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Economic, energy and environmental impact of coal-to-electricity policy in China: A dynamic recursive CGE study

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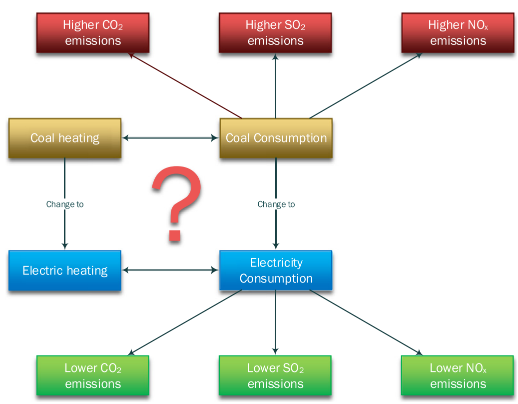
HIGHLIGHTS

- CtE project is an effective way to reduce SO_2 and NO_x emissions than CO_2 emissions.
- Coal consumption of industries may increase due to CtE project.
- Some energy saving policies can increase CO_2 reduction potential of CtE project.
- The subsidy of insulation layer is as important as that of electric heaters.

GRAPHICAL ABSTRACT



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ABSTRACT

In north China, many rural and urban residents still use coal for heating in winter. However, such method would result in a large amount of GHG emissions. China intends to change the heating method of its citizens from coal burning to electric heating to save energy, reduce emissions, which is called the project of Coal to Electricity (CtE). A dynamic recursive computable general equilibrium model is applied to analyze the real effect if the project is widely promoted in China. We found that CtE project is effective in reducing SO_2 and NO_x emission than CO_2 emissions. In essence, energy substitution is not energy-saving, so the contribution to CO_2 reduction of CtE project is limited. There is a certain co-benefit between CtE project and other energy saving policies (new energy generation, improving heating efficiency and building energy saving etc.). The findings indicate that single CtE policy can only bring better air quality. However, with other energy saving policies, CtE project can not only bring NO_x and SO_2 reduction, but also lead to less CO_2 emissions and more convenient life. Multiple emission reduction measures are suggested to maximize the reduction effects of these policies.

1. Introduction

Since the industrial revolution, human activities have led to a great deal of Greenhouse Gas (GHG) emissions, which caused global warming. The problem of air pollution is also emerging in recent years, such as SO_2, NO_x emission, which is harmful to human health.

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Fossil burning with uncleanness and excessive energy consumption may be the greatest contributors to global warming and environmental deterioration. In order to solve this problem, many scholars have made many efforts on low carbon business (Lin and Xie, 2014; Liu et al., 2017). They have been working on methods for sustainable development. Two aspects are noted: low-carbon policy and low carbon technology. Countries and organizations have made variety of attempts to mitigate the global warming, such as carbon tax (Tsai and Jhong, 2019; Wang-Helmreich and Kreibich, 2019), land carbon sinks (Gallego-Sala et al., 2018) (forest carbon sinks (Lin and Ge, 2019) etc.), green electricity certificate trading system (Suo et al., 2017), clean development mechanism (Kim and Park, 2018; Mori-Clement and Bednar-Friedl, 2019), and emission trading scheme (Chang et al., 2018; Lin and Jia, 2019a; Zhu et al., 2018) with clean development mechanism. Energy is one of the essential production factors, so the corresponding technologies of energy efficiency and energy structure are also hot research topics: the improvement of energy efficiency (Lin et al., 2017), grid energy storage (Zhang et al., 2019), electric vehicle (Cusenza et al., 2019; Machura and Li, 2019), new power generation technologies (Lin and Chen, 2018; Sun et al., 2018; Zeng et al., 2019) and carbon capture and storage (Lausselet et al., 2017) are now relatively hot technologies for emission reduction.

Among them, energy substitution, such as coal to electricity and coal to gas, is also a kind of energy-saving, emission-reducing and environment-friendly solution for the continuous deteriorating environment and the ever-warning planet. Aguilera and Ripple (2013) analyzed the mixture of primary energy in the Asia-Pacific by using a global energy market model. Løvold Rødseth (2017) analyzed the substitution of coal-to-gas in US power generation sector and found that the absence of environmental regulations causes ignorance of compliance costs and managerial allocative efficiencies are overestimated. Jenner and Lamadrid (2013) insisted that public health, environment quality, water consumption will be improved by a shift from coal to shale gas. Wigley (2011) found that gas may be more effective energy in the perspective of heating. Hartmann and Kaltschmitt (1999) analyzed the environment impact of electricity production from different biofuels co-combustion relative to electricity production from coal alone, and found that the former can be made to a more environmentally sound than the latter. Davidson et al. (2016) predicted the potential wind power energy and integrated the prediction into China's electricity structure model, estimating a potential production of 2.6 petawatt-hours per year in 2030 for future's wind energy substitution. In general, energy substitution is hot topic in the field of energy policy and energy economics, such as coal to gas (Lim et al., 2017; Yang et al., 2017), coal to biomass (Weldu et al., 2017), car use between oil vehicle and electric one (Blasius and Wang, 2018; Du and Lin, 2017; Lin and Wu, 2018) etc.

According to *BP Statistical Review of World Energy 2017* (BP, 2017), although the energy structure is continually improving, coal consumption is still the largest in energy consumption in China, which accounted for 62% of the total primary energy consumption. The Chinese government is keen to change the status of coal-based energy consumption. It is an effective way to developing the alternative energy for coal. Increasing the end use of natural gas or electricity may be good ways for sustainability.

Fig. 1 illustrates the Energy consumption in 2016. China is the largest emitter of the world, accounted for 23% energy consumption according to the *BP Statistical Review of World Energy 2017*. In addition, 11% of total energy consumption in China is resident energy consumption, which accounts for 3% of the world total energy consumption in 2016 (National Bureau of Statistics, 2016), indicating that the energy consumption of residents in China is tremendous. Although energy consumption per capita in China is lower than the consumption in most developed countries, the policy on huge, population-based consumption will affect total energy consumption significantly, whether it is more energy-saving or more energy-consuming. Therefore, the study on residents' energy consumption in China is necessary.

In China, many rural and urban residents still use coal for heating in winter. However, such warming method may waste lots of energy and may result in a large amount of GHG emissions. Therefore, China intends to change people's heating method from coal burning to electricity heating, which is called the project of Coal to Electricity (CtE). CtE project means that residents' heating methods have changed from burning coal to using electric energy to keep house warm. There are two main types, one is to replace the ordinary coal boiler with an electric boiler; the second is to replace the heating facilities such as electric heating film heater or heating cable. This is a huge project, which could change people's living standard (more convenient, less smog, and less labor input). In order to reduce coal pollution and improve air quality in winter, many cities in northern China began to promote CtE project from 2014. CtE project was first deployed in Beijing, but the promotion in other cities is relatively lagging behind.

