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The impact of electric vehicles and CCS in the context of emission trading scheme in China: A CGE-based analysis

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ABSTRACT

Global warming and harsh environment make China have to accelerate the pace of low-carbon economy. Promoting Electric Vehicles (EVs) and Carbon Capture and Storage (CCS) may be the significant ways to reduce CO_2 emissions. A recursive dynamic computable general equilibrium (CGE) model will be constructed to explore respectively the impacts of EVs and CCS on China's macroeconomics, environmental quality and energy demand, under 6 simulation scenarios. The simulation results show that the promotion policy at a basic-level with CCS can effectively reduce CO_2 emission and alleviate economic loss. Promoting the process of electric vehicles will lead to an economic loss, although it will make carbon emission peak occur in 2030. The basic-level promotion will have a better performance than the higher in carbon intensity: 0.073 and 0.079 kg-CO_2/RMB in 2050. Moreover, CCS technology with EVs promotion plays an important role in protecting energy transformation sectors, reducing the loss of gross domestic product (GDP) and reducing emission but oil dependence. We highly recommend that promoting EVs with CCS is a reliable strategy to energy-savings and CO_2 reduction. From 2015 to 2050, by applying this strategy, China will contribute to CO_2 reduction by 24.97 Bt-CO_2 or 74.35% of 2010 world total emission.
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1. Introduction

Since the industrial revolution, excessive carbon dioxide (CO_2) emission caused a series of environmental problems: global warming, extreme weather and environmental degradation etc. [1]. Unprecedented achievements in economic growth and urbanization have been made by China since 1978, however, the problems of excessive consumption of fossil fuels and huge amounts of greenhouse gas (GHG) emission have become a problem that needs to be solved urgently in today's China. Energy demand growth and CO_2 emission growth of the transport sector are faster than other sectors all over the world [2,3], and transportation has been considered as the most difficult sector to CO_2 reduction [4,5]. According to *Energy Technology Perspectives 2015* [6], CO_2 emission in global transportation accounts for approximately 27% of total emission, which is the second largest source of CO_2 emissions. During 2000–2012, the total CO_2 emission and per capita CO_2 emission of China's transportation have grown by 9.29% and 8.69% per year [7], and transportation accounts for near 1/3 of total emissions [8]. Therefore, the rapid growth of energy consumption and CO_2 emission in transportation has brought great challenges to China's oil security and environmental issues.

In order to deal with such series of problems, China has taken a series of measures to reduce GHG emissions. Since 2000, CO_2 reduction policy of transportation has been promoted to the national strategy in China. China has gradually promulgated *Energy Saving and New Energy Vehicle Industry Development Plan*, *China to extend electric car subsidies beyond 2015*, and puts forward that promoting electric vehicles (EVs) may be the main direction of restructuring automotive industry and be a significant way to carbon mitigation. During 2000–2012, CO_2 emission in China's transportation industry fell by 32% in general [9], which shows an initial effect of these mitigation policies on transportation. In June 2015, *Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions* had been published: by 2020 it will lower carbon dioxide emissions per unit of Gross Domestic Product (GDP) by 40%–45% from the 2005 level, increase the share of non-fossil fuels in primary energy consumption to about 15%. According to *Energy Technology Perspectives 2015* [10], transportation must reduce at least 140 Gt cumulative CO_2 emissions in 2050 under the 2DS, which means that transportation sector is

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facing tremendous pressure to reduce emission.

Available studies about CO_2 emissions reduction of electric vehicles could be traced back to early 21st century, Saitoh et al. [11] studied on the importance of development of electric vehicles to reduce the CO_2 emission in the urban area. In recent years, with the development of EVs technology, EVs has become one of the actual means to reduce emission. Therefore, more and more scholars came to realize that the promotion of EVs plays a significant role to deal with the problems of energy security and global warming, and these literature are main focused on the following three aspects: first is the effect of CO_2 emission reduction of electric vehicles and other new energy vehicles under different circumstances [12,13]. Onat et al. [14], for example, by comparing electric vehicles with plug-in hybrid electric vehicles and hybrid electric vehicles options across 50 states in America, taking into account factors of average and marginal electricity generation, found the regional driving patterns. Komiyama & Fujii [15] developed an energy system model to analyze whether the promotion of EVs would serve as an energy saving measure in Japan's whole energy system. Jochem et al. [16] analyzed CO_2 emissions in Germany at the year of 2030 using an optimizing energy system model (PERSEUS-NET-TS) combined with four kinds of evaluation methods, and then suggest that supporting the charging limit policy. The second major aspect is the emission reduction effect by considering progress of EVs technology or improvement of supporting facilities [17]. For example, some studies focused on cost reductions and environmental benefits caused by the progress of EVs' batteries technology: Zhu et al. [18] focused on a simple and scalable solution fabrication process preparing $Li_4Ti_5O_{12}$/graphene anode material for lithium-ion batteries; in Huang et al.'s [19] work, a novel Si/slightly exfoliated graphite (SEG)/carbon composite used as anode for LIBs with high volumetric capacity is fabricated; Liu et al. [20] and Kakunuri et al. [21] did the research on improvement of the charging and discharging efficiency of the cathode and anode of the battery by different process; Zhu et al. [22] reviewed the recent findings in the role of electrolytes, anodes, and cathodes in the low temperature performances of LIBs. Secondly, some papers are concentrated emission reduction of the improvement of energy storage equipment and charging system in electric vehicles: Lee et al. [23] was focused on cylindrical hybrid supercapacitor using activated carbon positive electrode and Ye et al. [24] proposes a model of solar-powered charging stations for electric vehicles to mitigate problems encountered in China's renewable energy utilization processes. The third angle is that developing a Life Cycle Assessment (LCA) model to assess the emission reduction effect of EVs [25]. Faria et al. [26] developed a LCA model of traditional internal combustion engine vehicles and EVs to assess emission effect under different energy resources and the vehicle operation phase. Abdul-Manan [27] developed a typical LCA and Monte Carlo stochastic simulation to analyze GHG emission in different situation. Zhou et al. [28] did the research on real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions. Besides, there are a few researches focused on the emission reduction benefits of electric vehicles under different charging options [29] and the optimal planning of the backbone transmission system with 100% electric vehicle [30].

Carbon capture and storage (CCS), as a hopeful strategy to reduce CO_2, has been researched on two aspects: technology and economy, and this technology has gradually been recognized by society [31]. Olateju et al. [32] found that revenues for selling the CO_2 captured for EOR (enhanced oil recovery) could reduce the GHG abatement costs, and an opportunity for revenue generation is realized in the UCG-CCS (underground coal gasification-CCS) case. Cormos et al. [33] evaluated how the integration of post-combustion calcium looping influences the economics of power plants providing up-dated techno-economic indicators. Gladysz et al. [34] presented the concept of a life cycle assessment based on the thermoecological cost implemented in an integrated OFC (oxy-fuel combustion) power plant with CO_2 capture, transport and storage and applied a mathematical model to evaluate the LC TEC (life-cycle thermoecological cost). However, little literature analyzed macroscopically the impacts of CCS on Energy-Environment-Economy. In Akgul et al.'s [35] study, a mixed integer nonlinear programming supply chain optimization framework for carbon negative electricity generation using biomass to energy with CCS is offered.

According to *Enhanced actions on climate change: China's intended nationally determined contributions*, national emission trading scheme (ETS) will get into market in 2017. Nevertheless, little literature focus on the macroscopic impact of the national policy of promoting EVs [36], or emission reduction brought from the application of feasible low-carbon technologies, such as CCS [37,38] in the context of ETS. The question this paper seeks to answer, then, is the macroscopic impact of promoting EVs and CCS on economy, energy and environment combined with the current situation in China, and find the best option to reduce CO_2—which is the core purpose of this study.

As a popular policy simulation tool in recent years, Computable General Equilibrium (CGE) model has an incomparable dominance on analyzing macroscopic impacts of policies or behaviors (such as ETS [39,40], environment tax [41], energy investment [42] and adjustment of energy price [43]) on energy, economic and environment, which has been constantly improved and developed by Fujimori et al. [44] and has been widely employed [45,46]. The direct and indirect influence of some variables can by analyzed by CGE model [47]. Dai et al. [48] and Xu et al. [49] did the research on household consumption pattern. Dong et al. [50] pursued air pollutant co-benefits of CO_2 mitigation. Solaymani et al. [51] examines the impact of carbon tax and its alternative, energy tax, on both the Malaysian economy and the transport sector, using a CGE framework. Cheng et al. [52] analyzed the impacts of low-carbon power policy on carbon mitigation in Guangdong Province, China. Dai et al. [53] assessed China's climate commitment and non-fossil energy plan towards 2020 using hybrid AIM/CGE model. In this paper, a dynamic recursive CGE model is constructed, by considering the national policies, to analyze the energy-environment-economic impact of EVs and CCS promotion in the context of ETS.

Section 2 introduces energy situation of China. Section 3 explains the CGE model and the dataset used in this paper. In section 4, we describe five counter-measured (CM) scenarios. Section 5 shows the simulation results and discussion. The conclusions are obtained in section 6. A list of abbreviation is provided, seen Table 1.

2. Energy situation of China

China's energy structure is abundant in coal and deficient in oil and gas, which is decide that coal in China's energy supply and consumption plays a dominant role. Primary energy consumption and consumption ratio is illustrated in Fig. 1. Coal and oil consumption is 3165.00 Mtce (Million tons of coal equivalent) and accounts for 84.40% of the primary energy usage in 2013. The consumption may continue to rise in recent years if government does nothing in energy management policy. Since global warming has been widely concerned, it is one of the most important issues in China that how to reduce the energy consumption and make the peak of carbon emission reach before 2030. Providing alternative energy sources for automobiles maybe a useful way to reduce energy consumption.

China has a serious dependence on oil imports. From a certain aspect, the rapidly developing transportation industry is arch-

Table 1
Abbreviation list in this paper.

