrial sectors and non energy-intensive industrial sectors.

2.3. Main framework

This hybrid energy CGE model is intertemperal dynamic, but not recursive dynamic. In a recursive dynamic CGE model, decisions about production, consumption and investment are made only on the basis of prices in the period of the decision, and consumers do not alter their saving and consumption on expectations of future returns on investment. But in the intertemperal dynamic CGE model, decisions today about production, consumption and investment are based on expectations that are simulated in the model. The evolution of the economy through time is driven by endogenous capital accumulation and exogenous labor growth. Such fully intertemporal optimization implicated that decisions about production, consumption and investment are based on expectations of future changes in the price of consumption or future returns on investment. Thus the forward-looking feature of this hybrid energy CGE model can better explain energy policy issues such as efficiency implications of environmental tax recycling and optimal emissions abatement paths among others (Babiker et al., 2009). Of course, CGE model is not the only numerical analysis tool for optimization of CO_2 abatement path. For example, by cost minimization of achieving the CO_2 concentration target, optimal CO2 abatement and carbon tax profiles can be characterized under different specifications for the channels through which technological progress occurs (Goulder and Mathai, 2000).

In current version of hybrid energy-economic model, the effects of technological progress for CO_2 abatement are simulated by technology type according to its action mechanism. For each economic sector within the framework of CGE model, two types of technological progress over time are exogenously given by AEEI parameters and technological progress coefficients. With energy efficiency improvement and industrial technology upgrading, the abatement of CO_2 emissions from each sector can be gained through energy intensity dropping via energy efficiency and added value rates. However, with induced technological progress, CO_2 abatement by oxy-fuel CCS technology introduction can be accelerated through learning-by-doing. The roles of such induced technological progress in coal-fired power industry can be expressed by technology learning curve. Accompanied with the simulation of economic growth during urbanization under the conditions setting above, energy demand such as electricity generation by coal-fired power units in China is forecasted by CGE model. The energy balance sub-model is linked with CGE model by a transformation matrix, which can transform monetary units of energy-related indicators in CGE model to physics units. By the energy balance sub-model, we can calculate coal consumption and electricity generation by coal-fired power industry in physics units during each period, which are used as input parameters to the coal-fired power sub-model. Meanwhile, the effects of developing low-carbon coal-fired power technologies are examined in the coal-fired power engineering sub-model, which is also directly linked with CGE model by electricity cost.

The CGE model uses a combination of Leontief and Cobb-Douglas production structure. Besides, this model has fully flexible coefficients in the demand function of production and consumption. Under given commodity demand and price, behavior of industrial sectors can be described by cost minimization problem as follows:

$$\text{Min}\sum_{i=1}^{22} p_i X_{ij} + \left(1 + tp_j\right)\left(w \cdot L_j + r \cdot K_j\right)(j = 1, \cdots, 22) \tag{1}$$

subject to

$$X_j = \min\left\{\frac{1}{v_j} f_j(L_j, K_j), \frac{1}{Tp_j}\prod_{i=1}^{22} X_{ij}^{a_{ij}}\right\} \tag{2}$$

$$f_j(L_j, K_j) = TC_j L_j^{a_j} K_j^{(1-a_j)} \tag{3}$$

$$\nu_j, TP_j, TC_j > 0, \sum_{i=1}^{22} a_{ij} = 1(a_{ij} \geq 0) \tag{4}$$

where p_i: the price of commodity i, X_{ij}: intermediate input of industry i's product in industry j, X_j: the output produced from industry j, tp_j: net indirect tax rate imposed on industry i's product, w: wage rate, r: capital return rate, L_j: labor input in industry j, K_j: capital input in industry j, v_j: value added rate in industry j, a_{ij}: direct input coefficient, and IA_j: technical parameter in industry j.

The energy input of sort s per unit of output in sector j and period t is revised by AEEI parameter, which is described as follows:

$$\frac{x_{sj}^t}{Y_j^t} = \left(1 - \eta_j^t\right) \cdot \left(\frac{x_{sj}^{t-1}}{Y_j^{t-1}}\right) \tag{5}$$

Here, η_j^t is used to determine the physical energy inputs required for production process, which is referred as AEEI parameter.

Industrial technology upgrading is represented by the increasing rate of technological progress coefficient in this model. The technological progress coefficient in sector j and final period n is assumed to be changed compared with its level in initial period 1, which is described as follows:

$$TC_j^n = TC_j^1 \cdot (1+\lambda_j)^n \tag{6}$$

where TC_j^1: technological progress coefficient in industry j in the first period, $IA(t) = Ge_{CCS}(t) \times (EF_{non-CCS} - EF_{CCS})$: average changing rate of technological progress coefficient during one period in sector j, and this parameter is given exogenously.