Based on the aforementioned review and information gathered by the researcher, it is evident that less work has been done on the impact of CtE project as the project has just appeared in China. Only two studies exists. Zhang and Yang (2019) found that CtE project carried out by Grid Company has poor economic performance during its life cycle. Chen and

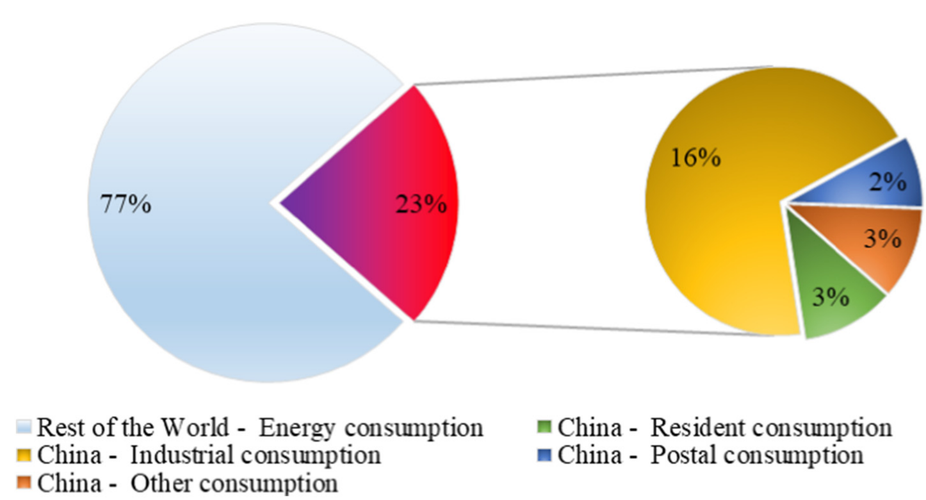


Fig. 1. Energy consumption in 2016.

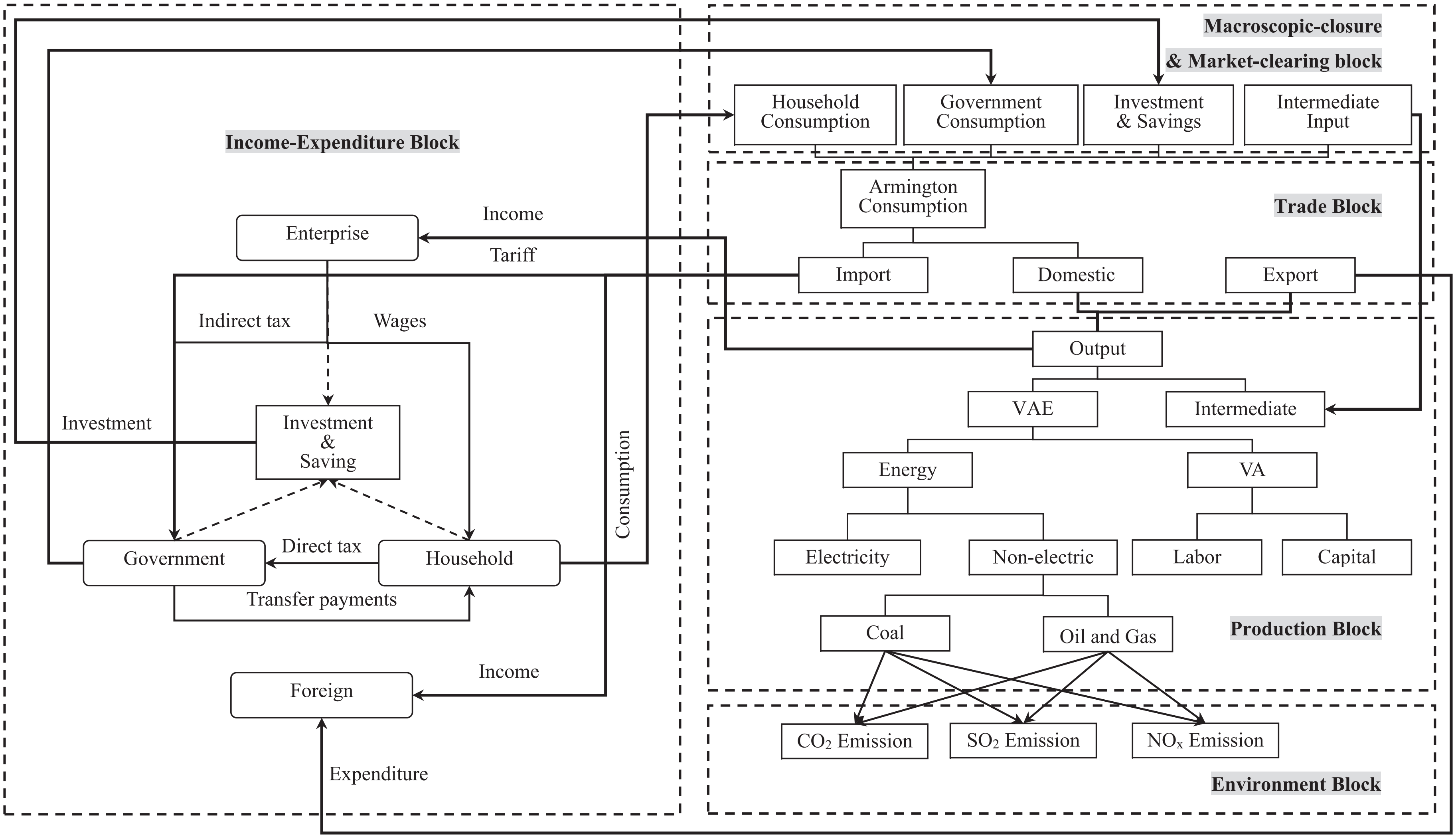


Fig. 2. General framework of the CGE model.

Chen (2019) found that CtE project could reduce NO_x and SO_2 emissions, as well as PM2.5. However, none osf them tried to address the knowledge gap to explore the energy, environmental and economic impact of CtE project. In thie regard, the paper seeks to answer the questions: is CtE project effective? Is CtE project energy-savings? Can CtE project reduce CO_2, SO_2 and NO_x emissions?

The contributions of this paper are as follows:

1) Topic: this paper explores the energy, environmental and economic impact of CtE project based on different scenarios, as almost none of the relevant literature has studied on this issue. Analyzing the effects of CtE project provides some implications to the energy policy in coal-based areas, such as China, India, South Africa, Poland, and Kazakhstan etc.
2) Methodology: this paper constructs a dynamic CGE model to analyze the issue. This will serve a reference for CGE modelers, and can be utilized to analyze the impact of energy substitution.
3) Findings and policy implications: this paper provides some interesting findings in CO_2, SO_2 and NO_x reduction and proposes several specific implications for coal-based countries.