Full name	Abbreviation	Full name	Abbreviation
Electric vehicles	EVs	Constant Elasticity of Substitution	CES
Computable general equilibrium	CGE	Constant Elasticity of Transformation	CET
Carbon capture and storage	CCS	Value Added	VA
Emission Trading Scheme	ETS	Value-added and Energy	VAE
Carbon dioxide	CO_2	Linear Expenditure System	LES
Gross Domestic Product	GDP	Autonomous Energy Efficiency Improvement	AEEI
Greenhouse Gas	GHG	Business as Usual	BAU
Life Cycle Assessment	LCA	Counter Measured scenario of CCS	CMC
World Input-Output Database	WIOD	Counter Measured scenario of Basic-level promotion	CMB
China Input-Output Association	CIOA	Counter Measured scenario of High-level promotion	CMH
Intergovernmental Panel on Climate Change	IPCC	Counter Measured scenario of High-level promotion with CCS	CMBC
International Energy Agency	IEA	Counter Measured scenario of Basic-level promotion with CCS	CMHC
Social Accounting Matrix	SAM	CO_2 emission Intensity	CI
China's Input Output table	CIOT		

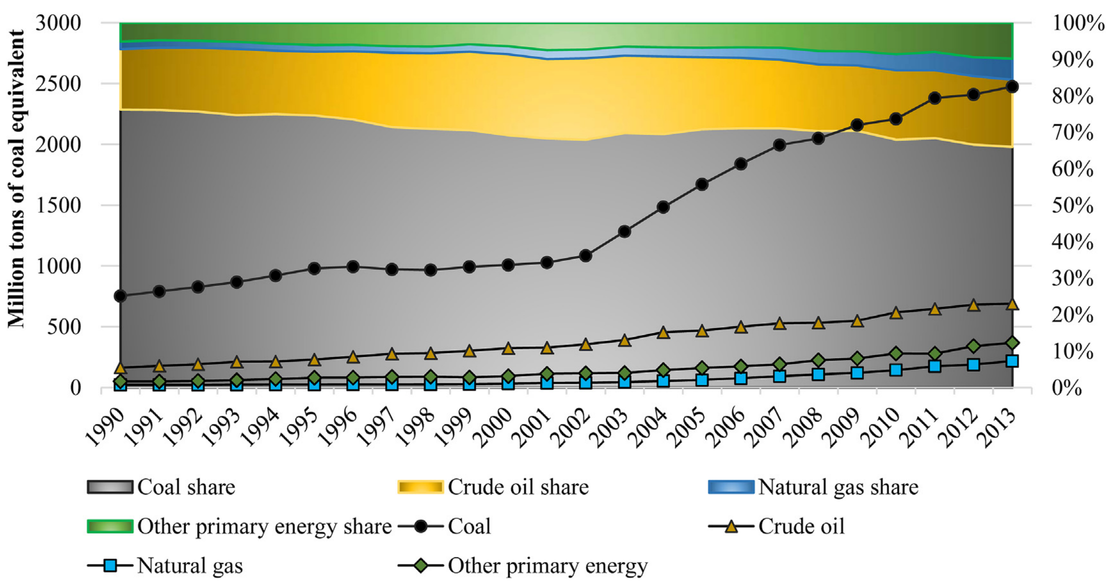


Fig. 1. Primary energy consumption in China during 1990–2013.

criminal, seen in Fig. 2 and Fig. 3. Import oil accounts for 58.9% of crude oil consumption in 2013, and most of the product oil is used in transportation. Which means that the transport sector has a strong direct potential for reducing emissions. The CGE model used in this paper can calculate the total (direct and indirect) emission reduction caused by promotion of EVs.

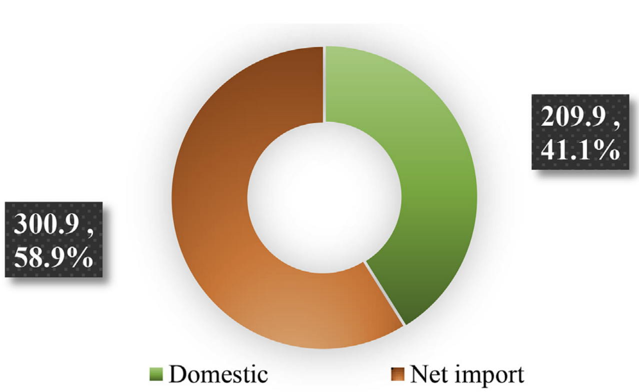


Fig. 2. Sources of crude oil consumption in 2013 (million ton).

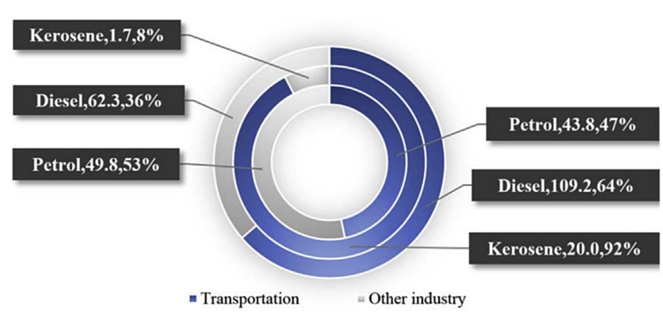


Fig. 3. Product oil consumption structure in 2013 (Mtce).

3. Methodology

3.1. Social accounting matrix (SAM)

A social accounting matrix (SAM) is a comprehensive, economy-wide data framework, typically representing the economy of a nation. A SAM is a square matrix in which each account is represented by a row and a column. Each cell shows the payment from the account of its column to the account of its row. Thus, each row and column of an account separately stand for the incomes and expenditures. The data source of the SAM in this paper is from World Input-Output Database (WIOD) [54], China Input-Output Association (CIOA) [55], Intergovernmental Panel on Climate Change (IPCC) [56] and International Energy Agency (IEA) [57]. In this model, we use the SAM of China in 2010 as the base data for the reason that the newest input-output table in CIOA is 2010 China's Input Output table (CIOT). The main data in SAM is from CIOA, the data of Land transportation and Water & Air transportation is from WIOD, the emissions data is from IPCC and IEA.

In this paper, we mainly consider the carbon emissions of transportation industry, especially of the land transport, so we reclassify the national industry according to CIOT from WIOD and CIOA as Table 2 shown. It should be noted that, two sectors of oil and natural gas cannot be divided since CIOT does not separate the oil and gas industry. How to distinguish between oil and gas product is described in 3.2.

3.2. CGE model

There are six blocks: production, income, expenditure, market, energy-policy, and macroeconomic closure blocks in the CGE model this paper described.

3.2.1. Production block

The first block, production, represents the structure of the production functions and is illustrated in Fig. 4.

Each producer (represented by an activity) is assumed to maximize profits, defined as the difference between revenue earned and the cost of factors and intermediate inputs. Profits are maximized subject to a production technology. The domestic output is constituted by a level of Leontief technology and 4 levels of Constant Elasticity of Substitution (CES) function. The inputs technology, at the top level, is specified by a Leontief function of the quantities of value-added and energy (VAE) bundle, aggregate intermediate input, additional cost or benefit by CCS, and extra cost by ETS. The VAE is nested by value added and energy inputs following a CES function in the second level. Value added bundle is a CES function of labor and capital. Moreover, energy aggregate is composited by electricity and fossil fuel (Non-electric) following a CES function. At the forth level, fossil fuel is consisted by coal and non-solid fossil fuel following a CES function. The last level refer to non-solid bundle, non-solid fossil fuel is consisted by oil and gas following a CES function. In this block, the energy commodities are double counted: the first is in intermediate demand and the next is in VAE bundle. However, energy is converted to a small number when it is embedded in the production block (See Table B1) by which the problem of double counting could be nearly ignored. Therefore, the impact of energy bundle to VAE is not as significant as intermediate commodities, but necessary.

Table 2
Description of activity classification.

Activities	Description
AGR	Agriculture, forestry, animal husbandry and fishery
EQU	Equipment manufacturing
MET	Metals
LAN	Land transportation
W_A	Water & Air transportation
COA	Coal
O_G	Oil & Gas
REF	Refined oil
ELC	Electricity
CON	Construction industry
OTH	Other industry
SER	Service

3.2.2. Income block

In this block, incomes are distributed to three institutional sectors: enterprises, government, and households. Seen in Fig. 5. Government revenue comes from direct tax, indirect tax, tariff and fine from ETS. The residents earn money from enterprise by selling their labor and transfer payment from ETS. Companies get revenue by selling their products and the CCS subsidy.

3.2.3. Expenditure block

Enterprises consume goods and partly save their income as final consumption in expenditure block. In addition to the purchase of goods and savings, companies also need to pay wages to the household providing labor. We consume that the total savings of household, enterprise and government are equal to the total investment. Government expenditure and capital formation are defined as a constant coefficient function. The Linear Expenditure System (LES) function is used for household consumption. According to the classical CGE model [58], we can abstract residents' behaviors: after residents obtain income, saves and pay taxes to the government, all of the remaining income are used to buy all kinds of goods by fixed proportional share.

3.2.4. Market block

For market block, domestic consumption, domestic production, foreign production (import) and foreign consumption (export) are converted by the following two methods, as illustrated in Fig. 6. One is the substitution of imported goods and domestic goods. The Armington commodity in each sector, which is supplied domestically, is composed of imported and domestic commodities following a CES function. The commodity is used for investment, intermediate inputs, household consumption and government consumption. The other is the conversion of exports and domestic sales. In this block, domestic output is divided into two pieces: one is for export and the other is used to be a part of Armington commodity. The producers, we assume, who customize the commodity according to the characteristics of the target market, supply their goods to the domestic market and international market by a certain percentage. We use a constant elasticity of transformation (CET) function to describe the process. After this local equilibrium is solved, the supply function of the export commodities and domestic supply is obtained.

3.2.5. Energy-environment-policy block

3.2.5.1. Emission trading scheme. Some of the energy transformation sectors are assumed that they are not just producing one kind of commodities, such as O_G and REF. The output of energy transformation activity is considered as the aggregate energy commodities following a CET function in order to cover the shortage of rough division in CIOT.

