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Impacts of carbon trading scheme on air pollutant emissions in Guangdong Province of China

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ABSTRACT

This study aims to assess the impacts of carbon emission trading scheme (ETS) policy on air pollutant emission reduction in Guangdong (GD) Province, especially with respect to the embedded air pollutant emission flow caused by carbon ETS. A Computable General Equilibrium (CGE) model is constructed to project the local emission trajectory of CO_2 and air pollutants under business as-usual (BaU) and policy scenarios in GD province and the rest of China from 2007 to 2020. To achieve the energy and carbon intensity targets, the carbon constraint and ETS policy are employed to promote energy saving and CO_2 emission reduction. The simulation results show that the carbon ETS has the co-benefits of reducing SO_2 and NO_x emissions by 12.4% and 11.7% in 2020 compared with the BaU scenario. Along with the carbon trading volume of 633 million tons created by the ETS scenario, an embedded amount of 38,000 tons of air pollutants is exchanged among carbon trading sectors, which valued about 50 million USD. Although the current carbon and air pollutant emission markets are independent from each other, the evaluation of the co-benefits needs to be considered further in the policy making process.

Introduction

As a result of the rapid development of China's economy, energy consumption increases drastically and various harmful substances from energy consumption are discharged to the atmospheric environment causing serious air pollution. Especially, due to China's coal dominated energy structure, acid rain and smog have seriously polluted the environment. Furthermore, as the ownership of China's automobile has greatly increased in recent years, nitrogen oxide (NO_x) and particle matter (PM) have become the main air pollutants in an urban area, causing adverse effects on the health of urban residents.

Although during the “11th five-year” (FYP during 2006–2010) period the energy intensity in GD decreased by 16.4%, the conventional growth mode of industrialization and urbanization results in rising energy demand and CO_2 emission as well as environmental degradation. As one of the most important economic provinces of China, Guangdong (GD) consumes 4.6% of China's coal, 21.9% of crude oil, 12.8% of natural gas and 10.6% of electricity in 2012 (Table 1). Consequently, air pollution in Guangdong and the Pearl River District has deteriorated in recent years.

In order to prevent further deterioration of air quality and protect human health and the ecosystem, the Chinese government has implemented a series of national control policies to reduce the emissions of air pollutants since 2005 (Wang and Hao, 2012). The 11th FYP for national environmental protection required the reduction of annual emissions of sulfur dioxide (SO_2) in 2010 by 10% from its 2005 level. Furthermore, in China's 12th FYP (2011–2015), nationwide controls of NO_x emission will be implemented along with the controls of SO_2 and primary particles. The Ministry of Environmental Protection (MEP) of China has set a target to reduce the national NO_x emissions in 2015 by 10% from the 2010 level.

At the regional level, the Guangdong provincial government has promulgated a serial policy in thermal power plant nitrogen, volatile organics, motor vehicle pollutant emission, industrial boiler pollution and cement industry, which all emphasizes on establishing the work progress report, supervising the notification mechanism, and strengthening the monitoring capacity-building (People's Government of Guangdong Province, no. 6, 2014). Furthermore, Guangdong Province also introduced a “comprehensive energy saving and reduction program” to achieve the main target of energy saving and air pollutant by 2015, which requires the energy consumption of per GDP to decrease by 18% and 31% in 2010 and 2005, respectively; chemical oxygen demand (COD) and sulfur dioxide (SO_2) emissions

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to reduce by 12% and 14.8% compared with 2010, respectively; and ammonia and nitrogen oxide (NH_3 and NO_x) emissions to decrease by 13.3% and 16.9% in 2010, respectively (People's Government of Guangdong Province, no. 14, 2012). Guangdong was also selected as a low-carbon pilot province designated as one of the 13 pilot low-carbon zones in China by the National Development and Reform Commission (NDRC) in 2010, with a tough target of reducing carbon intensity of GDP by 19.5% and at least 45% from 2005 level in 2015 and 2020, respectively. In addition, some pilot energy and climate polices at the regional level are implemented and assessing such policies with complex system models have attracted attention in China. For instance, Guangdong has been selected as a pilot to conduct the carbon emission trading scheme (ETS) in 2013, and the air pollutant trading market has started in 2014 in this province. Evaluation of the effectiveness of carbon mitigation policies is vital for future policy design at both national and regional levels.