The remaining part of the study is as follows: Section 2 introduces Computable General Equilibrium (CGE) model, Social Accounting Matrix (SAM) and model dynamics. Section 3 presents scenario design. The simulation results and discussions are in Section 4. Section 5 presents the conclusions and proposed policy implications of the study.

2. Methodology

2.1. CGE model

The CGE model is a policy analyzing tool which has been widely used (Cao et al., 2019; Su et al., 2019; Wang et al., 2019; Wei et al., 2019; Weng et al., 2019), CGE is good at simulating different policy, such as energy tax (Peng et al., 2019), tax reform (Wang et al., 2019), emission trading (Ma and Song, 2019) and policies under different target (Bohlmann et al., 2019; Nong et al., 2019; Qi et al., 2018). The purpose of CGE analysis is to describe the behavior the relationship of four social subjects, such as households, industries, government, and the rest of the world (Mayer et al., 2019). This model consists of five blocks: production block, income-expenditure block, trade block, environment block, and macroscopic-closure & market-clearing block. The general framework of the CGE model can refer to Lin and Jia (2019b), which is illustrated in Fig. 2, so that this paper only focuses on introduction of the dynamic ways and the treatment of parameters for CtE project.

2.1.1. Production block

Production block describes the production process of enterprises. Enterprises produce their goods through factor input under different production technology. The output itself is a Leontief function, consisting of Value-Added & Energy (VAE) input and intermediate input. VAE input is constituted by value-added input and energy input following a Constant Elasticity of Substitution (CES) function, like many other studies (Arto et al., 2019; Jin et al., 2019; Li et al., 2019). A CES function is used for VA input, consisting of capital and labor input, while it is used for energy input, consisting of electricity and non-electric (fossil energy) input. The fossil energy input is a CES function which consists of coal input and non-solid (oil and gas) input. Due to China's 139 sectors, the input-output table does not separate the oil and gas industries, and the main energy consumption in China is coal, this paper does not continue to subdivide oil and gas.

2.1.2. Environment block

Emission in this paper is calculated by energy consumption as shown in Eqs. (1)–(4), CO_2 emission coefficient of fossil energy is illustrated in Table 1, and SO_2 and NO_x emission factors of coal is depicted in Table 2. These two points worth noted: 1) the paper discusses CO_2 emissions only from fossil fuel consumption for production or heating, and 2) this paper assumes that power plants will utilize desulfurization and denitrification completely, while the residents will create SO_2 and NO_x emission into the air when they are burning coal for heating.

$$EM_i = QCOAL_i \times \gamma^{coal} + EM\_O\_G_i \tag{1}$$

$$EM\_O\_G_i = QO\_G_i \times \gamma^{o\text{-}g} \tag{2}$$

$$EM\_SO2_l = QCOAL_l \times \gamma^{coal-SO2} \tag{3}$$

$$EM\_NOx_l = QCOAL_l \times \gamma^{coal-NOx} \tag{4}$$

where EM_i represents total emission of sector i. $QCOAL_i$ represents coal consumption of sector i. γ^{coal} represents CO_2 emission coefficients of coal. $EM\_O\_G_i$ denotes emission by oil and gas energy consumption. QO_G_i and $\gamma^{o\text{-}g}$ are the consumption of oil and gas (which units has been converted to million tons of coal equivalent), and CO_2 emission coefficients of oil and gas (or the coefficients of coal equivalent). l represents rural residents or urban residents. $QCOAL_l$ is coal consumption by residents l. $\gamma^{coal-SO2}$ and $\gamma^{coal-NOx}$ are SO_2 and NO_x emission factors of coal. EM_SO2_l and EM_NOx_l are SO_2 and NO_x emission by coal consumption of residents.

2.2. Social accounting matrix

The most important basic data of CGE model is social accounting matrix, which can be compiled by the input-output table. This paper used 2012 China Input-Output Table (CIOT). The energy data of SAM is from the China Statistical Yearbook (National Bureau of Statistics, 2015) and the economic data is from China Input-Output Association (CIOA) (China Input-Output Association, 2017). SAM is balanced by using SG-RAS method (Wang et al., 2012).

In order to make the article more concise and expressive, we reclassify the 42 sectors in CIOT into 14 sectors, as shown in Table 3. In addition, we classify rural people and citizen, to analyze the different impact on rural and urban population (see Table 3).

2.3. Model dynamics

CGE model itself is a static model. We use a recursive method to convert the model into a dynamic model considering the capital, labor and Autonomous Energy Efficiency Improvement (AEEI).

Table 1
Coal equivalent coefficient and CO_2 emission coefficient of fossil energy.

Primary energy	Coal equivalent coefficient of primary energy	CO_2 emission coefficient of primary energy
Coal	0.743 kg/kg	1.852 kg/kg
Oil	1.429 kg/kg	3.561 kg/kg
Gas	1.330 kg/m^3	3.316 kg/m^3

Table 2
SO_2 and NO_x emission factors of coal.

Emissions	Emission factors of coal
SO_2	0.053 kg/kg
NO_x	0.016 kg/kg

Table 3
Description of sector classification and population classification.

Sectors	Description
AGR	Agriculture, forestry, animal husbandry and fishery
COL	Coal mining and washing industry
O_G	Petroleum and natural gas exploitation
PAP	Paper industry
CMT	Cement
FER	Chemical fertilizer
CMC	Chemicals
STL	Steel smelting and rolling processing industry
EQU	Equipment manufacturing industry
ELC	Electricity
CST	Construction industry
TRA	Transportation
OTH	Other industry
SER	Service
RUR	Rural population
CTZ	Urban population

Table 4
Scenario design of CtE project.*

Scenario	CtE project	Proportion of thermal power generation	Heating efficiency
BaU	–	–	–
C	Yes	–	–
H1	Yes	–	+10%
H2	Yes	–	+20%
P	–	−10%	–
PC	Yes	−10%	–
PH1	Yes	−10%	+10%
PH2	Yes	−10%	+20%

* In order to facilitate the memory of the scenario, this paper uses three letters of P, C, H to represent all scenarios. P simulates the assumption that the proportion of thermal power generation will reduce 10%. C simulates the assumption that government promotes CtE project. H simulates the assumption that government promotes CtE project with higher heating efficiency.