CGE model assumes complete information and complete competition, therefore, the auction price of carbon emission is equal to the trading price of carbon emissions rights in equilibrium state. All emission trading income of the government is assumed to return to consumers though transfer payment. In this model, we suppose the sectors which are over-emission will pay a fine with three times of the carbon transaction price, that is, the carbon emission rights are not always equal to carbon emission in sectors which are under ETS. The environment-policy block can be explained by 4 following equations.

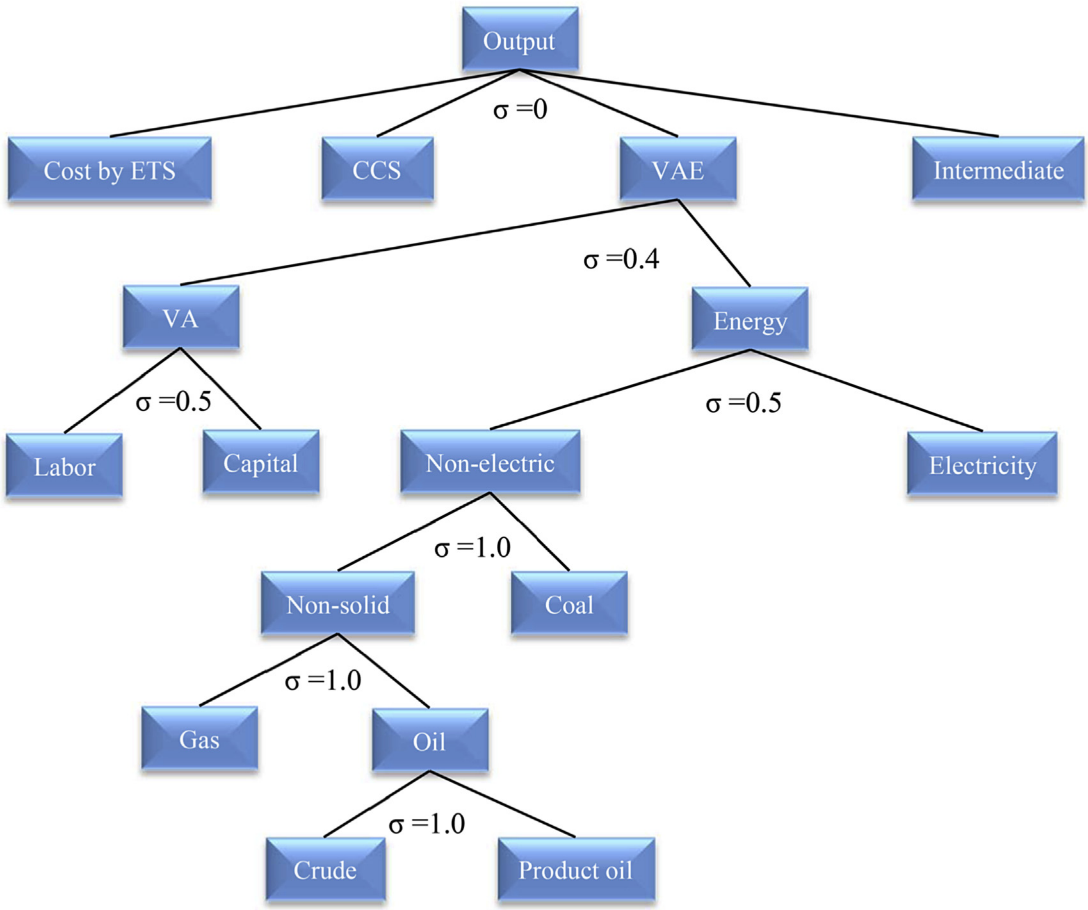


Fig. 4. The framework of production block.

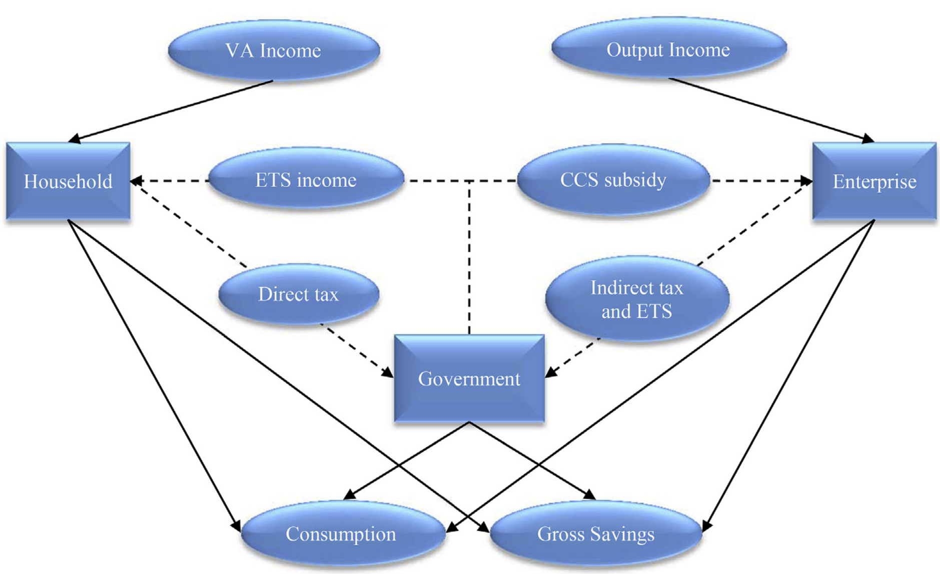


Fig. 5. The framework of income block.

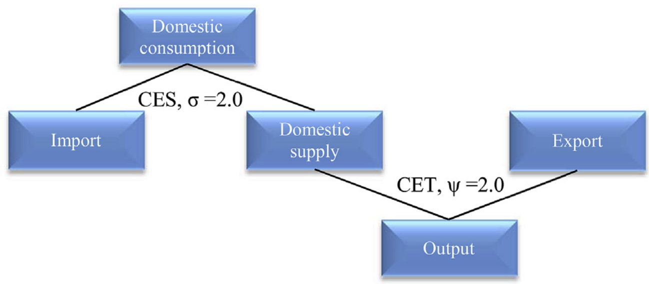


Fig. 6. The framework of market block.

$$EM_i = COAL_i \times \gamma^{coal} + OIL_i \times \gamma^{oil} + GAS_i \times \gamma^{gas} - CCS_i \,\big|\, i =' ele'$$
$$EM_i = COAL_i \times \gamma^{coal} + OIL_i \times \gamma^{oil} + GAS_i \times \gamma^{gas} \,\big|\, i \neq' ele' \tag{1}$$

$$PLC_i = p^t(CR_i - FP_i) + 3p^t(EM_i - CR_i) \tag{2}$$

$$CI = \sum_i EM_i \Big/ \sum_i (VA_i \cdot PVA_i) \tag{3}$$

$$fpr = FP_i/CR_i \tag{4}$$

where EM_i represents the total emission of the sector $i.COAL_i$, OIL_i and GAS_i represent coal, oil and gas input in sector i, respectively.γ^{coal}, γ^{oil} and γ^{gas} are carbon dioxide emission factor of the 3 primary energy, respectively. CCS_i is CO_2 captured by CCS technology. PLC_i is the policy cost of sector i. CR_i represents carbon credits. p^t is the emission trading price. CI is the carbon dioxide emission intensity in China. VA_i is represents value-added of sector i and PVA_i is the price of VA_i. fpr represents the proportion of free carbon rights distribution. FP_i is the free payment of carbon rights.

As for the Carbon emission rights allocation, carbon intensity is considered in this CGE model. Total emission (or) emission rights are calculated by the last year's carbon intensity and coefficient of decreasing carbon intensity per year.

$$CR_{i,t} = \frac{CR_{i,t-1}}{VA_{i,t-1}} \times VA_{i,t} \times (1-\omega) \tag{5}$$

where $CR_{i,t}$ and $CR_{i,t-1}$ represent carbon emission rights of sector i in current period and last period, respectively. $VA_{i,t}$ and $VA_{i,t-1}$ represent added value of sector i in current period and last period, respectively. ω represents coefficient of annual carbon emission reduction in sector i.

3.2.5.2. Promotion of EVs. As a large economic model, CGE model can hardly distinguish the difference between pure electric vehicles and plug-in hybrid electric vehicle, so that the paper finds an alternative way to show the substitution of the electric vehicle and the traditional fuel vehicle: the substitution of electricity and petrol-diesel. It is difficult for CGE model to simulate the number of EVs directly so that the share of EVs in all automobile is considered. The share of EVs is considered by a method using different exogenous variables, in order to simulate the EVs share. The EV shares for the different scenarios are taken to be exogenous and the exogenous variables are calibrated in order to generate exactly the EV share at each year considered. The EVs' cost is not calculated directly: it is calculated by the change of exogenous variable of production function in transportation.

We set two levels of promotion of electric vehicle: basic and high levels. The former level promotion is set in accordance with *The industry development planning energy-saving and new energy vehicles* [59]; the latter is set doubles as the former. Power generation structure is set in line with *Enhanced actions on climate change: China's intended nationally determined contributions* [60] and *China Renewable Energy Development Roadmap 2050* [61]. In this model, the share of electric vehicles in total vehicles is calculated in line with *The industry development planning energy-saving and new energy vehicles* [62]. The share of electric vehicles can be simulated by recalibration of parameters in product block to change the coefficients of the demand function through calculating energy substitution of the conventional and electric vehicles, which is illustrated in Table 3. Because CGE model is microeconomic model which considers macro factors, some micro policies and behaviors can hardly be expressed by mathematical equations, so this paper assumes that EVs are not going to return electricity to the grid.

3.2.5.3. Application of CCS. This paper assumed that only the fossil plant can install the CCS device, and there would be no idle equipment and CO_2 will not leak from storage facility. The application of CCS technology will incur an extra cost in electricity and generate additional revenue in equipment industry. Only if the carbon emission price surpasses the technology costs, CCS technology would be installed with a maximum increase of 5% per year and only be utilized by coal-fired plants. CCS technology would only become available after 2020, taking into account the developing of this technology. The cost of per unit emission reduction of CCS and a 25% emission reduction incentive (CCS subsidy) using CCS technology are according to *IEA (2008)* [63].