Cost minimization yields conditional demands for intermediate goods, labor and capital in production process. Zero profit condition is realized in industries under perfect competition at each time, which is described as follows:

$$profit = p_j X_j - \sum_i p_i x_{ij} - \left(1+tp_j\right)\left(w \cdot L_j + r \cdot K_j\right) = 0 \tag{7}$$

By considering intergenerational equality, the maximization of intertemporal utility discounted to present values till infinity is given as follows:

$$\max \int_0^\infty e^{-\rho t} \ln U(\cdot) dt \tag{8}$$

$$U(\cdot) = CH(t) \tag{9}$$

$$\text{subject to} \quad A(t) = \sum_t (1+r(t))^{-t}(Y_h - CH(t)) \geq 0 \tag{10}$$

where ρ: a constant utility discount rate; Y_h: disposable income;$A(t)$: aggregate budget of a represent household during period 0 − t; $r(t)$: instantaneous interest rate; and $CH(t)$: aggregate household consumption in period t.

Here, the aggregate budget $A(t)$ as constraint condition means that the total savings during whole life period of a represent household should not be less than zero. It means that disposable income can be consumed in present or be saved to consume in future. By solving this intertemporal utility maximization problem, optimal aggregate household consumption can be determined (Cheng and Dinopoulos, 1996). Thus instantaneous saving rate can be endogenously calculated.

Households in China are assumed to be classified into two types such as rural households and urban households. Hence, household consumption is also divided into rural and urban household commodity demand. The instantaneous utility function in each period is specified as a Cobb-Douglas type of aggregate household consumption, which is composed of 22 types of composite commodity demand from 22 sectors. Such composite commodity demand by sector can be also calculated as a Cobb-Douglas type of composition of rural and urban commodity demand by sector. The instantaneous budget constraint imposed on the household is the disposable income of each period. Hence, instantaneous utility function is maximized by subject to instantaneous budget constraint, which is described as follows:

$$MaxU = \prod_{i=1}^{22} (ch_i)^{\beta_{ih}} \quad \left(\sum_{i=1}^{22} \beta_{ih} = 1\right) \tag{11}$$

$$ch_i = \prod_s (ch_i^s)^{\beta_{ih}^s} \quad \left(\sum_s \beta_{ih}^s = 1\right) \tag{12}$$

$$\text{Subject to} \quad \sum_i \sum_s (p_i ch_i^s) = y_h \tag{13}$$

where i: sector, s: household type.

ch_i composite commodity demand from sector i;
ch_i^s commodity demand by household s from sector i;
y_h consumable income;
β_{ih} technical parameter;
β_{ih}^s technical parameter.

Then the demand of commodity from sector i by household s can be calculated as follows:

$$ch_i^s = \frac{\beta_{ih}\beta_{ih}^s y_h}{p_i} \tag{14}$$

where the technical parameter β_{ih}^s is revised by the change of urbanization rate in each simulation period. And the change of urbanization rate is defined as urbanization rate in current period divided by urbanization rate in previous period. Hence, final household consumption can be changed with urbanization rate, and production structure can also be revised endogenously.

International trade is simply studied by the estimation of exports and imports in the external sector. The external sector gains its income from imports, and then it expends the income on exports. Its savings are the difference between imports and exports. Since current financial policy in China is expanding inner demand, exports are assumed to be fluctuated with price, and imports are assumed to be proportional of output. Here, exports and imports are specified as follows:

$$EX_i = EX_i^* (p_i^*/p_i) \tag{15}$$

$$EM_i = EM_i^* (X_i/X_i^*) \tag{16}$$

where X_i^{ba}: output from sector i in base year; X_i^t: output from sector i in period t; EM_i^{ba}: import from sector i in base year; EM_i^t: import from sector i in period t; EX_i^{ba}: export from sector i in base year; EX_i^t: export from sector i in period t; p_i^{ba}: price of commodity i in base year; and p_i^t: price of commodity i in period t.

Thus the savings of the external sector are described as follows:

$$SO = \sum_i (p_i \cdot EM_i - p_i \cdot EX_i) \tag{17}$$

Setting a target of economic growth as the transverse condition of CGE model, to maximize the integration of discounted utility function over time subject to the lifetime budget, we can determine the parameters such as utility discounted rate and income discounted rate, which reflects the uncertain condition in the future.

About the level of disaggregation in CGE model and energy balance sub-model, it is assumed to be global and local relationship. CGE model depicts respectively the correlation interaction of all social economic sectors, while energy balance sub-model reflects the balance of energy supply/demand among these sectors. Then energy flow among social sectors simulated by energy balance sub-model should keep consistent with intersectoral economic effects calculated by CGE model. Obviously, energy consumption and production directly estimated by CGE model are all expressed in monetary units. But energy related indicators need to be expressed in physical units in coal-fired power sub-model. The level of disaggregation in CGE model and energy balance sub-model is assumed that energy input by sector and energy sort should be not less than zero and not infinite. The linkage between CGE model and energy balance sub-model is assumed to be the ratio of energy input by sector in 2002 respectively in physical unit to that in monetary unit. When 22 sectors have been combined as an industry, this ratio is aggregated as comprehensive energy utilization conversion factor, which is shown in Table 2.

Table 2
Comprehensive energy utilization conversion factor (unit: kgce/yuan).