1) Capital depreciation, it is determined by capital stock of current period and investment. Capital stock is endogenous except for the first period, while the investment is endogenous.

$$FF^{cap}_{t+1} = CAPSTK_t \times \left(1-\overline{depre}\right) + \sum_i XV_{i,t} \quad (5)$$

where FF^{cap}_{t+1} is total capital depreciation in next period. $CAPSTK_t$ represents current capital stock. $\overline{depre}$ denotes average depreciation rate of total capital stock. $\sum_i XV_{i,\ t}$ is investment of the whole society.

2) Labor endowment is exogenous and determined by *National Population Development Plan (2016–2030)* (The Central People's Government of the People's Republic of China, 2017).

$$FF^{lab}_{t+1} = FF^{lab}_t \times (1 + popgrowth_t) \quad (6)$$

where FF^{lab}_{t+1} is total labor input in next period. FF^{lab}_t represents current total labor input. While $popgrowth_t$ denotes population growth rate during period t.

3) AEEI is considered in this paper, which is set according to Zhang et al. (2018).

3. Scenario design

The essence of coal to electricity project is to create better air quality and less CO_2 emission. Thus, this paper tries to discuss the environment, energy and economy impact when CtE project is promoted completely. As the data and the model used by this paper is at the national level, this paper cannot distinguish the vary progresses of coal-to-electricity project in different places, so we assume that by 2020, all residents will complete the coal-to-electricity project. Since the perspective of our analysis is independent of the progress, this assumption is relatively reasonable. Moreover, the substitution of electricity may increase fossil energy consumption to some extent, so that this paper considers the proportion of thermal power generation as a variable in scenario design. The study used Business as Usual (BaU) scenario for comparison. C scenario is the scenario that CtE project is promoted in the north of China. P scenario is the scenario that the proportion of thermal power generation will decrease by 10%. This paper also considered heating efficiency (by the method of enhancing conversion rate, building's energy-efficient performance etc.). In H1 and H2 scenario, 10% and 20% heating efficiency improvement is assumed, while both heating efficiency improvement and proportion of thermal power generation is considered in PH1 and PH2 scenario. Table 4 illustrates the scenario design of CtE project.

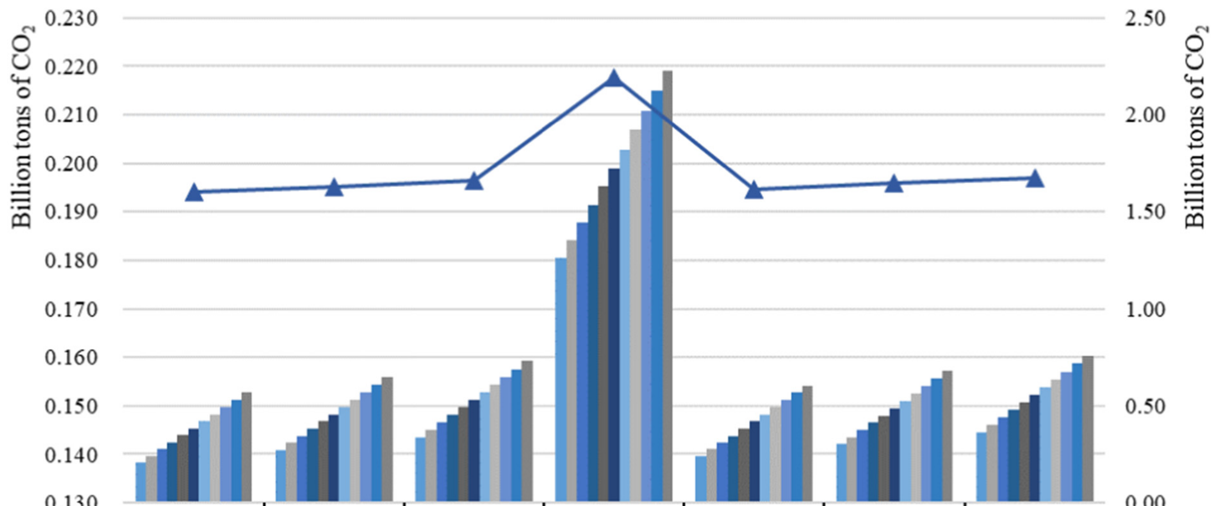
The main influence of CtE project is the energy consumption structure of residents, the consumption of residents, and the transfer payment (subsidy) of the government to residents. CtE project will lead to an average investment increase of 11.08 thousand yuan per household, and 30% fee reimbursed by the government, which data comes from a confidential project so that we cannot offer detailed information of the source of the investment and cost. It is difficult for the CGE model to simulate the number of substitution of coal to electricity directly so that exogenous share parameters of resident consumption is considered to simulate energy consumption change of residents, such method is applied to Li et al. (2017). The energy consumption of residents for the different scenarios was taken to be exogenous firstly, and the exogenous share parameters each year are acquired by calibration, then take the exogenous parameters into the CGE model to simulate the changing preference of coal and electricity. The scenario of reducing the rate of coal-fired power plant is similar to the method above. This paper assumes that each household needs 3.257 tons of clean coal for heating every year while after CtE project each household will consume 4854kWh per year for heating, according to a group company that collects electric power consumption information and dominants CtE project promotion in China. We also assume the project can reduce almost all coal consumption of urban population and reduce 95% coal consumption of rural population since 2020. If CtE project is promoted completely in 2020, the coal consumption of residents will reduce by 66.33 million tons of coal equivalent.

4. Results and discussion

4.1. Emission reduction

4.1.1. CO_2 emission reduction

Fig. 3 illustrates CO_2 emission reduction in all counter-measured (CM) scenarios during 2020–2030. It is important to note that CO_2 reduction in C, H1, H2 and P scenarios are compared with BaU scenario, while the reduction in PC, PH1 and PH2 scenarios are compared with P scenario. The following analyses of other items are also based on such comparison method. The reason why this paper makes such a comparison is that we want to find out whether the reduction effect would increase or not if the power generation structure had improved. In C, H1 and H2 scenarios, CO_2 emission will reduce by 138.3–159.1 million tons of CO_2 (Mt-CO_2), and the cumulative increase in emission will be 1.60–1.66 billion tons of CO_2 (Bt-CO_2). In PC, PH1 and PH2 scenario, the emission reduction will be 154.2, 157.3 and 160.4 Mt-CO_2, respectively. The cumulative in CO_2 reduction during 2020–2030 in PC, PH1