3.2.6. Macroeconomic closure block

It is commonly known that macroeconomic closure is mandatory for any model to be solved mathematically [64]. The CGE model in this study includes three macroeconomic balances: (i) the government balance, (ii) the external balance, and (iii) the savings-investment balance. For the government balance, the closure is that all tax rates are fixed while government saving is flexible. For the external balance, which is expressed in foreign currency, the closure is that the real exchange rate is flexible residual while foreign savings is fixed. Given that the foreign saving and current account deficit are fixed in the external balance, the total trade balance is also fixed. For the savings-investment balance, this model follows the principle of neoclassical closure, and assumes that all the savings are transformed into investment and the total investment equals total savings endogenously, thus the model is saving-driving.

3.3. Model dynamics

This model can be categorized as a recursive dynamic model instead of a static one when recursive dynamic formulation is adopted to incorporate inter-temporal behavior. For the capital stock growth, it is endogenous and determined by capital stock of last period, depreciation and investment supplied by each sector. Growth rate of labor supply is an exogenous parameter determined by *National Population Development Strategy Research Report* [65], and this model assumes that there is no unemployment and the total population is equal to quantity of employment. Autonomous Energy Efficiency Improvement (AEEI) in this paper is determined exogenously in according with *Medium and Long-term Energy Saving Special Planning* [66], so that we assumed that the energy consumption level of high energy consuming sector in China is close to or reached the advanced level in the world in 2020. The

Table 3
Parameters relating the share of EVs in product block.

	Year	The share of EVs	Parameters relating the share of EVs in product block					
			δ_{lan}^{ene}	δ_{lan}^{noe}	δ_{lan}^{nos}	δ_{lan}^{oil}	$\delta_{lan}^{product}$	δ_{lan}^{opo}
Basic level	2010	1%	0.228	0.318	0.715	0.334	0.407	0.533
	2020	5%	0.229	0.321	0.712	0.338	0.405	0.527
	2030	10%	0.231	0.323	0.709	0.343	0.402	0.520
	2040	20%	0.235	0.329	0.703	0.352	0.395	0.505
	2050	40%	0.244	0.342	0.688	0.373	0.376	0.468
High level	2010	1%	0.228	0.318	0.715	0.334	0.407	0.533
	2020	10%	0.231	0.323	0.709	0.343	0.402	0.520
	2030	20%	0.235	0.329	0.703	0.352	0.395	0.505
	2040	40%	0.244	0.342	0.688	0.373	0.376	0.468
	2050	80%	0.265	0.375	0.649	0.435	0.287	0.329

population growth from 2010 to 2030 is illustrated in Table 4 and the AEEI in each activity is shown in Table 5.

4. Scenarios

A Business as Usual (BAU) scenario and 5 counter measured (CM) scenarios are set for CGE model simulation, which are illustrated in Table 6. According to recent policy trends in China and factors associated with the transportation industry, the promotion of EVs and CCS technology are considered in this model. Moreover, national emission trading scheme will access to market in 2017 from *Enhanced actions on climate change: China's intended nationally determined contributions*, so this paper assumes that emission trading will be established in all of the scenarios besides BAU after 2017. CMC is the scenario of CCS used in thermal power plant. CMB and CMH are the scenarios of basic and high-level promotion of EVs. CMBC and CMHC are the scenarios of basic and high-level promotion of EVs with the application of CCS technology.

5. Results and discussion

5.1. Macroeconomic indicators

5.1.1. GDP

GDP, as an important macroeconomic indicator, is illustrated in Fig. 7. In this model, 2010 price is a benchmark price, so the GDP we discussed here is real GDP. GDP in BAU scenario will rise from 40.89 trillion RMB in 2010 to 114.18 trillion RMB in 2050, by 2.60% increasing per year. GDP in CMB and CMBC scenarios will fall to 107.46 and 108.15 trillion RMB compared to BAU scenario in 2050. GDPs in scenarios of CMH and CMHC, about 103.06 trillion RMB and 102.48 trillion RMB, are lower than GDP in other scenarios. GDP in CMC scenario is just 0.33% lower than that in BAU scenario.

GDP growth is severely restricted by the promotion at high-level options during 2040–2050, by 0.90–1.65% per year. However, the limitation is less in scenarios of basic promotion without CCS: the growth rate is 1.16–1.67% during 2040–2050. In high-level promotion, GDP losses are high, by 9.76%–10.25%, while the losses in basic level are 5.29–5.89%. The CCS technology performs well to be an option with EVs promotion on protecting GDP from serious decline when the promotion is not too radical. The results show that CCS could lead to GDP loss, however, it will protect GDP from a heavy loss when EVs are promoted. The reason why CCS can alleviate GDP loss from the promotion of EVs will be discussed in 5.1.2.

Table 4
The population growth from 2010 to 2035.

Year	Population growth rate
2011–2015	0.74%
2016–2020	0.61%
2021–2025	0.14%
2026–2030	0.12%
2031–2035	−0.08%
2036–2040	−0.13%
2041–2045	−0.33%
2046–2050	−0.52%

Table 5
Autonomous Energy Efficiency Improvement of each sector.

Activity	AGR	EQU	MET	LAN	W_A	COA
AEEI	0.025	0.035	0.025	0.036	0.025	0.006
Activity	O_G	REF	ELC	CON	OTH	SER
AEEI	0.006	0.01	0.025	0.006	0.016	0.023

Table 6
Scenarios for CGE model simulation.

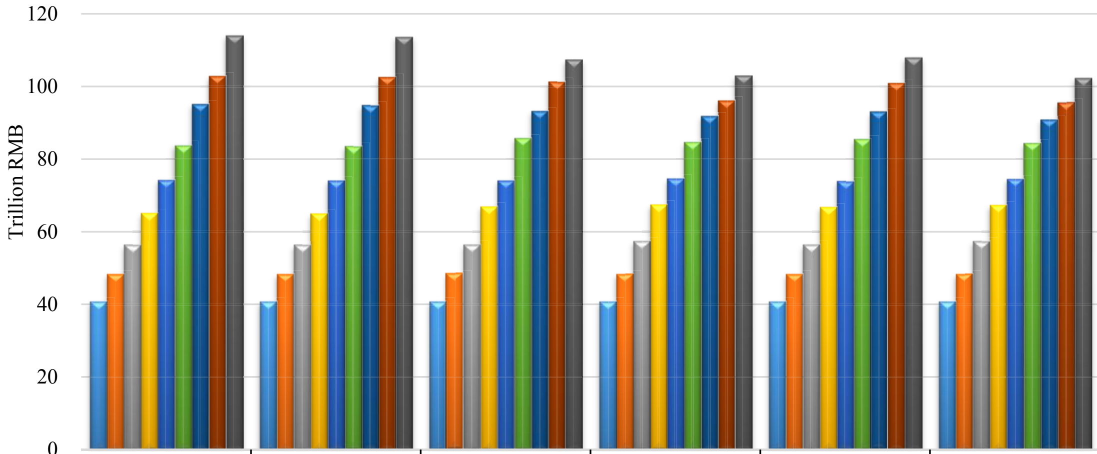
	Promotion of EVs		CCS
	Basic level	High level	
BAU	–	–	–
CMC	–	–	Yes
CMB	Yes	–	–
CMH	–	Yes	–
CMBC	Yes	–	Yes
CMHC	–	Yes	Yes

Notes: in all CMs, the symbol B is basic level, H is high level, and C is CCS.

5.1.2. Sectorial output and consumption

The impact of promotion of EVs and CCS on social industry is illustrated in Table 7. In the scenarios of promoting electric vehicles, refined oil will suffer a heavy output cut by 9.10–15.06% in 2050. Coal mining and washing industry, oil and gas industry, water & air transportation and metal industry would reduce their product value by 7.28–8.91%, 8.51–10.07%, 9.22–11.00% and 8.46–10.05% compared with BAU scenario in 2050. There will be 4.41% output increasing of land transportation in scenarios of basic-level promotion, however, the increasing will down to -7.35% when the share of EVs will reach 80% in 2050. Using CCS technology with the EVs promotion would protect the electricity industry by 0.76–2.15% compared with those without CCS, as well as the coal industry, water & air transportation, and oil and gas industry, by 8.44%–9.40%, 3.16–4.04% and 5.02–7.85%, respectively. It is easy to see that CCS can be a nice protector for industrial sectors by comparing BAU and CMC, CMB and CMBC, or CMH and CMHC scenarios.

The promotion will directly cut the output of refined oil industry because of alternative energy applying in vehicles, which



	BaU	CMC	CMB	CMH	CMBC	CMHC
2010	40.89	40.89	40.89	40.89	40.89	40.89
2015	48.48	48.48	48.48	48.48	48.48	48.48
2020	56.51	56.51	56.56	57.53	56.56	57.53
2025	65.19	65.09	67.06	67.57	66.90	67.43
2030	74.36	74.19	74.23	74.77	74.03	74.59
2035	83.90	83.67	85.89	84.80	85.63	84.52
2040	95.25	94.97	93.32	92.02	92.98	90.97
2045	103.00	102.68	101.42	96.25	101.02	95.78
2050	114.18	113.81	107.46	103.06	108.15	102.48

2010 2015 2020 2025 2030 2035 2040 2045 2050

Fig. 7. GDP in all scenarios during 2010–2015.

Table 7
The sectorial output variation relative to BAU scenario in 2050 (%).