Table 2
Common socio-economic assumptions shared by all scenarios.

	2007–2010	2011–2015	2016–2020
Guangdong			
Expected GDP growth rate	10.8%	8.0%	7.5%
TFP improvement	5%	4%	3.5%
Population growth rate	3%	0.64%	0.47%
Energy efficiency improvement	4% for solid fuel; 2% for liquid fuel; 2% for gas fuel; 8% for electricity		
Air pollutant abatement rate	25% for SO_2; 0% for NO_x		50% for SO_2; 20% for NO_x
Rest of China			
Expected GDP growth rate	10.0%	8.0%	7.5%
TFP improvement	5%	5%	5%
Population growth rate	0.63%	0.62%	0.54%
Energy efficiency improvement	5% for solid fuel; 5% for liquid fuel; 2% for gas fuel; 4% for electricity		

Literature review

So far there is a growing awareness that sustainable development requires an integrated and system-level redesign of the entire socio-ecological regime to coordinate different management policies. Some researchers discussed the concept of co-benefits in the air pollution control and counter climate change (Kanad et al., 2013; Nemet et al., 2010; Jack and Kinney, 2010). If well established, the evaluation of such dual or multiple benefits or profit schemes could provide strong incentives for the adoption of air pollutant control protection measures and CO_2 emission reduction actions which will help to construct a whole reduction market financed by different stakeholders. Several previous studies have already analyzed the implications of climate and energy saving policies on air pollutants in developed and developing countries (e.g. Hasanbeigi et al., 2013; Williams et al., 2012; Bollen et al., 2009). A range of studies have focused on the co-benefits of carbon mitigation measures induced air pollutant reduction in China (Aunan et al., 2004; Jiang et al., 2013; Dong et al., 2015), co-benefits of energy saving entail reductions in air pollution and the improvement of public health (Chen et al., 2007), environmental benefits of various vehicles by employing a case study in Shenyang, China (Geng et al., 2013), and co-benefits of energy and carbon mitigation policies on air pollutant reduction (Mao et al., 2012; Xi et al., 2013; He et al., 2010). For example, Aunan et al. (2004) found that the implementation of carbon-abating options could lead to reduction of SO_2 and particles. And the paper argued that the co-benefits need to expand the practical scope for Greenhouse Gas (GHG) mitigation measures under the clean development mechanism (CDM). Chen et al. (2007) found that the energy saving policies can entail reductions in air pollution and the improvement of public heath as a co-benefit. Geng et al. (2013) analyzed the cost effectiveness and environmental benefits of various vehicles by employing a case study in Shenyang, China. Mao et al. (2012) used the CIMS model to predict the air pollutant reduction under the constraint of CO_2 emission intensity of the Chinese transportation, and compared the air pollutant reduction in carbon tax and fuel tax policy. And by combining a top-down type Computable General Equilibrium (CGE) model and bottom-up type GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies)-China model, Dong et al. (2015) analyzed the co-benefit of mitigating carbon emissions on air pollution in 30 provinces of China.

In general, these studies show that climate policy implementation has co-benefits on air pollutant reduction and decreases the risk of political opposition.

However, as Williams et al. (2012) argued, the previous studies demonstrated the increasing prevalence and importance of integrating co-benefits into impact studies conducted in developing countries such as China. Nevertheless, data limitations and a lack of resources and experience with large-scale general equilibrium (such as CGE) or bottom-up models and sophisticated air quality models can present significant barriers to assess the economic co-benefits. In addition, these aforementioned studies have widely conducted policy analyses on national or sectoral in China and around the world.

As defined by the general equilibrium theory of Walras, the economy composed with supply and demand is equalized across all of the interconnected markets in the economy, such as in energy products and carbon emission mitigation policy. Further, the abstract general equilibrium structure formalized by Arrow and Debreu is combined with realistic economic data to solve numerically for the levels of supply, demand and price that support equilibrium across a specified set of markets, which is called the Computable General Equilibrium (CGE) model (Sue Wing, 2006). So, CGE models are widely used in analyzing and estimating the impacts of policies such as taxes, subsidies, quotas or transfer instruments on the economy and other

Table 1
Selected indicators of Guangdong Province in 2012.
Source: energy data from NBS (2013), economic data from GDBS (2013), population from NBS (2013) and the authors' calculation.