	C	H1	H2	P	PC	PH1	PH2
2020	0.1383	0.1409	0.1435	0.1805	0.1396	0.1421	0.1445
2021	0.1397	0.1423	0.1450	0.1841	0.1410	0.1435	0.1460
2022	0.1411	0.1438	0.1465	0.1877	0.1424	0.1450	0.1476
2023	0.1425	0.1453	0.1480	0.1914	0.1438	0.1465	0.1491
2024	0.1439	0.1467	0.1496	0.1951	0.1453	0.1480	0.1507
2025	0.1453	0.1482	0.1511	0.1990	0.1467	0.1495	0.1522
2026	0.1468	0.1497	0.1527	0.2028	0.1482	0.1510	0.1538
2027	0.1482	0.1513	0.1543	0.2068	0.1497	0.1526	0.1554
2028	0.1497	0.1528	0.1559	0.2108	0.1512	0.1541	0.1571
2029	0.1512	0.1543	0.1575	0.2149	0.1527	0.1557	0.1587
2030	0.1527	0.1559	0.1591	0.2190	0.1542	0.1573	0.1604
Total	1.5995	1.6313	1.6632	2.1922	1.6148	1.6452	1.6755

Fig. 3. CO_2 emission reduction in all CM scenarios during 2020–2030 (The effect of reduction in C, H1, H2 and P scenarios is relative to CO_2 emission in BaU scenario, while the effect in PC, PH1 and PH2 scenarios is relative to P scenario).

and PH2 scenarios will be 1.61, 1.65 and 1.68 Bt-CO_2, respectively, which account for 0.16–0.17‰ of China CO_2 emission in 2017.[1]

The effect of CtE project will increase by time. The essential reason is that the amount of substitution increases continuously as time goes on, as the increasing energy consumption, which will increase the differences between BaU scenario and CM scenarios. We also find that CtE project has a positive impact on CO_2 emission reduction. The reduction effect will increase by improving heating efficiency or reducing the rate of coal-fired power plant, especially by the latter method, which implicates that if China wants to maximize CO_2 reduction effect of CtE project, China should do efforts on other aspects in energy saving and low carbon methods, because there is a synergistic reduction effect between CtE project and other energy saving methods. Moreover, despite the positive impact on CO_2 reduction of CtE project, the accumulative CO_2 emissions reduction during 2020–2030 will be no more than 0.5% of 2015 world total CO_2 emission (BP, 2018).

We found that there are co-benefits between different low carbon behaviors. The improvement of power generation structure and CtE project can increase the capacity of energy savings of each other. Because CtE project will increase electricity consumption, and if power generation side uses less fossil energy and more renewable energy, CtE project will directly get more benefits of fossil energy savings and CO_2 reduction from cleaner structure of power generation. And the improvement of heat efficiency can directly enhance CO_2 emission reduction of CtE project. The reason is simple: if the heating efficiency increase, household will use less electricity to keep the house warm.

4.1.2. NO_x, SO_2 emission reduction

Table 5 shows NO_x and SO_2 emission reduction by residents in 2030. As we can see, the change in heating efficiency (comparison of C, H1 and H2 scenarios) and the structure of electricity generation (comparison of C and PC scenarios, or H1 and PH1 scenarios, etc.) can hardly affect the emission reduction of SO_2 and NO_x. The reason is simple: both of them

Table 5
NO_x, SO_2 emission reduction by residents in 2030 (unit: million ton. The benchmark in C, H1 and H2 scenarios is BaU scenario, and the benchmark in PC, PH1 and PH2 scenarios is P scenario. This is also the case with the latter figures and tables).

	SO_2	NO_x
BaU	–	–
C	1.78359	0.53844
H1	1.78356	0.53843
H2	1.78353	0.53842
P	–	–
PC	1.78358	0.53844
PH1	1.78355	0.53843
PH2	1.78352	0.53842

[1] The data of carbon emission is from Global Carbon Budget 2018. Website: https://www.icos-cp.eu/GCP/2018.

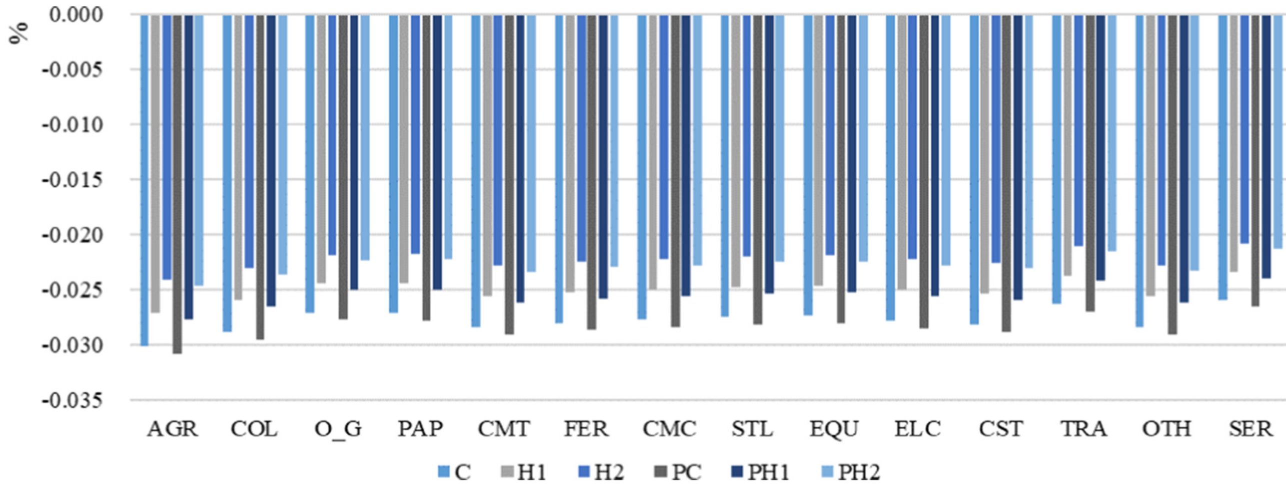


Fig. 4. Commodity prices in all scenarios compared with BaU and P scenarios in 2030.

can hardly affect the amount of heating by residents, so the total amount of the substitution of coal remains unchanged. However, we find a positive impact of CtE project on NO_x, SO_2 emission reduction: NO_x, SO_2 emission will reduce by 0.538 and 1.784 million ton in 2030, which is nearly 82.59% and 60.09% of NO_x and SO_2 emission of residents in China in 2015, respectively (Nakakoji et al., 2007), and this result is similar to the result of Chen and Chen (2019). Thus, we found that CtE project plays an important role in reducing NO_x and SO_2 emission, although the performance of CO_2 emission effect of CtE project is not very well. China's SO_2 emissions are main from coal combustion (Coal-fired SO_2 emissions account for more than 85% of total SO_2 emissions). And NO_x emissions are mainly from the combustion of fossil fuel and biomass fuel. We find that coal consumption by the rural household will directly result in bad air quality in the north of China, especially in winter. For this reason, we consider that CtE project does can be an environment-friendly project.