	AGR	EQU	MET	LAN	W_A	COA	O_G	REF	ELC	CON	OTH	SER
BAU	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CMC	0.16	1.85	0.34	0.45	1.61	9.14	7.41	5.04	0.78	0.20	-0.09	-0.34
CMB	-5.39	-9.02	-10.05	4.41	-11.00	-8.91	-8.51	-9.10	-6.36	-7.68	-8.83	-9.19
CMH	-5.00	-6.64	-8.46	-7.35	-9.22	-7.28	-10.07	-15.06	-5.49	-6.95	-7.62	-7.90
CMBC	-5.01	-8.23	-8.74	5.71	-7.84	-0.47	-2.39	-9.00	-5.60	-7.26	-7.85	-9.90
CMHC	-4.19	-5.05	-6.67	-4.71	-5.18	2.12	-3.32	-13.87	-3.33	-5.86	-5.81	-7.81

declination would cause a series of output drops on REF's upstream and downstream sectors, such as oil mining, metals and water & air transportation. Land transportation increases the output in basic EVs promotion because of the new and constantly increasing demand of EVs. The CCS technology is a compatible alternative option for coal-fired power plant when the carbon emission price is high, in other words, CCS technology will reduce the cost of electricity sector under the environment of emission trading. Furthermore, the application of CCS technology has positive effects on the other industries due to the less burden of the power system.

The consumption of all commodities is illustrated in Table 8. As the amount of China's import and export is very small relative to domestic commodity output value, the variation of China's consumption value are consistent with sectorial output in general. The share of EVs is associated with loss in refinery revenues. In addition, CCS can improve GDP when EVs are promoted, because of protection of CCS to fossil plants and its upstream sectors: energy intensive companies will reduce ETS costs because of the emission reduction capability of CCS. Thus, the industrial chain (COA, O_G and ELC) will meet better prospects for development by applying CCS in the context of ETS than that without CCS. However, the promotion of EVs will strike refinery, with or without CCS, especially in high-level promotion.

5.1.3. ETS price

ETS price (Carbon price) in all scenarios is illustrated in Fig. 8. In BAU scenario, carbon price would gradually rise from 171 RMB per tons of CO_2 (RMB/t-CO_2) in 2020 to 291 RMB/t-CO_2 in 2050. The promotion of EVs could make the price higher. In 2050, the prices in scenarios of the basic promotion and high promotion are 330 RMB/t-CO_2 and 335 RMB/t-CO_2, respectively. However, CCS, as an option to reduce the cost of ETS, has a strong impact on carbon price. The ETS price will not increase or even drop in the scenarios of CMC, CMBC and CMHC. The main reason is that coal-fired power plants—accounting for 40% of the total emissions in China—could reduce emission by applying CCS technology to decrease the cost of ETS, and decreasing demand for carbon emission rights will lead the ETS price continue to decline.

Table 8
Consumption variation relative to BAU scenario in 2050 (%).

	AGR	EQU	MET	LAN	W_A	COA	O_G	REF	ELC	CON	OTH	SER
BAU	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CMC	0.18	1.87	0.37	0.45	1.75	10.36	5.28	4.98	0.84	0.21	-0.10	-0.37
CMB	-4.96	-8.42	-10.46	4.58	-11.61	-7.45	-3.91	-8.58	-6.76	-7.76	-9.02	-10.13
CMH	-5.01	-6.71	-7.54	-7.00	-9.11	-7.39	-5.88	-15.84	-5.22	-7.66	-7.81	-8.26
CMBC	-4.48	-8.20	-9.26	4.94	-7.94	-0.48	-1.16	-9.20	-5.17	-7.47	-7.61	-10.04
CMHC	-4.30	-5.40	-6.68	-4.78	-5.50	2.41	-2.07	-15.26	-3.52	-6.49	-5.84	-7.30

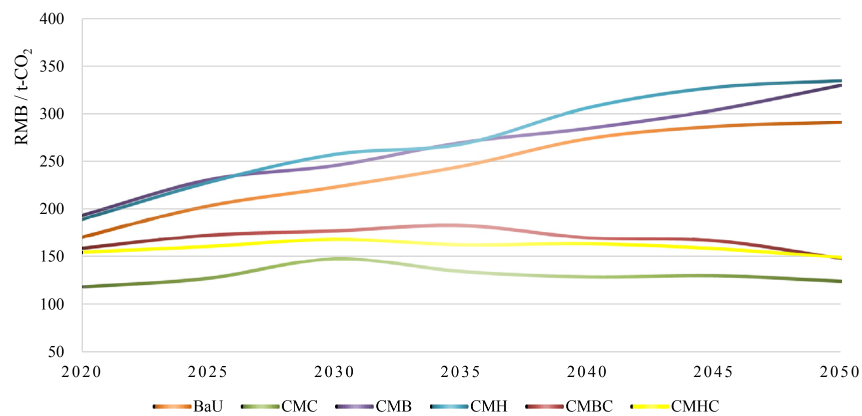


Fig. 8. Carbon price in all scenario.

5.2. *Carbon emission and carbon intensity*

5.2.1. *Carbon emission*

Carbon emission in all scenarios during 2015–2050 is illustrated in Fig. 9. In BAU scenario, carbon emission per year will up to 9.05 billion tons of CO_2 (Bt-CO_2) until 2040, then remains at about 9.02 Bt-CO_2 in 2050. The peak emission in scenarios of basic-level promotion will down to 8.90 Bt-CO_2 and in higher level it will down to 8.46 Bt-CO_2. Carbon emission in all CM scenarios except for CMC can reach a peak in 2030. The promotion with CCS technology can reduce the emission to some extent, by 1.12–1.54 Bt-CO_2 in 2050, while the promotion without CCS will decrease by 0.84–1.24 Bt-CO_2. Furthermore, there is also a positive correlation between the share of electric vehicles and the emission reduction contribution of EVs, 0.84 Bt-CO_2 mitigation for 40% electric vehicles and 1.24 Bt-CO_2 mitigation for 80% electric vehicles in 2050. The reason for the slowdown of the growth of carbon emissions in promotion scenario during 2015–2030 is that transformation of industrial structure would lead economic losses and then, lead to the reduction of energy demand, which can refer to Fig. 7. Then, the energy consumption, especially oil consumption is reduced which make the emission down during 2030–2050 (energy consumption is illustrated in Section 5.4). Moreover, high-level promotion will accelerate transformation of industrial structure and the deceasing

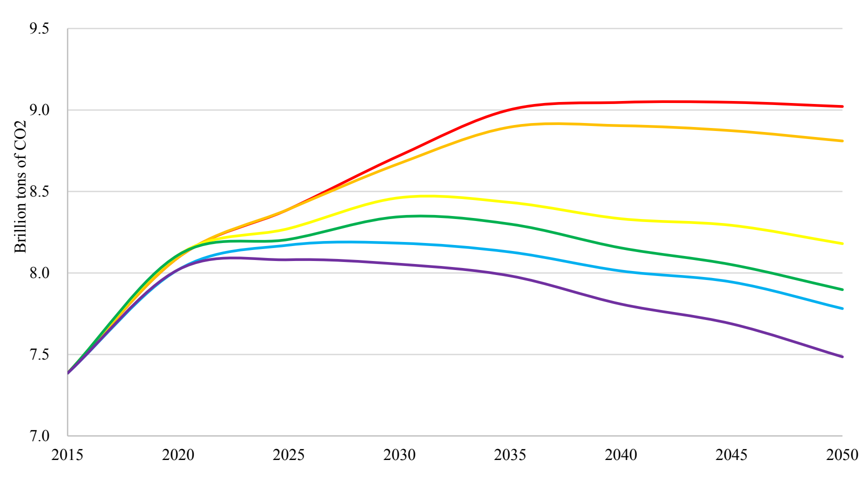


Fig. 9. Carbon emission in all scenarios.

demand of energy consumption. So in basic-level and high-level promotion scenario, the peak year will moving forward to 2030 and 2025.

5.2.2. Carbon intensity

The CO_2 emission intensity (CI) in all promotion scenarios during 2020–2050 is illustrated in Fig. 10. In the BAU scenario, the CI will be 0.14 kg-CO_2/RMB in 2020 and it will slightly decrease to 0.08 kg-CO_2/RMB or to 55.15% in 2050. CI in other scenarios in 2050 will be lower than that in 2050 BAU scenario. The promotion will reduce the CI in the CMB, CMH, CMBC and CMHC scenarios by 46.87%, 47.30%, 49.02% and 49.01% from 2020 BAU scenario, respectively. Furthermore, the CI will be reduced more in the CMBC and CMHC scenarios compared with that in CMB and CMH scenarios.

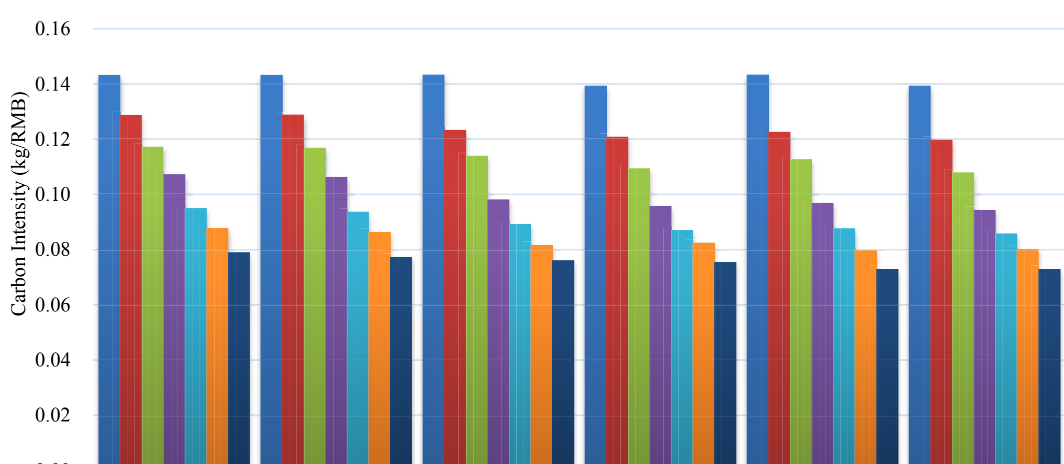
The application of CCS technology will have little effect on CI: the CI will decrease 2.02% in 2050 CMC scenario compared to 2050 BAU scenario, and it will reduce 3.66% and 4.44% in scenario of CMB and CMH, respectively. Nevertheless, the CI can be reduced significantly by the option of promoting EVs with CCS, by 7.57% and 7.55% in CMBC and CMHC scenario. Therefore, we find that the two strategies play complementary roles to reduce CI but both of them cannot significantly reduce CI. Just because CO_2 reduction of EVs and CCS is higher, however, which is not significantly higher than GDP loss.