Energy Sort	Sum	Industry	Urban household	Rural household
Coal	3.286444935	3.356181817	1.2437261	4.199703014
Oil, natural gas	0.885022732	0.877975657	1.5196806	0
Petrochemical products, coke, nuclear fuel	0.676565693	0.681993024	0.3621308	0.588087637
Electricity and heat	0.31738087	0.320422507	0.2547113	0.493436024
Gas	2.126792713	2.588681348	1.4053295	0

Note: Above data are estimated according to the references (CSY, 2006; CESY, 2006).

Therefore, a transformation matrix which transforms physical units to monetary units is constructed in the energy-balance sub-model, which is composed by energy conversion factors. And such energy conversion factor by social sector and by energy sort is extended from the comprehensive energy utilization conversion factor, which is estimated from energy supply/demand balance table by sector in physical units associated with the input–output table of 2002 Chinese economy. It means that industry shown in Table 2 will be divided into 22 economic sectors. And exports, imports and capital formation of energy commodities also should be included in the estimation of energy conversion factor. According to the composition of the total energy consumption, energy balance sub-model clearly distinguishes the final energy consumption, the energy losses during energy transformation and other energy losses by energy sort. In order to avoid the repeated accounting problem about total energy consumption, it also needs to estimate energy transformation efficiency and energy loss coefficient by energy sort according to the published energy balance table of energy supply/demand by sector (CESY, 2006). Here in the calculation of energy losses coefficient, total energy losses include the energy losses during the course of energy transportation, distribution, and storage in a given period of time. Especially, in current version of the hybrid energy-economic model, coal consumption by coal-fired power industry is the key parameter for further result analysis. For the technological progress of energy balance processes, it is assumed that energy losses coefficient of each energy sector will be decreased by 15% during the entire simulation period, and energy transformation efficiency of sector 2, sector 3, sector 6 and sector 7 will be increased by 5%, 0%, 30% and 10%, respectively, during the entire simulation period.

As mentioned above, the composition of household consumption is changed with the increase of urbanization rate. Then the production structure of industrial sectors including five energy sectors is endogenously revised according to final consumption structure. Hence, energy substitution among traditional fossil fuels can be calculated endogenously with the urbanization rate given exogenously.

Electricity generation is represented by the production of sector 6 in the CGE model. Of course, electricity and heat production sector (sector 6) not only includes coal-fired power units, natural gas-fired power units and oil-fired power units, but also includes hydropower generation units and other renewable generation units. Thus the generation amounts of above power generation technologies in physical unit can be forecasted by the energy balance sub-model. However, in this version of the hybrid model, only coal-fired power industry is carefully examined by coal-fired power engineering sub-model.

The endogenous parameter inputted to coal-fired power sub-model is coal consumption by coal-fired power industry, which is a parameter outputted from energy balance sub-model. And the parameter endogenously calculated by coal-fired power sub-model is the price change of electricity generation, which is used as an endogenous parameter inputted to the CGE model. Especially, the techno-economic parameters of coal-fired power technologies in China are sorted out by published existing studies (Huang, 2008; Lin et al., 2005; Lanz and Rausch, 2011), which is used as the data base for estimation of electricity price, generation efficiency and emissions factors. In current version of the model, the charging fee for newly increased amount of CO_2 emissions from coal-fired power industry during each year from 2020 can be endogenously calculated, and electricity generation by CCS units can be estimated. Then how electricity price will be changed by CCS technology introduction can be simulated. The alternative measure of buying extra expensive CO_2 permit allowance is to introduce CCS technology. The newly increased amount of CO_2 emissions from coal-fired power industry is described as follows:

$$Al(t) = (x_{26}(t) - x_{26}(t)) \times \lambda_{coal} \times \xi_{coal} \times \phi_{coal-power} \tag{18}$$

where $Al(t)$: the newly increased amount of CO_2 emissions from coal-fired power industry from period t_1 to t (i.e., CO_2 permit allowance in emissions trading market); λ_{coal}: unit conversion factor of coal consumption from monetary units to physical units in coal-fired power industry; ξ_{coal}: emissions coefficient of coal consumption in coal-fired power industry; $\phi_{coal-power}$: the share of coal consumption by coal-fired power units among that in the sector of electricity and heat production and supply.

Generally speaking, $Al(t)$ in this model is similar to CO_2 permit allowance which should be bought from emissions trading market by coal-fired power industry. Then the charging fee for $Al(t)$ is estimated as follows:

$$Ch(t) = Al(t) \times p_{CO2} \tag{19}$$

where $Ch(t)$: the charging fee which should be paid for the newly increased amount of CO_2 emissions by coal-fired power industry in period t; p_{CO2}: the price of charging CO_2 emissions.

The carbon price is proportional to the price of electricity and heat generation, which can be described as follows:

$$p'_{CO2}(t) = p_{CO2} \times p_6(t)/p_6(t_1) \tag{20}$$

where $p_{CO2}'(t)$: the relative price of newly increased CO_2 emissions from coal-fired power industry in period t compared with that in period t_1.