4.2. Economic impact

4.2.1. Commodity price

Fig. 4 illustrates the commodity prices in all scenarios compared with BaU and P scenario in 2030. Note that the commodity price in C, H1, and H2 scenarios in Fig. 4 is compared with BaU scenario, while the price in PC, PH1 and PH2 scenarios is compared with P scenario.

	AGR	COL	O_G	PAP	CMT	FER	CMC	STL	EQU	ELC	CST	TRA	OTH	SER
C	-0.031	-0.163	0.000	-0.001	-0.006	-0.027	-0.011	0.004	0.014	0.669	0.005	-0.002	-0.009	-0.007
H1	-0.025	-0.192	0.001	0.000	-0.005	-0.022	-0.009	0.002	0.012	0.602	0.005	-0.003	-0.007	-0.005
H2	-0.019	-0.221	0.002	0.001	-0.003	-0.017	-0.007	0.000	0.010	0.536	0.004	-0.003	-0.005	-0.003
PC	-0.031	-0.181	0.001	-0.001	-0.006	-0.027	-0.010	0.004	0.014	0.669	0.006	-0.002	-0.009	-0.007
PH1	-0.025	-0.209	0.002	0.000	-0.004	-0.022	-0.009	0.002	0.012	0.603	0.005	-0.003	-0.007	-0.005
PH2	-0.019	-0.237	0.003	0.001	-0.003	-0.016	-0.007	0.000	0.010	0.536	0.004	-0.003	-0.005	-0.003

C H1 H2 PC PH1 PH2

Fig. 5. Sectorial output in CM scenarios in 2030.

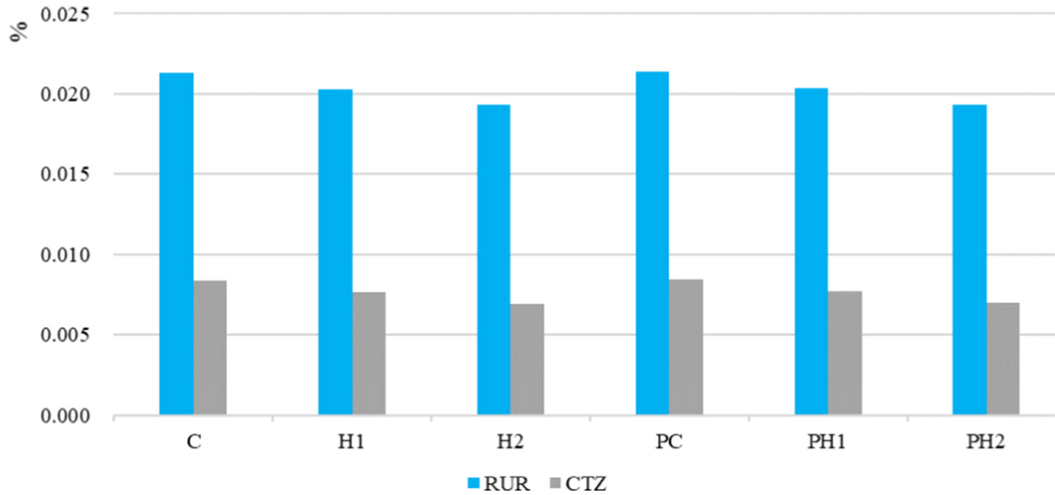


Fig. 6. The variation of Social Welfare by promoting CtE project in 2030.

Commodity prices will fall by 0.02–0.03%. This can reflect in the stimulating effect on the economy: CtE project will make the demand of residents to coal reduce sharply, which will change relation between supply and demand in coal market. The price of coal will decrease directly by the CtE project. As the coal industry is the most basic energy industry, it will drive the cost of energy intensive industry down, so that the downstream enterprises of coal enterprises commodity prices will decline. At the same time, the decline in the price of coal trading will also cause competition pressure to other energy industries, leading to a decline in prices of other energy commodities. However, in general, CtE project has little impact on commodity price, as the negative impact is no more than 0.035%.

4.2.2. Sectorial output

Fig. 5 depicts the sectorial output in CM scenarios compared with BaU scenario in 2030. Sectorial output and Energy consumption in C, H1, and H2 scenarios are compared with BaU scenario while those in PC, PH1 and PH2 scenario are compared with P scenario. The CtE project has a certain impact on the industrial structure and has a more significant impact on energy consumption structure, which is reflected in the output of coal industry and electricity industry. Coal industries will suffer a loss of output by promoting CtE project, by 0.16–0.24%, and output of electricity will increase by 0.54–0.67%, other industries received less impact, which is no more than 0.04%. Among them, oil, gas, steel, equipment and construction will increase while others will decrease output by promoting CtE project. The reason for the increase in oil and gas consumption is that the reduction of energy price (see Section 4.1.1) makes purchasing power of residents increase. In general, CtE project has positive impact on adjustment of energy structure: more electricity consumption, less coal consumption. And coal consumption will reduce more if China changes the structure of power generation, which means that CtE project can get benefits from the development of renewable energy, as CtE project is aimed at using more electricity and less coal.

Table 6
The variation of energy consumption of residents in 2030.

Scenario	Consumption	Rural	Urban
C	Coal	−94.71%	−98.68%
	Electricity	26.80%	4.82%
H1	Coal	−94.71%	−98.68%
	Electricity	24.15%	4.34%
H2	Coal	−94.71%	−98.68%
	Electricity	21.50%	3.87%
P	Coal	−94.71%	−98.68%
	Electricity	26.80%	4.82%
PH1	Coal	−94.71%	−98.68%
	Electricity	24.15%	4.34%
PH2	Coal	−94.71%	−98.68%
	Electricity	21.50%	3.87%

4.2.3. Social welfare

The study introduced Hicksian equivalent variation as a measure of changes in social welfare (Hosoe et al., 2010; Weber, 2010). Fig. 6 illustrates the variation of social welfare in all CM scenarios compared with BAU or P scenario in 2030. Social welfare in this paper means that the highest level of utility that the purchasing power of residents can reach. In all CM scenarios, social welfare of rural population will increase by 0.019–0.021% and that of urban population will increase by 0.007–0.008%. We can see that the CtE project can promote the rise of rural population welfare, and it has a positive impact on the welfare of urban residents as well. Moreover, neither improving heating efficiency nor power structure can hardly change the variation tendency of social welfare.

4.3. Energy impact

4.3.1. Energy consumption of residents

Table 6 shows the variation of energy consumption of residents. The consumption of coal in rural and urban people will reduce by 94.71% and 98.68%, respectively. The electricity consumption of rural and urban population will increase by 26.80% and 4.82%, respectively. The reason why the rise of electricity is lower than the reduction of coal consumption is that the amount of electricity consumption by residents is far greater than that of coal consumption, especially by urban population. Improving heating efficiency will reduce electricity consumption by residents directly. Moreover, the CtE project cut almost all the coal consumption by residents. However, the effect of CO_2 emission is relatively low as Section 4.1.1 shows. Section 4.3.2 shows detail discussion of the reason.