5.3. Emission reduction

Emission reduction of EVs is illustrated in Fig. 11 and the usage of CCS (emission reduction of CCS) is shown in Fig. 12. The reduction capabilities of EVs and CCS will be increasing year by year, and the reduction of high-level EVs is 470–487 Mt-CO_2 more than that of basic-level. Moreover, the reduction capacity of EVs is better than that of CCS. During 2017–2020, basic-level promotion will have no contribution to CO2 reduction. However, the reduction will be increasing continuously, for example, in CMB scenario the emission reduction in 2020 is -18 Mt-CO_2 but 993 Mt-CO_2 per year in 2050. In general, CCS could increase the reduction of EVs by 31–106 Mt-CO_2. The reduction of CCS is not better than EVs, about 249 Mt-CO_2 per year in 2050. The reduction of CCS can get a great elevation when EVs is promoted—the reduction will increase by 33.63–40.01%. EVs and CCS, both have a positive impact on each other. Moreover, CCS can get more benefits from EVs promotion. The main reason for this phenomenon is that electricity generation is increasing caused by the promotion policy, which makes the power plants be more willing to apply CCS technology under the pressure of ETS.

5.4. Fossil energy consumption

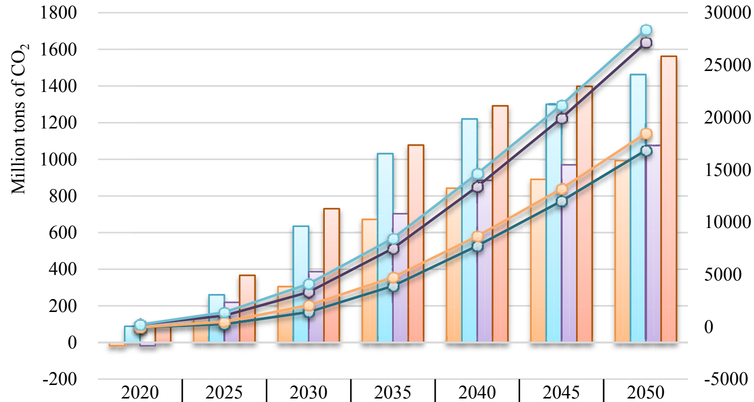
Fossil energy consumption during 2010–2050 in all scenarios is illustrated in Fig. 13. In BAU and CMC scenarios, fossil energy consumption will reach a peak by 3249.75 Million tons of coal equivalent (Mtce) and 3275.33 Mtce in 2040, respectively. The peak consumption in scenarios of CMB, CMH and CMBC will be about 3034.80 Mtce, 2935.15 Mtce and 3104.92 Mtce, respectively, at the year of 2030. In CMHC scenarios, the consumption will reach a peak in 2025, by 2989.49 Mtce. Coal consumption is reduced by −9.16%, 9.92%, 12.70%, 1.68% and 5.25% in scenarios of CMC, CMB, CMH, CMBC and CMHC compared with BAU scenario in 2050. Oil consumption is reduced by 17.86%, 8.78%, 19.14%, 22.77% and 28.44% in scenarios of CMC, CMB, CMH, CMBC and CMHC compared with BAU scenario in 2050. Gas consumption is reduced by 30.55%, −5.01%, 2.84%, 10.76% and 24.93% in scenarios of CMC, CMB, CMH, CMBC and CMHC compared with BAU scenario in 2050. A strong promotion of electric cars with CCS significantly shortens the arrival time of the peak year. CCS technology, as an alternative to fossil power plant, shows another way to protect environment: energy consumption in scenarios with CCS is higher than that without CCS



	BaU	CMC	CMB	CMH	CMBC	CMHC
2020	0.1433	0.1433	0.1434	0.1394	0.1434	0.1394
2025	0.1287	0.1289	0.1234	0.1209	0.1227	0.1198
2030	0.1173	0.1169	0.1140	0.1094	0.1127	0.1080
2035	0.1073	0.1063	0.0982	0.0959	0.0969	0.0944
2040	0.0950	0.0938	0.0893	0.0871	0.0877	0.0858
2045	0.0878	0.0864	0.0818	0.0825	0.0797	0.0803
2050	0.0790	0.0774	0.0761	0.0755	0.0730	0.0730

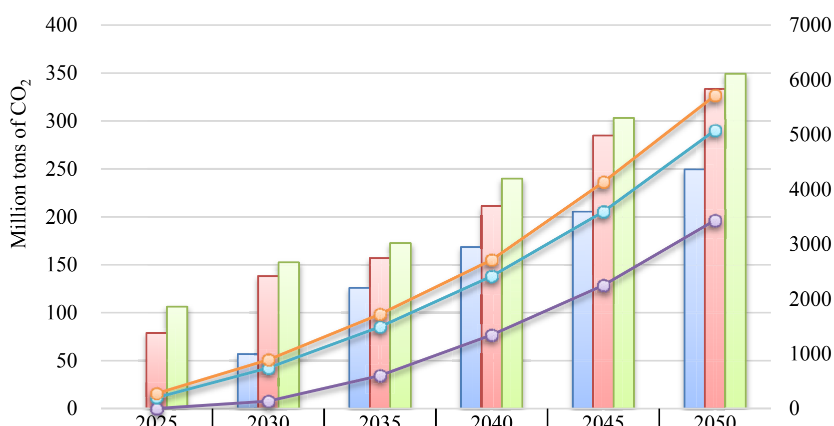
2020 2025 2030 2035 2040 2045 2050

Fig. 10. CO_2 emission intensity in all promotion scenarios during 2020–2050.



	2020	2025	2030	2035	2040	2045	2050
(A)Basic level	-18	140	305	672	842	891	993
(B)High level	89	260	635	1031	1220	1301	1463
(C)Basic with CCS	-18	219	387	703	885	970	1076
(D)High with CCS	89	367	730	1078	1292	1398	1563
Accumulative reduction of (A)	-47	249	1409	3900	7725	12014	16859
Accumulative reduction of (B)	217	1071	3318	7487	13388	19935	27135
Accumulative reduction of (C)	-43	475	2058	4726	8652	13189	18486
Accumulative reduction of (D)	213	1379	4095	8454	14625	21179	28382

Fig. 11. Emission reduction of EVs.



	2025	2030	2035	2040	2045	2050
(A)CCS in BaU	0	57	126	168	205	249
(B)CCS in Basic level	79	138	157	211	285	333
(C)CCS in High level	106	152	173	240	303	349
Accumulative reduction of (A)	0	135	602	1344	2248	3437
Accumulative reduction of (B)	199	741	1491	2415	3595	5081
Accumulative reduction of (C)	274	890	1723	2713	4133	5717

Fig. 12. Emission reduction of CCS.

(i.e. 2946.81 Mtce in 2050 CMB scenario and 3007.30 Mtce in 2050 CMBC scenario), but the emission in scenarios with CCS is lower than that without CCS (i.e. 8.18 Bt-CO2 in 2050 CMB scenario while 7.90 Bt-CO2 in 2050 CMBC scenario). That is, the balance between carbon emission mitigation and protection of fossil energy industry can be achieved by the application of CCS technology.

5.5. Oil security

As China is a country with a severe shortage of oil, 68.54% domestic consumption of the crude oil is dependent on imports. Imported crude oil in all scenarios during 2020–2050 is illustrated in Fig. 14. Imported crude oil will soar to 544.73 Million ton (Mt) in

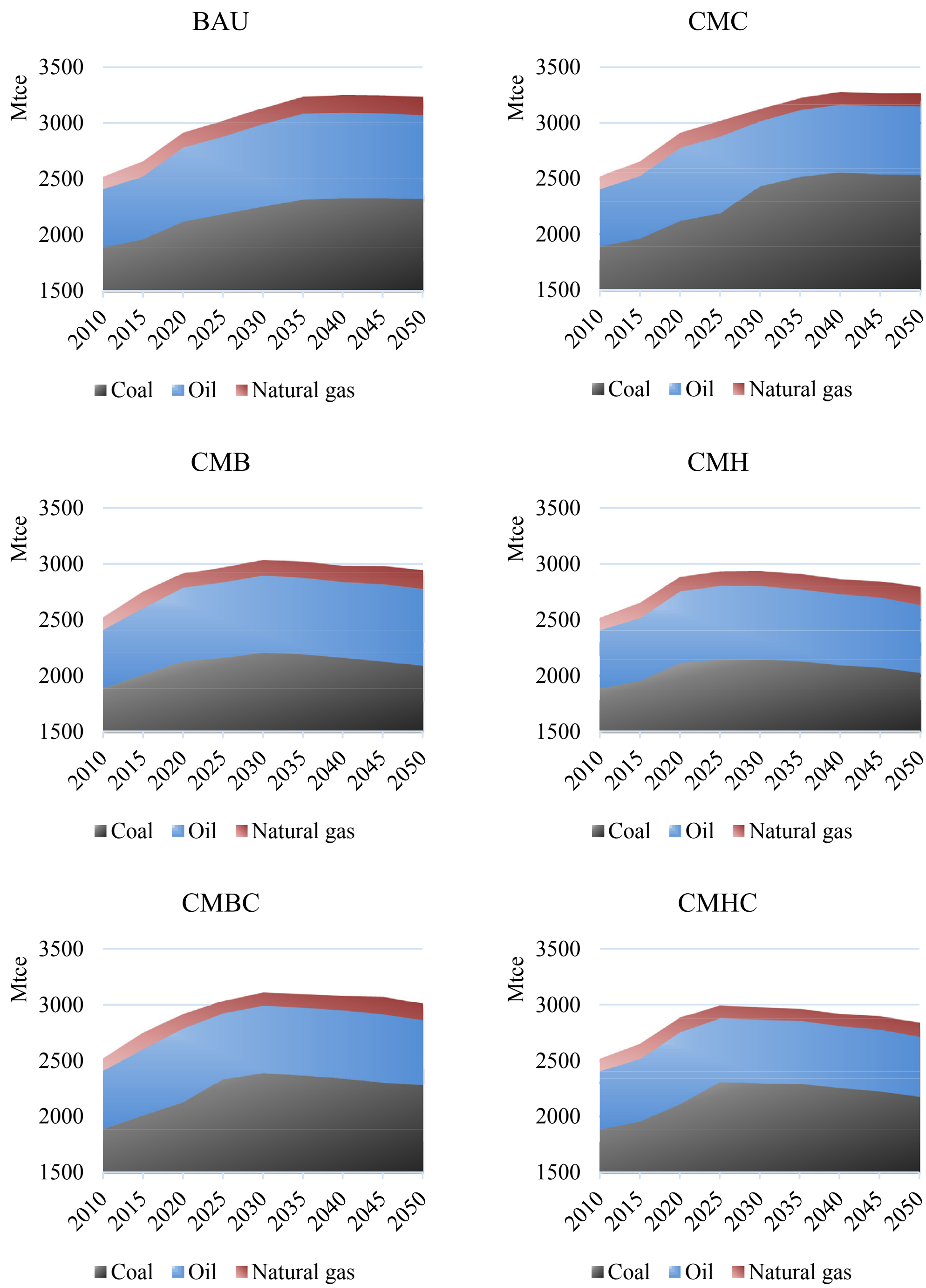


Fig. 13. Fossil energy consumption in all scenarios during 2010–2050.