Due to carbon charging, the price of electricity and heat generation is changed with induced technological progress, which can be described as follows:

$$RC_6(t) = p'_{CO2}(t) \times Al(t)/(X_6(t) + p'_{CO2}(t) \times Al(t) \tag{21}$$

where $RC_6(t)$: the price change of electricity and heat production due to charging CO_2 emissions, which is used to input to the CGE model.

As mentioned above, the induced technological progress indicates CCS introduction to coal-fired power industry for low-carbon electricity generation. Then electricity generation by CCS units is estimated as follows:

$$Ge_{CCS}(t) = Al(t)/(egCost_{CCS} - egCost_{non-CCS}) \tag{22}$$

where $Ge_{CCS}(t)$: electricity generation by CCS units; $egCost_{non-CCS}$: generation cost of non-CCS units; $egCost_{CCS}$: generation cost of CCS units.

Although the reduction of generation cost of CCS units is accompanied with technological progress through research, demonstration and commercialization of CCS technology, generation cost of CCS units is still much higher than that of non-CCS units. And the increment of generation cost of CCS units can be described as follows:

$$exCost_{CCS} = egCost_{CCS} - egCost_{non-CCS} \tag{23}$$

where $exCost_{CCS}$: the difference of generation cost between CCS units and non-CCS units.

Moreover, the reduction of generation cost of CCS units due to technological progress is described by technology learning curve. The relationship between the cost reduction of CCS units and its cumulative production is expressed as follows:

$$exCost_{CCS} = C_0 \times C_{un}{}^{b} \tag{24}$$

Table 3
Main indicators of Chinese coal-fired power generation in BAU scenario.

	2002	2010	2015	2020	2030
Electricity and heat generation (10^8 kWh)	14,567	44,312	62,469	85,751	111,615
Generation efficiency (%)	39.3	42.8	45.5	48.4	51.2
Power generation share (%)	82.3	79.1	79.8	81.5	79.5
Coal consumption share (%)	46.0	48.1	48.2	48.4	47.2

$$LR = 1-2^b \quad (25)$$

where C_0: the initial difference of generation cost between CCS units and non-CCS units, and C_{un}: the times of doubling the cumulative generation; b: the experience index, and LR: the learning rate, which indicates the rate of cost reduction with each doubling of the cumulative production.

Here, induced CO_2 abatement is specifically defined to quantify CO_2 emissions reduction owing to CCS technology introduction to coal-fired power industry, which is estimated as follows:

$$IA(t) = Ge_{CCS}(t)(EF_{non-CCS}-EF_{CCS}) \quad (26)$$

where $IA(t)$: induced CO_2 abatement from coal-fired power industry; $EF_{non\text{-}CCS}$: CO_2 emissions coefficient of non-CCS units; EF_{CCS}: CO_2 emissions coefficient of CCS units.

Finally, the increased production cost of coal-fired power industry revises the price equation, which can be expressed as:

$$P(t) = \left[I-A^T(P(t)) \times (I+DET(t))\right]^{-1}\left(1+tp_j(t)\right) \times (\omega(t) \times \mathrm{l}_j(t) + \mathrm{r}(t) \times k_j(t)) \quad (27)$$

where $P()$: vector of producer prices; I: a unit matrix; $A^T()$: the transposed matrix of direct input coefficient; ω: wage rate; l_j: labor input in unit output of sector j; r: capital return rate; k_j: capital input in unit output of sector j; and DET: a diagonal matrix, the diagonal elements of which is RC_j (when $j\neq 6$, $RC_j=0$).

3. Results and discussions

As mentioned above, in this version of the hybrid energy-economic model, the increasing rates of technological progress coefficients and AEEI coefficients in 2030 China are set respectively among agriculture sector, energy-intensive sectors and non energy-intensive sectors.

If without induced technological progress, market shares of efficient and clean coal-fired power technologies are exogenously given by conforming to government program about coal-fired power technologies (Huang, 2008). And the assumption setting of market shares also needed to refer to the dropping of energy intensity, which should be same with AEEI parameters. However, if with induced technological progress, direct carbon removal technology such as oxy-fuel CCS units could be introduced to Chinese coal-fired power industry under the policy of climate change. Since oxy-fuel CCS technology is still in its research and demonstration phase in China, its technology learning effects have been considered in the process of commercialized utilization. In the coal-fired power engineering sub-model, market shares of oxy-fuel CCS technology introduction are endogenously calculated according to carbon charging fee in coal-fired power industry. Thus we can synthetically evaluate several CO_2 abatement pathways for Chinese coal-fired power industry in two studied cases: without and with induced technological progress. Since 2002 China input–output table is used as data base, the GDP and other economic indicators are calculated at 2002 comparable price.

Table 4
Technical parameters about advanced coal-fired power and heating technologies in China.