4.3.2. Coal consumption

Fig. 7 illustrates the variation of coal consumption in all industries in 2030. Coal consumption in the coal industry will reduce by 0.70–1.00 million tons of coal equivalent (Mtce). The consumption in other industries except for electricity will almost be steady. However, the consumption of electricity will increase from 11.27 to 14.76 Mtce. In addition, the total coal consumption of industries will reduce the CO_2 reduction benefit. In 2030, total coal consumption of industries will increase from

	AGR	COL	O_G	PAP	CMT	FER	CMC	STL	EQU	ELC	CST	TRA	OTH	SER
C	-0.01	-0.70	0.00	0.01	-0.01	0.00	0.00	0.06	0.09	14.76	0.00	0.00	-0.05	0.00
H1	-0.01	-0.83	0.00	0.01	-0.01	0.00	0.00	0.04	0.08	13.30	0.00	0.00	-0.03	0.01
H2	-0.01	-0.95	0.00	0.01	0.00	0.00	0.00	0.03	0.07	11.83	0.00	0.00	-0.02	0.01
PC	-0.01	-0.76	0.00	0.01	-0.01	0.00	0.00	0.06	0.09	14.06	0.00	0.00	-0.04	0.01
PH1	-0.01	-0.88	0.00	0.01	-0.01	0.00	0.00	0.05	0.08	12.66	0.00	0.00	-0.03	0.01
PH2	-0.01	-1.00	0.00	0.01	0.00	0.00	0.00	0.03	0.07	11.27	0.00	0.00	-0.02	0.01

C H1 H2 PC PH1 PH2

Fig. 7. The variation of coal consumption in all industries in 2030.

10.37 to 14.14 Mtce. The reason why most of the industries' coal consumption will increase is that, maybe, coal price will be reduced by promoting CtE project (see Section 4.2.1) so that enterprises can buy little more coal for production.

5. Conclusion, policy implications and limitation

5.1. Conclusion

This paper establishes two benchmark scenarios (BaU and P scenarios) and six counter-measured scenarios (C, H1, H2, PC, PH1 and PH2 scenarios), and constructs a dynamic recursive computable general equilibrium model to focus on the impact of promoting coal to electricity project on CO_2, NO_x and SO_2 emission reduction, commodity price, sectorial output, social welfare, energy consumption of residents and coal consumption. The following conclusions were drawn from the study:

Environment impact: CtE project has a positive impact on CO_2 emission reduction; however, the positive impact will reduce by the increase of industrial energy consumption. The reduction effect will increase by improving heating efficiency and reducing the rate of coal-fired power plant, especially by the former method. However, the reduction of CO_2 emission is low, compared with NO_x, SO_2 emission reduction. CtE project plays an important role in reducing NO_x and SO_2 emission. NO_x, SO_2 emissions will reduce by 0.538 and 1.784 million ton in 2030, which is nearly 82.59% and 60.09% of NO_x and SO_2 emission of residents in China in 2015, respectively.

Economic impact: CtE project has little impact on commodity price, as the negative impact is no more than 0.035% and has a positive impact on adjustment of energy structure: thus, more electricity consumption, less coal consumption. The welfare of rural population will increase more than that of urban population, which is the original intention of the CtE project: improving the quality of life of rural residents. Neither improving heating efficiency nor power structure can hardly change the variation tendency of social welfare.

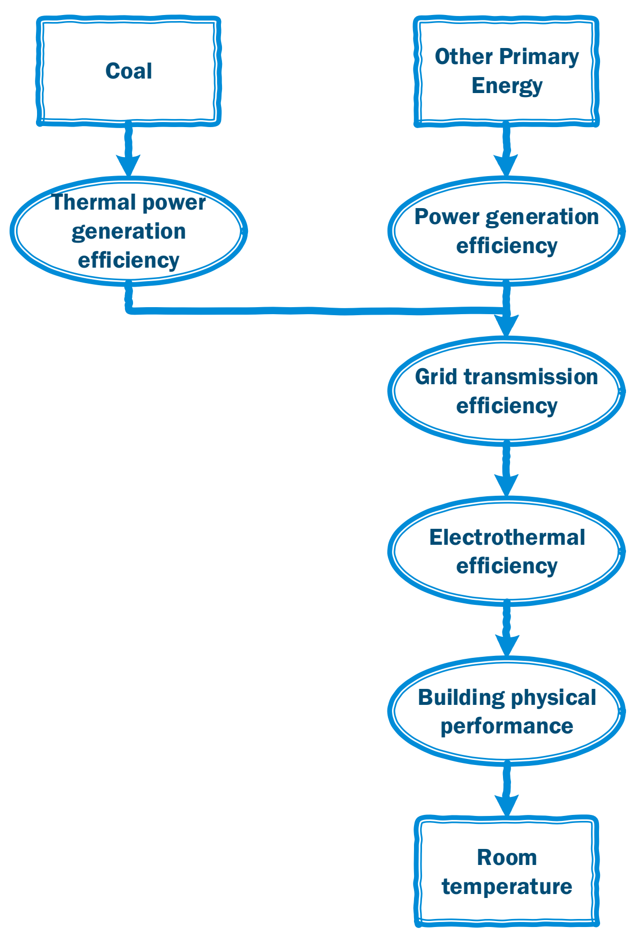


Fig. 8. Energy transfer chain of electric heating from primary energy to room temperature.

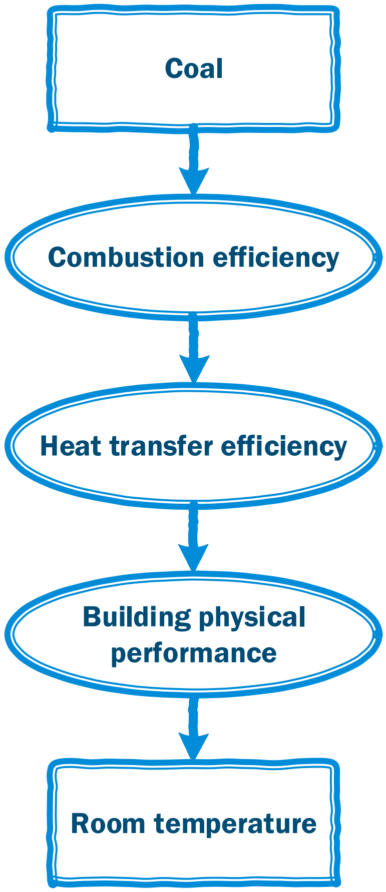


Fig. 9. Energy transfer chain of coal heating from primary energy to room temperature.