2050 in BAU scenario. Imported oil will be 522.36–577.57 Mt in scenarios of CMC, CMB and CMBC in 2050, while it will be 424.61 Mt and 413.67 Mt in scenarios of CMH and CMHC respectively. The reduction in CMH and CMHC scenarios is the most significant: 120.12 Mt and 131.06 Mt cut, which is equal to reduce 22.05–24.54% of 2050 BAU scenario. CCS technology helps almost nothing to reduce oil dependency. In CMHC scenario, the import of oil will reach a peak in 2040, and the peak is 429.81 Mt. We find that the basic promotion could only reduce the import oil consumption by 1.95–4.11%. However, the high-level promotion could reduce it by 22.05–24.06%. We also find that the reduced ratio of import oil is higher than the ratio of oil consumption. The reason is that the demand elasticity of energy on import oil is higher than that on domestic oil which caused by the shortage of domestic oil production capacity.

5.6. Electricity demand

The variation of electricity demand in EVs' scenarios compared with BAU scenario in 2050 is illustrated in Fig. 15. The electricity demand in transportation is increased 35.93%, 83.18%, 36.99% and 86.91% in CMB, CMH, CMBC and CMHC scenario, respectively. However, the demand in metal and refined oil is decreased significantly, by 22.71–25.27% and 18.61–29.34%, as well as the coal

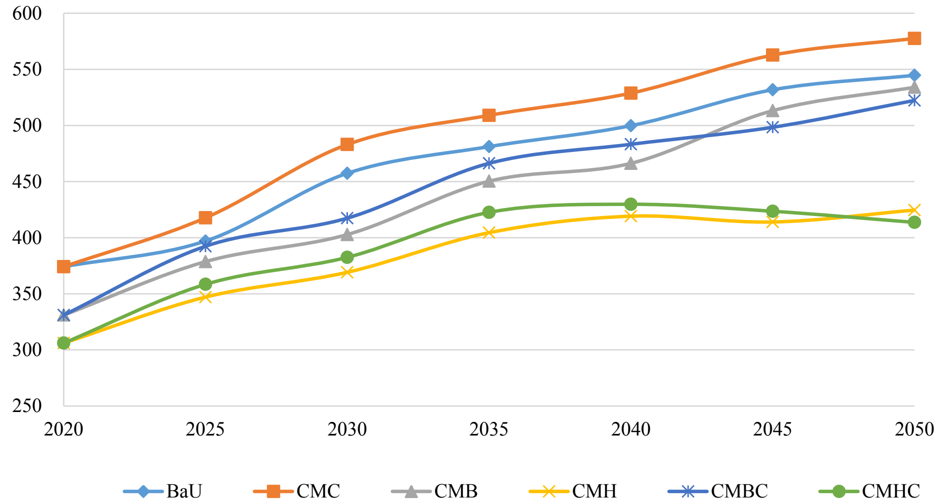


Fig. 14. Imported crude oil in all scenarios during 2020–2050.

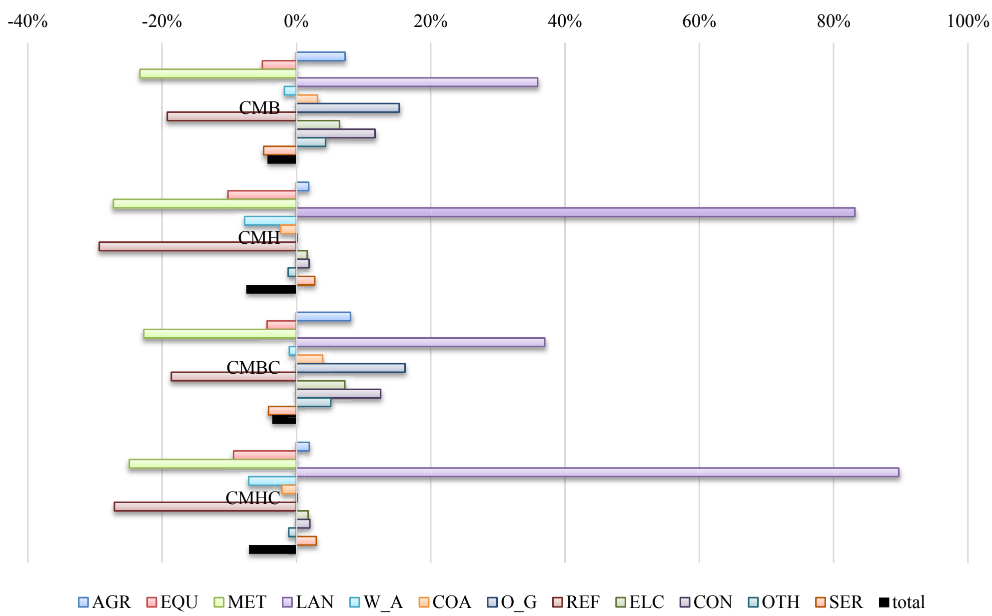


Fig. 15. The variation of electricity demand in EVs' scenarios compared with BAU scenario in 2050.

industry. Since the electricity demand in sectors of equipment, metal or refined oil are higher than transportation in China, total electricity demand will reduce by 4.30%, 7.45%, 3.58% and 6.75% in CMB, CMH, CMBC and CMHC scenario, respectively. Economic losses caused by the promotion may be the main reason for the decrease of electricity demand. Through the change of the demand for electricity, it can be seen clearly that the high-level promotion has even greater negative impact on the economy than basic-level promotion: the variations of COA, OTH and SER are increased in basic level but decreased in high level compared with BAU scenario. The demand of electricity in other sectors (except for land transportation) in CMH and CMHC scenario will be reduced compared with CMB and CMBC scenario. In the process of popularization of EVs, protection of refined oil is worth considering.

5.7. Other benefits

The promotion of EVs is also associated with less urban air and noise pollution. According to Table 3 (The share of EVs), current technology (Desulfurization and denitrification technology) and the forecast of vehicle ownership [67], we can estimate urban air pollution reduction (Table 9). In CMB and CMBC scenarios, CO, NO_x and C_xH_x emission could reduce by 71.6, 19.13 and 8.1 million ton in 2050. However, power plants may emit more SO_2, by 30.19 million ton in 2050. The reduction amount of air pollution emission will be double in CMH and CMHC scenario. According to the result of Pallas et al. [68], we can also estimate that in 2050, urban noise reduction may be 6–8 dB (dB) in all EVs scenario.

Table 9
Air pollution mitigation in scenarios of EV promotion compared with BAU scenario in 2050 (million ton).

	Basic level	High level
CO	71.60	143.20
NO_x	19.13	38.26
C_xH_x	8.10	16.19
SO_2	−30.19	−60.38

6. Conclusion

In this paper, a dynamic recursive CGE model is established to analyze the impact of EVs promotion and CCS application in China during 2010–2050. We establish 6 scenarios to simulate the impact of single strategies and mixed strategies of EVs and CCS. The main research object of this paper is the economic, energy and environmental impact of EVs and CCS, find the best option to save energy and reduce CO_2. Results show that policy on promoting electric vehicles plays an important role in carbon emission reduction. If the national plan on EVs' promotion is on schedule, the emission will down 9.33% in 2050. Moreover, the CCS technology would have positive effects on GHG mitigation. Greater efforts to promote electric vehicles may be counterproductive: more GDP losses although higher CO_2 reduction compared with basic-level promotion, however, the emission peak year will be advanced to 2030 in higher promotion scenario. It is an effect way to mitigate GDP losses by promoting EVs with CCS technology, so that CCS technology is highly encouraged as a simultaneous option with EVs promotion. The effect of electric vehicle on reducing carbon emission intensity is not obvious. The promotion could effectively reduce fossil energy consumption, especially in coal and oil consumption; however, the scenarios with CCS may consume more fossil fuels relative to those without CCS. EVs promotion plan will directly ease China's oil security issues and high-level promotion will go further: in the scenario of high-level promotion with CCS, the oil import will reach a peak in 2040. The import of crude oil would be little impacted by CCS. Overall speaking, the promotion in the basic-level performs better than that in the high-level and CCS plays an important role to protect economy. So promoting EVs at a basic-level with CCS technology is a highly recommended strategy to energy saving and CO_2 reduction in this paper. From 2015 to 2050, China will contribute to CO_2 reduction through this strategy by 24.97 Bt-CO_2 or 74.35% of 2010 world total emission.

This paper offers further possibilities for future work. Because CGE is a microeconomic model, which considers macro factors, some micro policies and behaviors could not be considered, such as the construction of supporting facilities, charging in electricity trough, returning electricity to the grid, and refinement of EV classification to hybrid electric vehicle, battery electric vehicles and others. These require more systematic data and new ideas to build CGE's equation. Moreover, this paper did not distinguish electric power industry, because we could not find a CIOT whose electricity is subdivided into renewable energy and fossil energy to construct a SAM which can classify different power plants.