	Generation efficiency	Generation cost (yuan/kWh)	CO_2 coefficient (g/kWh)
Subcritical unit 1	0.33	0.341	1019
Subcritical unit 2	0.33	0.349	1050
Subcritical unit 3	0.384	0.359	813
Ultra-supercritical units	0.44	0.29	710
Supercritical units	0.405	0.325	771
CHP 1	0.55	0.26	630
CHP 2	0.75	0.21	462
FBC	0.37	0.43	873
IGCC	0.419	0.42	744

Note: Above data are estimated according to the references (Huang, 2008; Lin et al., 2005). Subcritical units 1 means subcritical units without $deSO_2$ and $deNO_x$. Subcritical units 2 means subcritical units with $deSO_2$ only. Subcritical units 3 means subcritical units with $deSO_2$ and $deNO_x$. CHP1 means common CHP units without $deSO_2$ and $deNO_x$. CHP2 means advanced CHP units with $deSO_2$ and $deNO_x$.

Table 5
Generation mix of coal-fired power and heating units in China (%).

	2002	2010	2015	2020	2025	2030
Subcritical unit 1	87.3	16.4	5.5	4	2	0
Subcritical unit 2	6.4	46.1	31	17	11	3
Subcritical unit 3	0	5.5	17	25	22	22
Ultra supercritical units	0	1	2	2	4	6
Supercritical units	0	15	20	28	30	30
CHP 1	6.3	8.5	10	6	4	0
CHP 2	0	7	13	15	19	26
FBC	0	0.5	1.5	1	1	1
IGCC	0	0	0	2	7	12

Firstly, the share of coal-fired power generation among the total electricity & heat generation (i.e., power generation share) and the share of coal consumption by power generation among the total coal consumption (i.e., coal consumption share) are estimated in the main time nodes from 2002 to 2030 in China, which are shown in Table 3. Of course, the indicators in 2002 and 2010 are used for calibration. Other energy indicators in Table 2 such as electricity and heat generation and generation efficiency are used for forecasting the development scale and energy conversion efficiency of coal-fired power industry in China. And all these results about general situation of coal-fired power industry are the basis of further study, which should be following government programme about coal-fired power technologies (Huang, 2008). On the other side, the commercialized utilization of oxy-fuel CCS technology is assumed to begin from 2020 in Chinese coal-fired power industry. In terms of the abatement of air pollution most coal-fired power plants in China are assumed to be installed with desulfurization and denitrification devices by 2020. Then CO_2 abatement pathways of CO_2 emissions are compared in two cases: without and with induced technological progress. As mentioned above, induced technological progress is specifically referred to oxy-fuel CCS technology introduction in this study.

Then according to the levels of carbon price setting for charging the newly increased CO_2 emissions in Chinese coal-fired power industry

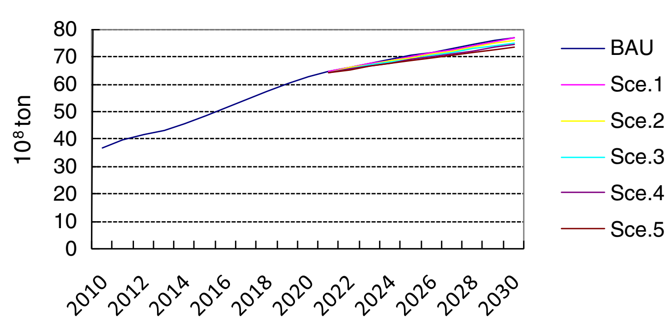

Fig. 2. Total CO_2 emissions from Chinese coal-fired power industry without induced technological progress.

Table 6
Indirect CO_2 emissions abatement from Chinese coal-fired power industry in BAU.

	2002	2010	2015	2020	2030
CO_2 emissioncoefficients (g/kWh)	908	851	826	779	717
Relative CO_2 emission reductions(10^8 tons)	/	2.4	5.1	11.0	21.3
Total CO_2 emissions (10^8 tons)	13.2	37.8	51.6	66.8	80.0

from 2020 to 2030, six scenarios are set as follows: (1) BAU: no any carbon charging; (2) Sce.1: carbon price is assumed as 40 RMB_{2002} yuan/t CO_2; (3) Sce.2: carbon price is assumed as 100 RMB_{2002} yuan/ton CO_2; (4) Sce.3: carbon price is assumed as 200 RMB_{2002} yuan/t CO_2; (5) Sce.4: carbon price is assumed as 300 RMB_{2002} yuan/t CO_2; (6) Sce.5: carbon price is assumed as 400 RMB_{2002} yuan/t CO_2.

3.1. Case 1: Without induced technological progress

With direct carbon removals such as oxy-fuel CCS technology being put aside temporarily, only energy-saving is considered as CO_2 abatement technique in case 1. Since expensive fuel inputs can be saved by energy efficiency improvement, it seems reasonable to assume that energy-saving will still occur with no any climate policies.