	Value	Share in China
Population (million persons)	105.9	7.8%
Primary energy (million ton coal equivalent)[a]		
Coal	117.3	4.6%
Crude oil	64.5	21.9%
Gas	15.2	12.8%
Electricity	43.8	10.6%
Economic indicators (billion 2012 US dollar (USD))		
GDP	907.9	11.0%

[a] The value of conversion factor is (1 kgCE = 29,306 kJ) and (1 kWh = 0.1229 kgCE).

Table 3
Key carbon policy assumptions — all scenarios.

Scenario	Renewable energy	Emission trading	Emission constraint
BaU	Low level	None	No carbon cap.
BaU_RE	High level	None	No carbon cap.
SAV	High level	None	Carbon intensity reduces 45% over 2005–2020; annual growth rate of carbon between 2013 and 15: power sector 0.3%, oil refinery 2%, cement 1%, iron and steel 6%; 2016–20: power sector 0.1%, oil refinery 2%, cement 1%, iron and steel 5%.
SAVET	High level	Yes	

Table 4
The effects of carbon cap and ETS policy on air pollutant reduction.

	2015			2020		
	BaU_RE	SAV	SAVET	BaU_RE	SAV	SAVET
CO_2 (million ton)	575	553	555	692	621	633
SO_2 (kilo ton)	840	797	805	692	614	625
NO_x (kilo ton)	954	919	907	774	722	716
CO_2 reduction rate		−3.8%	−3.5%		−10.2%	−8.6%
SO_2 reduction rate		−5.1%	−4.2%		−11.3%	−9.7%
NO_x reduction rate		−3.6%	−4.9%		−6.7%	−7.5%

Table 6
The welfare cost of Guangdong and China in the model.

	GD		China	
	SAV	SAVET	SAV	SAVET
2012	0.00%	0.00%	0.00%	0.00%
2013	−0.20%	−0.13%	0.00%	0.00%
2014	−0.19%	−0.09%	0.00%	0.00%
2015	−0.22%	−0.13%	0.00%	0.01%
2016	−0.28%	−0.22%	0.00%	0.01%
2017	−0.40%	−0.37%	0.00%	0.00%
2018	−0.55%	−0.53%	0.00%	0.00%
2019	−0.76%	−0.72%	−0.01%	0.00%
2020	−1.08%	−1.05%	−0.02%	−0.02%

economic factors, such as labor, capital, energy and other materials (Bhattacharyya, 1996; Zhang, 1998; Wang et al., 2009; Mahmood and Marpaung, 2014).

Recently, assessing the cost and benefit of energy and climate policy on economy and CO_2 emission reduction with CGE models has attracted increasing interest in China, such as (Zhou et al., 2012) using the CGE model to evaluate the impact of the renewable energy deployment on the CO_2 emission reduction (He et al., 2010; Lu et al., 2010), estimate the effect of the energy efficiency change and energy investment on the economy and industry development using CGE (Wang, 2003; Dai et al., 2011), assess the economic loss of national carbon intensity-based constraints on completing the reduction target and according to their model analysis to propose some carbon reduction measures.

Especially, several studies extended the model function to construct multi-region CGE model to assess the impact of inter-provincial emission trading or regional carbon intensity targets on economy loss or CO_2 emission reduction based on GTAP data or China provincial data base (Zhang et al., 2012; Cui et al., 2014; Tang and Wu, 2014). However, most existing multi-region CGE models are static, and ETS is among regions, such as among different provinces or pilot provinces. In addition, few studies focus on the relationship of carbon emission trading policy on the impact of the air pollutant change and ETS is designed in sector level with CGE model of Guangdong Province.