Energy impact: the project cuts almost all the coal consumption by residents and increase residents' electricity consumption. The growth rate of electricity consumption in rural residents is much greater than that in urban residents, indicating that reasonable subsidy to urban residents should be considered. The total coal consumption of industries will reduce the CO_2 reduction benefit as the industrial coal consumption will rise to a certain degree.

This paper considers that the current Chinese government's coal-to-electricity project is a project with energy replacement. CtE project changes the energy transfer chain. Energy transfer chains of electric heating or coal heating from primary energy to room temperature are shown in Figs. 8 and 9. It can be seen that after CtE project, coal consumption is sensitive to the proportion of coal-fired power plants, power generation efficiency, power transmission and distribution efficiency, and building's energy-efficient performance (or building physical performance we mentioned in Figs. 8 and 9). In some coal-based developing countries, such as China and India, CtE project may reduce the efficiency of coal use, unless doing something we mentioned above. For this part, CtE project and other projects can promote each other's emission reduction capacity. That's why our results show increasing thermal efficiency and changing the power supply structure have a positive impact on the emission reduction effect of CtE project.

In general, below are the conclusions based on the findings:

1) CtE project is an effective way of reducing SO_2 and NO_x emissions, and the environment in China will improve directly by the project. NO_x, SO_2 emission in 2030 will reduce more than half of residents' NO_x and SO_2 emission in China. Moreover, the reduction effect of SO_2 and NO_x emissions can be hardly influenced by heating efficiency and power generation structure. Because the amount of substitution is relatively fixed.
2) However, the CO_2 emissions reduction effect will be offset by increased energy consumption in thermal power plants to some extent, as the substance of CtE project is energy substitution, not energy saving. Some energy saving projects can reduce energy consumption and CO_2 emission more significantly than CtE projects, such as improving the efficiency of power generation of fossil energy plants, improvement of interval temperature, and biofuels and coal co-firing etc. (Nauclér and Enkvist, 2009).
3) CtE project plays a positive role in adjusting the energy structure, as it will reduce coal consumption and increase electricity consumption. However, the positive impact on energy structure is not as significantly as other energy policies (Blesl et al., 2010; Liu and Li, 2011).
4) There are significant co-benefits of CO_2 emission reduction between CtE project and decreasing the proportion of power generation by fossil energy. Because electricity itself is secondary energy generated by several of primary energy. A better power structure can make electricity consumption cleaner and increase the effect of CtE project on CO_2 emission reduction dramatically.

5.2. Policy implications

Before the formal introduction of policy implications, this paper supplements the advantages and disadvantages of electric heating relative to coal heating from the micro level, as we can only analyze the impact of CtE project from a macro perspective using CGE model.

Advantage of electric heating:

1) Security. Conventional coal-fired boilers may produce substances such as carbon monoxide due to incomplete combustion of coal, leading to unexpected accidents.
2) No pollution. Compared with coal heating, no exhaust gas will be generated during the electric heating process.
3) Convenient. The indoor temperature can be adjusted more conveniently and efficiently with different output powers.
4) Increase in utilization of power grid facilities. It helps to smooth the fluctuation of grid load and increase the grid load rate, especially the use of heaters with heat storage function.

Disadvantages of electric heating:

1) High energy consumption. Electric heating relies too much on building energy conservation. If the building's energy-efficient performance is bad, it will lead to higher energy consumption or lower room temperature.
2) High cost. Compared to coal heating, the purchase cost of electric heaters is higher, and the annual electricity bills for heating may be higher than the cost of coal burning.

Based on the above conclusions and the analysis of the advantages and disadvantages of the electric heating method, we have drawn the following policy implications, serve as reference for countries which are coal-dominate, such as China, India, South Africa, Poland, and Kazakhstan etc.

1) The energy-saving effect of the coal-to-electricity project cannot be overestimated. It can be seen from the conclusions of this paper that the impact of coal-to-electricity carbon reduction is minimal. To improve its energy-saving effect, it needs to be combined with the front and the end of residential heating to achieve energy-saving and emission-reducing effects. The main significance of CtE project is not to reduce CO_2 emissions but to improve the environment. The fundamental reason is that CtE project is an energy substitution method, not energy saving method. If the supply side (power generation structure) and consumption side (building's energy-efficient performance, such as building insulation capacity,

ventilation, infiltration, passive radiation, wall-to-window ratio, etc.) of residential heating are not efficient enough, CtE project may even bring greater energy consumption and carbon dioxide emissions.

2) The environmental significance of coal to electricity cannot be ignored. From this point of view, it is very meaningful to promote CtE project. Since there is no treatment of the resident burnt coal to exhaust gas, a large amount of nitrogen oxides, sulfur dioxide and particulate matter are directly discharged into the air, which directly leads to environmental deterioration. After the coal consumption was changed to electricity, the primary energy use terminal was changed from residents to a power plant. The environmental benefits are reflected as the power plant was equipped with a desulfurization and denitrification device.
3) When promoting coal-to-electricity project, we must pay attention to the subsidies for residents in various aspects. Because there is a cost to transfer from coal-fired heating to electricity-using heating. Ordinary rural residents are unwilling to bear this expense, so the government needs to subsidize this part of the expense (the Chinese government is already doing it). In addition, it is necessary to install a thermal insulation layer for some buildings with poor energy-efficient performance. This will not only greatly enhance the enthusiasm of residents for CtE project, but also improve the efficiency of social electricity consumption and achieve the effect on energy saving and emission reduction. As the CO_2 reduction cost of installation of the insulation layer is negative (Nauclér and Enkvist, 2009), this paper considers that the subsidy to building insulation may as important as the subsidy to the purchase of electric heaters, however, there is no such kind of subsidy in China.
4) When promoting coal-to-electricity projects, we can reduce fluctuations in grid load by using fluctuations in electricity prices (which may promote the use of heaters with heat storage or of air source heaters). The fluctuation of grid load in winter may be reduced and there may be a positive effect on energy efficiency after the marketization of electricity prices.

5.3. Limitation

The proportion of different electric heating methods will bring different power consumption. There are many ways of electric heating: electric heaters with heat storage, air source heat pumps, electric heating film heaters, and solar energy + electric heating auxiliary heating. In this paper, only the comprehensive electricity consumption of heating is extracted from the residential electricity load data covered by CtE project of Beijing Power Grid. In other words, the paper assumes that different heating methods are rising in the same proportion. In future researches, we will find ways to separate these electric heating methods and discuss their economic and energy environment impacts.

Declaration of competing interest

We declare that we have no conflict of interest.

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