Since CCS technology is still in research and demonstration phase with uncertain development prospects, such uncertain technology is assumed to not been commercialized by 2030 in case 1. However, energy-saving related low-carbon coal-fired power technologies are assumed to have been mature. And these low-carbon technologies' techno-economic parameters are shown in Table 4. For these mature technologies, we also assume that their price can be acceptable by market, and their development prospects have a high certainty. In this version of the hybrid energy-economic model, generation mixes (i.e., market shares) of such efficient and clean coal-fired power technologies are given exogenously, which are shown in Table 5. In CGE model, cost minimization condition of production sectors has been adopted. Therefore, production optimization of electricity generation has been applied in the simulation. In this version of the hybrid energy-economic model, the satisfied solution of CO_2 abatement pathway is stopping the upward trend of total CO_2 emissions from coal-fired power industry from 2020 at the least GDP losses. Although such methodology seems very simple, we think it can be effective to choose the optimum CO_2 abatement pathway in coal-fired power industry. In case 1 without induced technological progress, total CO_2 emissions from Chinese coal-fired power industry in above six scenarios during the whole studied period are shown in Fig. 2. Of course, charging for newly increased CO_2 emissions without induced technological progress can reduce the total CO_2 emissions to certain extent. However, such reduction extents seem not enough. Even with high carbon pricing at 400 RMB_{2002} yuan/t CO_2 in scenario 5, total CO_2 emissions from Chinese coal-fired power industry still appears upward by 2030.

Here, we only analyze the relative reduction of CO_2 emissions in the main time nodes in BAU, which is based on the change of CO_2 emissions coefficients of whole Chinese coal-fired industry within each period. And the relative reduction of CO_2 emissions is treated as the indirect abatement, which means that carbon intensity declines while total CO_2 emissions continuously grow. According to the extent of generation efficiency improvement (i.e., coal consumption reduction per unit of power generation), indirect CO_2 abatement by AEEI and total CO_2 emissions from coal-fired power industry are calculated, which is shown in Table 6. Although indirect CO_2 emissions become larger and larger by year, the upward trend of CO_2 emissions will not be changed only through AEEI even with high carbon pricing by 2030. Since energy-saving tends to happen even without any policy influences, macroeconomic impacts of developing advanced coal-fired power technologies in case 1 without induced technological progress are neglected. However, for the choice of induced CO_2 abatement pathway, macroeconomic impacts of charging for newly increased CO_2 emissions in coal-fired power industry will be analyzed latter in case 2 with induced technological progress.

3.2. Case 2: With induced technological progress

There are mainly three types of carbon capture technologies for coal-fired power plants: post-combustion capture, pre-combustion capture (IGCC) and oxy-fuel combustion. Among these three types of CCS technologies, oxy-fuel combustion technology has been widely accepted as a technological feasible and economic affordable approach for newly built/retrofit purpose. Oxy-fuel combustion is a carbon capture technology with relatively high technology maturity and full industry infrastructure, which has become the most promising way to be commercialized in the near future. Especially, oxy-fuel combustion technology can be easily applied in the mainstream units of existing power plants, and it is suitable for the reform of the existing power units and the ones under-construction. Besides, oxy-fuel combustion can be easily implemented in CCS units with a relatively low overall cost and high-purity CO_2 gas. Moreover, oxy-fuel combustion is likely to be the lowest cost option for clean utilization of the existing fossil power plants and storing CO_2 by geographic sequestration, and it has been extensively investigated and developed in recent years. For the simplification of simulation, performance parameters of oxy-fuel CCS technologies are represented by combining typical coal-fired power units in current China. Main technical parameters of CCS technology in typical oxy-fuel combustion plants (i.e., supercritical units) are depicted in Table 7.

In the coal-fired power engineering sub-model in case 2, the newly increased amount of CO_2 emissions from coal-fired power industry from 2020 is assumed to be charged. However, in the carbon permit transaction market, if the charging fee is used by coal-fired power industry to introduce oxy-fuel CCS technology, and the newly increased CO_2 emissions will be abated by induced technological progress of coal-fired power industry. For the estimation of technology learning effects of oxy-fuel CCS technology in coal-fired power engineering sub-model, the initial generation is assumed to be 2×10^8 kWh, and the learning rate *LR* is set as 0.08. From data about generation cost in Table 7, the initial difference of generation cost between CCS units and non CCS units is estimated at 135.17 RMB_{2002} Yuan/MWh.

Then by applying the hybrid energy-economic model, induced CO_2 abatement and the GDP losses by oxy-fuel CCS technology introduction are estimated, which are shown in Table 8. As mentioned above, the newly increased amount of CO_2 emissions from 2020 is assumed to be equal to the amount of permit allowance which is needed to buy by coal-fired power industry in case 1 without induced technological progress. However, in case 2 with induced technological progress, the changing fee to by permit allowance are used to introduce oxy-fuel CCS

Table 7
Techno-economic parameters of CCS technology in typical oxy-fuel combustion plants.

	Generation efficiency	Generation cost	SO_2 emissions	NO_x emissions	CO_2 emissions
	(%)	(RMB_{2002} Yuan/MWh)	(g/MWh)	(g/MWh)	(kg/MWh)
Supercritical units in oxy-fuel combustion plants	36.0	459.69	52.01	139.67	33
Supercritical units in normal plants with deNO_x and deSO_2)	40.5	324.51	119.54	334.47	771

Note: Above data are estimated according to the references (Xiong et al., 2009; Xiong, 2011).

Table 8
The effects of oxy-fuel CCS introduction in 2030 Chinese coal-fired power industry.