However, few studies have assessed the co-benefits and implications of ETS policy of carbon mitigation on air pollutant emission change, especially at the regional level. This article used a two-region dynamic CGE model to analyze the effectiveness of carbon cap and ETS policies implemented recently in Guangdong in an integrated scheme. Various policy instruments, namely, renewable development policy, carbon constraint, and carbon emission trading scheme policy are examined and compared. The purpose is to compare the effectiveness and contribution of different instrument(s) to achieve the carbon intensity reduction targets, and more importantly, to disclose the regional co-benefits of CO_2 mitigation polices on local air pollutant emissions.

The paper is structured as follows: the third section describes the CGE model and scenario. In the fourth section, we compare future emission trajectory in different scenarios, and discuss the co-benefits of mitigation policy on air pollutant reduction. Our study concludes in the fifth section.

Methodology

The CGE model

This study uses a dynamic CGE model jointly developed by Guangzhou Institute of Energy Conversion (GIEC) China and National Institute for Environmental Studies (NIES) Japan. The model is a two-region recursive dynamic CGE model that includes Guangdong (GD) Province and the rest of China (ROC). The technical description of the static module is provided in the paper (Wang et al., 2015).

The major model features are similar to the one-region dynamic version (Dai et al., 2012). It includes a production block, a market block with domestic and international transactions, as well as government and household incomes and expenditure blocks (Fig. A1). The main difference of two-region IO table used in this study from the one-region IO table is that in the former, Guangdong Province and the rest of China are linked with each other through inter-provincial trade. For instance, the outflow of certain commodity from the rest of China to Guangdong is equal to the inflow of this commodity from Guangdong to the rest of China. It should be noted that inter-regional flow of labor and investment is not explicitly captured in the current IO table. Other parts of the IO table are the same as one-region table.

The model is comprised of 33 sectors (Table A1) which are classified into basic and energy transformation sectors, and 7 power generation technologies (Table A2). Activity output of each sector follows a nested constant elasticity of substitution (CES) production function. Inputs are categorized into material commodities, energy commodities, land, labor, capital and resource.

The major difference from the one-region model lies in the market block. On the export side, output produced in each region is converted through a constant-elasticity-of-transformation (CET) function into goods destined for own regional, other regional,

Table 5
Embedded trade volume (unit: million tons for CO_2 and kilo tons for SO_2, NO_x).

Year	Object	Power	Refinery	Cement	Iron & steel	Trade volume (Mt/Kt)	Trade price (USD/ton)	Trade value (million USD)
2015	CO_2	9.3	−0.7	−2.0	−6.7	9.4	5.8	54
	SO_2	17.6	0.0	−3.0	−16.7	19.7	255.6	5
	NO_x	26.6	−0.4	−1.4	−9.7	11.5	3194.9	37
2020	CO_2	9.4	−2.5	−14.2	−4.4	21.1	2.6	55
	SO_2	13.2	0.0	−14.5	−9.5	24.0	255.6	6
	NO_x	20.0	−1.2	−7.6	−5.1	13.9	3194.9	44

Table A1
Sector definition in the CGE model.

Nr.			Nr.		
1	AGR	Farming, forestry, animal husbandry and fishery	18	I_S	Iron and steel
2	COA	Mining and washing of coal	19	NFM	Smelting and pressing of nonferrous metals
3	OIL	Extraction of petroleum	20	MPD	Metal products
4	GAS	Extraction of natural gas	21	MCH	Manufacture of machinery
5	OMN	Mining and dressing of other ores	22	ELP	Manufacture of electrical machinery and equipment
6	FOD	Manufacture of food	23	ELE	Production and supply of electric power
7	TEX	Textile industry	24	GDT	Production and supply of gas
8	LUM	Timber processing, bamboo, cane, palm fiber & straw products	25	WTR	Production and supply of water
9	PPP	Papermaking and paper products	26	CNS	Construction
10	OMF	Other manufacturing	27	TRL	Road transport
11	P_C	Petroleum refining	28	TRD	Railway transport
12	COK	Coking	29	TPL	Public transport
13	CRP	Manufacture of raw chemical materials and chemical products	30	TWT	Waterway transport
14	CMT	Cement manufacturing	31	TAR	Air transport
15	ONM	Other nonmetal mineral products	32	TPP	Pipe transport
16	GLS	Glass manufacturing	33	CSS	Services
17	ETW	Ceramic product manufacturing			

and international markets. On the import side, Armington assumption (Armington, 1969) is adopted, whereby goods produced from other provinces and abroad are imperfectly substitutable for domestically produced goods. Labor is assumed to be fully mobile across industries within a region but immobile across regions, whereas vintage capital is assumed to be immobile across either regions or industries.