Acknowledgments

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Appendix A. Equation system of the dynamic CGE model

A.1 Production block

$$VAE_i = \alpha_i^{vae}\left[\delta_i^{vae} VA_i^{\rho_i^{vae}} + (1-\delta_i^{vae}) ENE_i^{\rho_i^{vae}}\right]^{1/\rho_i^{vae}} \tag{A.1}$$

$$\frac{PVA_i}{PENE_i} = \frac{\delta_i^{vae}}{1-\delta_i^{vae}}\left(\frac{ENE_i}{VA_i}\right)^{1-\rho_i^{vae}} \tag{A.2}$$

$$PVAE_i \cdot VAE_i = PVA_i \cdot VA_i + PENE_i \cdot ENE_i \tag{A.3}$$

$$VA_i = \alpha_i^{va}\left[\delta_i^{va} LAB_i^{\rho_i^{va}} + (1-\delta_i^{va}) CAP_i^{\rho_i^{va}}\right]^{1/\rho_i^{va}} \tag{A.4}$$

$$\frac{PLAB_i}{PCAP_i} = \frac{\delta_i^{va}}{1-\delta_i^{va}}\left(\frac{CAP_i}{LAB_i}\right)^{1-\rho_i^{va}} \tag{A.5}$$

$$PVA_i \cdot VA_i = PLAB_i \cdot LAB_i + PCAP_i \cdot CAP_i \tag{A.6}$$

$$ENE_i = \alpha_i^{ene}\left[\delta_i^{ene} ELE_i^{\rho_i^{ene}} + (1-\delta_i^{ene}) NOE_i^{\rho_i^{ene}}\right]^{1/\rho_i^{ene}} \tag{A.7}$$

$$\frac{PELE_i}{PNOE_i} = \frac{\delta_i^{ene}}{1-\delta_i^{ene}}\left(\frac{NOE_i}{ELE_i}\right)^{1-\rho_i^{ene}} \tag{A.8}$$

$$PENE_i \cdot ENE_i = PELE_i \cdot ELE_i + PNOE_i \cdot NOE_i \tag{A.9}$$

$$NOE_i = \alpha_i^{noe}\left[\delta_i^{noe} COAL_i^{\rho_i^{noe}} + (1-\delta_i^{noe}) NOS_i^{\rho_i^{noe}}\right]^{1/\rho_i^{noe}} \tag{A.10}$$

$$\frac{PCOAL_i}{PNOS_i} = \frac{\delta_i^{noe}}{1-\delta_i^{noe}}\left(\frac{NOS_i}{COAL_i}\right)^{1-\rho_i^{noe}} \tag{A.11}$$

$$PNOE_i \cdot NOE_i = PCOAL_i \cdot COAL_i + PNOS_i \cdot NOS_i \tag{A.12}$$

$$NOS_i = \alpha_i^{nos}\left[\delta_i^{nos} OIL_i^{\rho_i^{nos}} + (1-\delta_i^{nos}) GAS_i^{\rho_i^{nos}}\right]^{1/\rho_i^{nos}} \tag{A.13}$$

$$\frac{POIL_i}{PGAS_i} = \frac{\delta_i^{nos}}{1-\delta_i^{nos}}\left(\frac{GAS_i}{OIL_i}\right)^{1-\rho_i^{nos}} \tag{A.14}$$

$$PNOS_i \cdot NOS_i = POIL_i \cdot OIL_i + PGAS_i \cdot GAS_i \tag{A.15}$$

$$OIL_i = \alpha_i^{oil}\left[\delta_i^{oil} CRUDE_i^{\rho_i^{oil}} + \left(1-\delta_i^{oil}\right) PRODUCT_i^{\rho_i^{oil}}\right]^{1/\rho_i^{oil}} \tag{A.16}$$

$$\frac{PCRUDE_i}{PPRODUCT_i} = \frac{\delta_i^{oil}}{1-\delta_i^{oil}}\left(\frac{PRODUCT_i}{CRUDE_i}\right)^{1-\rho_i^{oil}} \tag{A.17}$$

$$POIL_i \cdot OIL_i = PCRUDE_i \cdot CRUDE_i + PPRODUCT_i \cdot PRODUCT_i \tag{A.18}$$

$$INT_{i,j} = a_{i,j}^{INT} Z_j \tag{A.19}$$

$$VAE_j = a_j^{VAE} Z_j \tag{A.20}$$

A.2 Income and Expenditure block

$$\begin{aligned} PZ_j &= a_j^{vae} PVAE_j + \sum_i a_{i,j}^{INT} PQ_i \\ &\quad + \left(PLC_j + PCCS_j \cdot CCS_j - sub_j \cdot CCS_j \cdot PCCS_j\right)/Z_j \Big| j =' elc' \\ PZ_j &= a_j^{vae} PVAE_j + \sum_i a_{i,j}^{INT} PQ_i + \left(PLC_j - PCCS_j \cdot CCS_j\right)/Z_j \Big| j =' equ' \\ PZ_j &= a_j^{vae} PVAE_j + \sum_i a_{i,j}^{INT} PQ_i + PLC_j/Z_j \Big| j \neq 'equ',' elc' \end{aligned} \tag{A.21}$$

$$TD = \tau^d \sum_i (PCAP_i \cdot CAP_i + PLAB_i \cdot LAB_i) - \sum_i PLC_i \tag{A.22}$$

$$\begin{aligned} TZ_i &= \tau^z PZ_i Z_i - sub_j \cdot CCS_j \cdot PCCS_j | j =' elc' \\ TZ_i &= \tau^z PZ_i Z_i | j \neq 'elc' \end{aligned} \tag{A.23}$$

$$TM_i = \tau^m PM_i M_i \tag{A.24}$$

A.3 Market block

$$PE_i = \varepsilon PWE_i \tag{A.25}$$

$$PM_i = \varepsilon PWM_i \tag{A.26}$$

$$\sum_i PWE_i E_i + SF = \sum_i PWM_i M_i \tag{A.27}$$

$$Q_i = \gamma_i \left(\delta m_i M_i^{\eta_i} + \delta d_i D_i^{\eta_i}\right)^{1/\eta_i} \tag{A.28}$$

$$M_i = \left[\frac{\gamma_i^{\eta_i} \delta m_i PQ_i}{\left(1 + \tau_i^m\right) PM_i}\right]^{\frac{1}{1-\eta_i}} Q_i \tag{A.29}$$

$$D_i = \left[\frac{\gamma_i^{\eta_i} \delta d_i PQ_i}{PD_i}\right]^{\frac{1}{1-\eta_i}} Q_i \tag{A.30}$$

$$Z_i = \theta_i \left(\xi e_i E_i^{\phi_i} + \xi d_i D_i^{\phi_i}\right)^{\frac{1}{\phi_i}} \tag{A.31}$$

$$E_i = \left[\frac{\theta_i^{\phi_i} \xi e_i \left(1 + \tau_i^z\right) PZ_i}{PE_i}\right]^{\frac{1}{1-\phi_i}} Z_i \tag{A.32}$$

$$D_i = \left[\frac{\theta_i^{\phi_i} \xi d_i \left(1 + \tau_i^z\right) PZ_i}{PD_i}\right]^{\frac{1}{1-\phi_i}} Z_i \tag{A.33}$$

A.4 Energy-policy block

$$\begin{aligned} EM_i &= COAL_i \times \gamma^{coal} + OIL_i \times \gamma^{oil} + GAS_i \times \gamma^{gas} - CCS_i \Big| i =' elc' \\ EM_i &= COAL_i \times \gamma^{coal} + OIL_i \times \gamma^{oil} + GAS_i \times \gamma^{gas} \Big| i \neq 'elc' \end{aligned} \tag{A.34}$$

$$PLC_i = p^t (CR_i - FP_i) + p^f (EM_i - CR_i) \tag{A.35}$$

$$CI = \sum_i EM_i \Big/ \sum_i \left(XV_i + XG_i + XP_i + E_i - M_i\right) \tag{A.36}$$

$$fpr = FP_i / CR_i \tag{A.37}$$

A.5 Macroeconomic closure block and Market clearing

$$XV_i = \frac{\lambda_i}{PQ_i} (SP + SG + \varepsilon SF) \tag{A.38}$$

$$SP = ss^p \sum_i \left(PCAP_i \cdot CAP_i + PLAB_i \cdot LAB_i\right) \tag{A.39}$$

$$SG = ss^g \left(TD + \sum_i TZ_i + \sum_i TM_i\right) \tag{A.40}$$

$$XG_i = \frac{\mu_i}{PQ_i} \left(TD + \sum_i TZ_i + \sum_i TM_i - SG\right) \tag{A.41}$$

$$XP_i = \frac{\beta_i^{xp}}{PQ_i} \left(\sum_i (PCAP \cdot CAP_i + PLAB \cdot LAB_i) - SP - TD\right) \tag{A.42}$$

$$Q_i = XP_i + XG_i + XV_i + \sum_j X_{i,j} \tag{A.43}$$

$$\sum_i LAB_i = TOTLAB \tag{A.44}$$

$$\sum_i CAP_i = TOTCAP \tag{A.45}$$

Appendix B. Social account matrix used in CGE model

Table B1
Social account matrix used in CGE model.

		A	FA L	C	EN	IN	T	H	G	I$S	F	SUM
	A	103331						16008	5822	18231	13716	157108
FA	L	24857										24857
	C	7273										7273
	EN	14										14
	IN	7715										7715
	T	1121										1121
	H		24857	7273	14							32143
	G					7715	1121	578				9414
	I$S							15558	3592		−919	18231
	F	12796										12796
	SUM	157108	24857	7273	14	7715	1121	32143	9414	18231	12796	

Notes: FA is factor, A is activity, L is labor, C is capital, EN is energy, IN is indirect tax, T is tariff, H is household, G is government, I$S is investment and savings. F is foreign, and SUM is the summary.

Conflicts of interest

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

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