	CO_2 price	CO_2 charging fee	CCS generation	CCS share	Permit allowance	Induced abatement	Additional emissions	GDP losses
	(RMB_{2002} Yuan/t)	(10^8 RMB_{2002} Yuan)	(10^4 MWh)	(%)	(10^4 ton)	(10^4 ton)	(10^4 ton)	(%)
Sce.1	40	559	51,831	4.67	139,748	38,251	190	0.14
Sce.2	100	1335	139,645	12.69	133,486	103,058	512	0.33
Sce.3	200	2488	282,991	26.03	124,383	208,847	1038	0.62
Sce.4	300	3498	417,162	38.77	116,608	307,866	1530	0.86
Sce.5	400	4395	540,911	50.73	109,876	399,193	1983	1.06

technology. With carbon price going higher from scenarios 1 to 5, the charging fee to buy permit allowance keeps a sustained growth, although the amount of permit allowance needed to be bought appears a decline. Meanwhile, GDP growth and electricity demand also become declining. In case 2, it is assumed that the charging fee is used to introduce oxy-fuel CCS technology into coal-fired power industry. With more and more charging fee from scenarios 1 to 5, electricity generation by oxy-fuel CCS units (i.e., CCS generation) and their shares among the total coal-fired power generation (i.e., CCS generation share) also appear an upward trend. And induced CO_2 abatement from scenarios 1 to 5 also keeps a growth. According to the simulation results as shown in Table 7, CO_2 abatement per percent of the GDP losses from scenarios 1 to 5 are estimated at 216.1, 217.8, 220.5, 223.0 and 225.3 tons in 2030 Chinese coal-fired power industry respectively. Obviously, this indicator appears a little increase from scenarios 1 to 5. However, the growth extent of this indicator appears gradually declining by year within each scenario.

Moreover, fluctuation range of CCS generation share between different scenarios seems very large, and CCS generation share increases over 10 times from scenarios 1 to 5. Especially, the CCS generation share is only less than 5% in scenario 1, but it surpasses 50% in scenario 5. However, due to the cost reduction effects of technology learning, induced CO_2 abatement also tends to be upward sharply from 2020 to 2030 within each scenario. With higher carbon pricing from scenario 1 to 5, the GDP losses also appear to be reduced more and more with the increase of CCS generation share in 2030. Compared with that in BAU, the GDP losses in 2030 remain less than 0.2% in scenario 1, but it surpasses 1% in scenario 5. And the GDP losses increase about 7 times from scenarios 1 to 5 in both cases 1 and 2.

On the other side, as a result of extra energy consumption by oxy-fuel CCS units (i.e., energy penalty for carbon capture), additional CO_2 emissions could be brought with oxy-fuel CCS technology introduction. Although additional CO_2 emissions are very limited compared with induced CO_2 abatement, they will gradually be increased with higher and higher market shares of oxy-fuel CCS technology during the process of its commercialization. With more and more charging fee from scenarios 1 to 5, CCS generation share in 2030 is estimated to be increased over 11 times, and additional CO_2 emissions will be increased over 9 times. However, additional CO_2 emissions still appear to be very small compared with the newly increased CO_2 emissions. And their proportions are estimated at 1.36‰, 3.84‰, 8.35‰, 13.12‰ and 18.05‰ respectively from scenarios 1 to 5. Undoubtedly, with CCS generation share going higher, the amount of additional CO_2 emissions also will become unignorable in the future coal-fired power industry when oxy-fuel CCS technology has been commercialized. Moreover, extra energy consumption also remains the key factor of high operation cost of oxy-fuel CCS units. Since extra energy consumption created due to the operation of oxygen generator system, energy utilization during the process of oxygen generation should be reformed. Then how to improve energy efficiency of oxygen generator system remains the key point to accelerate the commercialized utilization of oxy-fuel CCS technology.

Then by apply the hybrid energy-economic model, induced CO_2 abatement pathways and total CO_2 emissions trend of Chinese coal-fired power industry with induced technological progress are shown in Figs. 3 and 4. With carbon price going higher and higher from scenarios 1 to 5, the amount of induced CO_2 abatement also grow rapidly. Without induced technological progress, total CO_2 emissions in all above scenarios appear an upward trend by 2020, which are the same with that of BAU. But with induced technological progress from 2020, total CO_2 emissions among these scenarios appear quite different. In BAU and scenario 1, total CO_2 emissions still remain an upward trend from 2020. But in other scenarios, the amount of induced CO_2 abatement becomes so large that total CO_2 emissions can stop an upward trend from 2020, and even turn to decrease from scenarios 3 to 5.