The model is solved at one-year time step towards 2030 in a recursive dynamic manner, in which the selected parameters, including capital stock, labor force, land, natural resource, energy efficiency improvement (EEI), total factor productivity (TFP), land productivity, and extraction cost of fossil fuels, are updated based on the modeling of inter-temporal behavior and results of previous periods.

Carbon emission trade module

For the purpose of this study carbon emission trade module is added in which cap-and-trade policy could be implemented at sectoral level. As Fig. 1 illustrates, C_1 and C_2 are the demand curves of carbon emission rights of sectors 1 and 2, when emission allowances, Q_1 and Q_2, are allocated to each sector without carbon trading, the CGE model will find equilibrium points, *A* and *B*, with carbon shadow prices of P_1 and P_2 ($P_1 < P_2$) for sectors 1 and 2, respectively. By contrast, when free carbon trading is allowed, a carbon trading market will be formed. Sector 1 tends to purchase ΔQ_1 unit of carbon emission rights from the market while sector 2 tends to sell ΔQ_2 unit of carbon emission rights to the market. The CGE model will find a new equilibrium point, A' and B', with carbon shadow price of P' that clears the carbon market by satisfying the conditions in Eqs. (1) and (2).

Carbon selling amount equal to purchasing amount:

$$\Delta Q_1 = \Delta Q_2. \tag{1}$$

Expenditure of buyers (S_2) equal to revenue of sellers (S_1):

$$\Delta Q_1 P' = \Delta Q_2 P'. \tag{2}$$

Analogously, when more sectors participate in carbon emission trading, the above condition will hold as showed in Eqs. (3) and (4).

$$\sum_s \Delta Q_s = \sum_b \Delta Q_b \tag{3}$$

$$\sum_s \Delta Q_s P' = \sum_b \Delta Q_b P' \tag{4}$$

where:

s and *b*: seller and buyer in carbon trading market, respectively
ΔQ: carbon trading volume in ton
P: carbon shadow price

Data

Basic data in 2007

The data required by the model include input–output table (IOT) (NBS, 2011), energy balance table (EBT) (NBS, 2008), carbon emission factors, energy prices of coal, oil and gas, and cost information of renewable energy technology. All the datasets are converted to the base year of 2007.

Regarding the historical simulation, the CGE model is calibrated to data from the Guangdong Statistical Yearbook 2008–2013. In sum, two kinds of indicators are used in the calibration of model historical simulation from 2008 to 2012. The first one is macroeconomic indicators, including the real GDP, investment, private consumption and population, and the annual growth rates of these indicators have been used in our calibration. The second one is energy consumption and environmental indicator such as CO_2, SO_2 and NO_x emissions, which referred from the China and Guangdong Statistical Yearbook 2008–2013.

This step is crucial since base-year sectoral energy consumption data affect future projection and sectoral carbon abatement cost significantly. Actually, for the historical periods over 2008–2013 we have adjusted the model in terms of GDP and energy consumption. The results showed in the figures (Figs. A2–A3) indicate that the model outputs match statistical data well.

Table A2
The power sector technologies in CGE model.

Number	Sector	Number	Sector
1	Coal power	5	Hydro power
2	Oil power	6	Wind power
3	Gas power	7	Garbage power
4	Nuclear power		

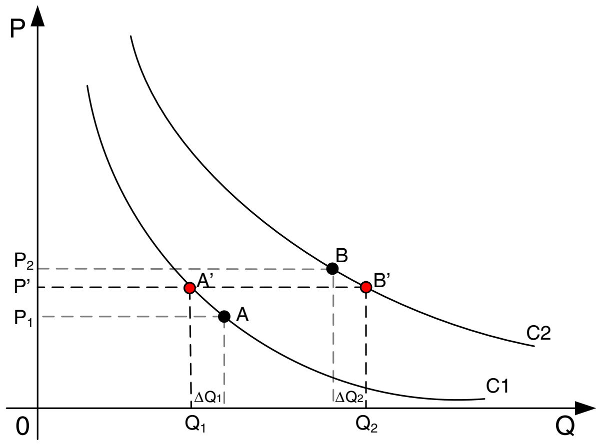

Fig. 1. Mechanism of carbon emission trade between sectors.