For the choice of optimal CO_2 abatement pathway for Chinese coal-fired power industry, the synthetical indicators such as induced CO_2 abatement, additional CO_2 emissions, CCS share and the GDP losses should be compared and analyzed. As shown in Table 8, all these indicators become larger and larger with carbon price going higher. Besides, total CO_2 emissions which are shown in Fig. 4 also need to be considered. In term of scenario 1, induced CO_2 abatement, additional CO_2 emissions and the GDP losses are very low, and total CO_2 emissions from coal-fired power industry cannot stop an upward trend. Obviously, carbon pricing at 40 RMB_{2002}yuan/t CO_2 in scenario 1 is too low. And the charging fee is suggested to buy permit allowance rather than CCS technology introduction in scenario 1. However, induced CO_2 abatement could be raised to be over 1 billion tons in scenario 2. Moreover, the GDP losses also seem not very large and total CO_2 emissions from coal-fired power industry could almost keep stable. Since we hope that greenhouse gas emissions cannot be remarkable increased in coal-fired power industry from 2020, carbon pricing at 100 RMB_{2002} yuan/t CO_2 in scenario 2 can be just thought of exactly suitable. Although induced CO_2 abatement can be greatly raised and total CO_2 emissions appear to be decreased from scenario 3 to 5, additional CO_2 emissions and the GDP losses also become to increase rapidly. Particularly, induced CO_2 abatement in scenario 5 even becomes 2.5 times over the level of permit allowance in 2030. Additional CO_2 emissions also rapidly increase, and the GDP losses also seem too large. In fact, induced CO_2 abatement in scenario 5 becomes so huge that the total CO_2 emissions in 2030 even drop to below the level in 2010. Of course, the levels of carbon pricing in scenario 3, 4 and 5 at 200, 300 and 400 RMB_{2002} yuan/t CO_2 seem too high. By overall consideration, induced CO_2 abatement pathway in scenario 2 can be regard as optimal in this study.

With high energy penalty for carbon capture, energy efficiency and economic performance are reduced for the entire oxy-fuel CCS power plant. In order to improve energy efficiency of oxy-fuel CCS units,

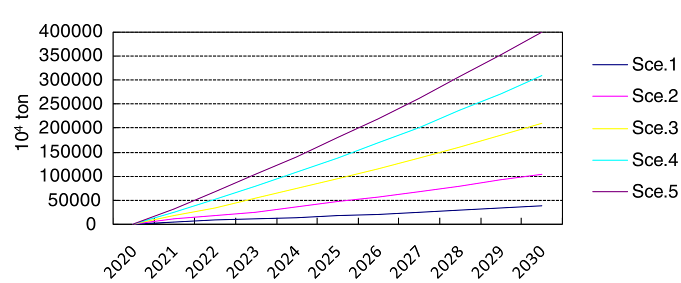

Fig. 3. Induced CO_2 abatement from 2020 to 2030 in Chinese coal-fired power industry.

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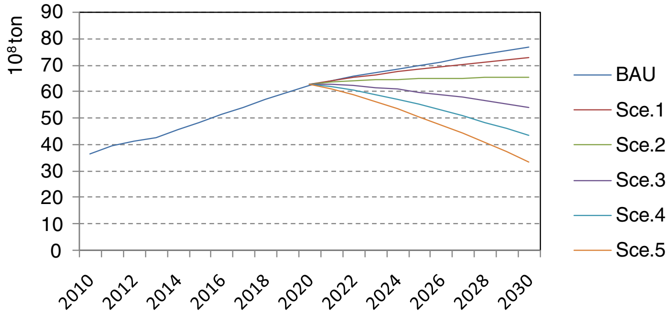

Fig. 4. Total CO_2 emissions from Chinese coal-fired power industry with induced technological progress.

technological renovation of oxygen generator system should be implemented. Owing to the expensive cost of oxy-fuel CCS technology, huge public funds also should be subsidized for accelerating its demonstration and commercialization. Since charging for the newly increased CO_2 emissions is only one of possible method for raising funds, how to finance and invest oxy-fuel CCS projects still needs further research in the future.

4. Conclusions

Based on above analysis, the total amount of CO_2 emissions from Chinese coal-fired power industry could be gradually mitigated through energy efficiency improvement and CCS technology introduction. If without induced technological progress (i.e., only through energy saving), a huge amount of indirect CO_2 abatement could be created. However, the upward trend of CO_2 emissions from Chinese coal-fired power industry cannot be changed by 2030 even with very high carbon pricing. But if with induced technological progress (i.e., also through CCS technology), total CO_2 emissions from Chinese coal-fired power industry may stop its upward trend from 2020 when carbon pricing is high enough. Although higher level of carbon price setting for charging newly increased CO_2 emissions from 2020 could be benefit for accelerating CCS introduction, it also can make GDP growth be greatly reduced. By overall consideration, carbon pricing at 100 RMB_{2002} yuan/t CO_2 with induced technological progress can be acceptable in the view of CO_2 abatement and macroeconomic effects. When carbon pricing at 100 RMB_{2002} yuan/t CO_2 with induced technological progress, total CO_2 emissions from Chinese coal-fired power industry can almost keep stable, and the GDP losses is not very large. Therefore, the induced CO_2 abatement pathway when charging for the newly increased CO_2 emissions at 100 RMB_{2002} yuan/t CO_2 with induced technological progress can be regard as optimal. Since the cost of CO_2 abatement in coal-fired power industry is much higher compared with that of other industries in China, this study can also provide a reference basis for studying carbon price formation mechanism in future Chinese carbon market.

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