Scenario

In total, four scenarios are constructed including one business as usual scenario (BaU), one renewable development scenario (BaU_RE), one carbon limit scenario (SAV) and one carbon cap and emission trading (SAVET) scenario.

The baseline scenario (BaU) assumes population and GDP growth rate based on the 12th FYP before 2015 and assumptions up to 2020 (Table 2). No carbon mitigation policies are considered in the BaU and BaU_RE scenarios. By contrast, other two scenarios are defined according to Guangdong's mitigation target and Copenhagen commitment which requires all sectors to save energy and the four industrial sectors to implement carbon limit and carbon emission trade, respectively. In reality, the emission caps on the four sectors are summation of caps of existing enterprises and future new enterprises.[1] The carbon emission cap of Guangdong's existing enterprises is calculated based on reference method (Eq. (5)) and historical method (Eq. (6)), while that of the new enterprises is set based on reference method (Eq. (7)) and energy consumption method (Eq. (8)):

Reference method for existing enterprises:

$$CAP_{ext,i,t} = Output_{i,ave} * REF_{ext,i} * (1-RED1_{i,t}) \tag{5}$$

Historical method for existing enterprises:

$$CAP_{ext,i,t} = EMS_{i,ave} * (1-RED2_{i,t}) \tag{6}$$

Reference method for new enterprises:

$$CAP_{new,i,t} = Output_{i,new} * REF_{new,i,t} \tag{7}$$

Energy consumption method for new enterprises:

$$CAP_{new,i,t} = ENE_{i,en,t} * EF_{en} \tag{8}$$

where:

$CAP_{ext,i,t}$: emission cap of existing enterprise *i* in the year *t* (unit: mil ton);
$CAP_{new,i,t}$: emission cap of new enterprise *i* in the year *t* (unit: mil ton);
$Output_{ext,i,ave}$: average annual output level of existing enterprise *i* during 2010–12 (unit: bil. yuan);
$Output_{ext,i,ave}$: designed annual output level of new enterprise *i* (unit: bil. yuan);
$EMS_{i,ave}$: average annual emissions of existing enterprise *i* during 2010–12 (unit: bil. yuan);
$REF_{ext,i}$: reference carbon intensity of existing enterprise *i* (unit: mil ton/bil. yuan);
$REF_{new,i,t}$: reference carbon intensity of new enterprise *i* (unit: mil ton/bil. yuan);
$RED1_{i,t}$: annual reduction rate of carbon intensity for existing enterprise *i* and year *t* (unit: %);
$RED2_{i,t}$: annual reduction rate of emission for existing enterprise *i* and year *t* (unit: %);
$ENE_{i,en,t}$: annual consumption of energy *en* for new enterprise *i* (unit: EJ);
EF_{en}: emission factor of energy *en* (unit: mil ton/EJ).

In the BaU_RE scenario the power sector is set in a way that nuclear power generating capacity increases by 6% (compared with 4% in BaU scenario) per year, gas power increases by 9% (6% in BaU), wind power and solar power increase by 22% (9% in BaU), and oil power will be shut down in 2013–2020 (12th FYP of Guangdong Energy Development Plan).

The SAV scenario sets carbon cap on power, cement, iron & steel, and oil refinery sector in line with Guangdong's energy and carbon intensity reduction targets. The overall energy intensity of

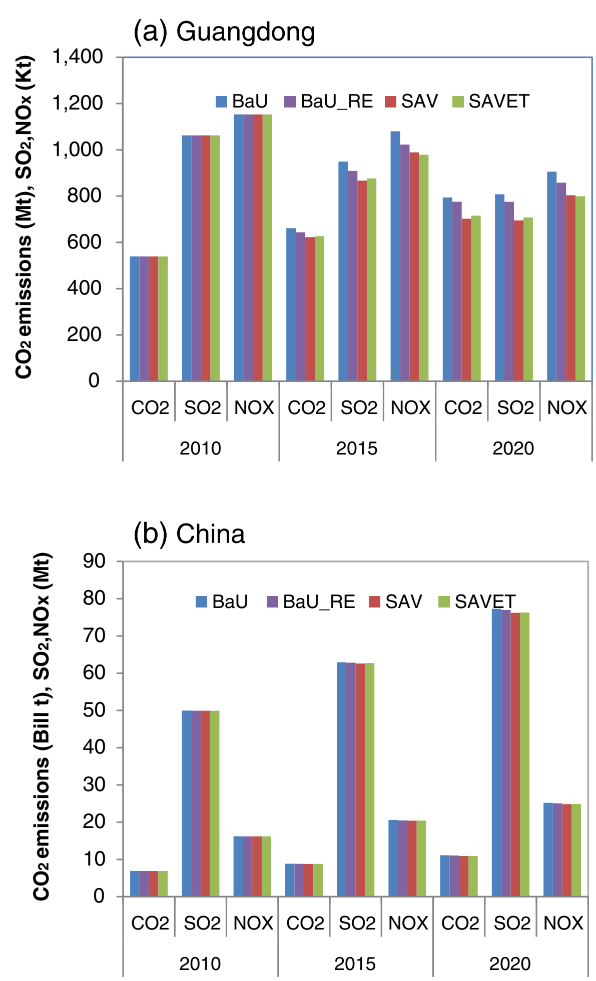

Fig. 2. The total emission trajectory of CO_2, SO_2 and NO_x in Guangdong (a) and China (b).

[1] The Guangdong government has established a carbon cap allocation method for the four sectors, see: http://www.gddpc.gov.cn/xxgk/tztg/201311/t20131126_230325.htm. Retrieved on 24th June 2014.

Guangdong Province will reduce by 18% from 2010 to 2015, which reflects the official 12th FYP of Guangdong government. Emissions of power sector could increase by 0.3% per year, oil refinery sector could increase by 2% per year, cement sector could increase by 1% per year, and iron and steel sector could increase by 6% per year over 2013–15 (Table 3). From 2015 to 2020, energy intensity of Guangdong further reduces by 18%, and emissions of power sector could only increase by 0.1% per year, oil refinery sector could increase by 2% per year, cement sector could increase by 1% per year, whereas iron and steel sector could increase by 5% per year. The carbon cap is sufficient to achieve the Copenhagen commitment of reducing carbon intensity by 45% in 2020 compared with 2005.

Scenario SAV does not allow emission trading, while scenario SAVET allows emission trading but is similar to SAV in all other aspects.

Simulation results

Total CO_2, SO_2 and NO_x emission trends

The model simulation results show that the total CO_2 emission will keep increasing 1.5 times from 2010 to 2020 in the BaU scenario and CO_2 emissions of Guangdong share in China will decrease from 8% in 2010 to around 7% in 2020, reflecting the trend that China's CO_2 emissions increase 1.6 times over the same period (Fig. 2).

On the other hand, under the BaU scenario, the SO_2 and NO_x emissions in 2020 will be 0.76 and 0.79 times of that from 2010. Then the SO_2 and NO_x of Guangdong Province in 2015 will decrease by 11% and 6% compared to 2010, but this is not sufficient to achieve the SO_2 and NO_x reduction targets specified in the 12th FYP (14.8% and 16.9% reduction from 2010 to 2015).

Therefore, additional climate policy is needed to be considered. The results also show that when the renewable development policy, carbon caps and ETS policy are implemented in the SAV and SAVET scenarios, the CO_2 emissions in 2020 will increase 1.44, 1.30 and 1.33 times compared with 2010 level in BaU_RE, SAV and SAVET scenarios, respectively, and the corresponding SO_2 (NO_x) emissions would be 0.73 (0.74), 0.65 (0.70), and 0.67 (0.69) times from the 2010 level, implying that carbon mitigation policy would bring slower growth in air pollutant emissions.

Accordingly, the SO_2 and NO_x emissions will decrease 14%, 18%, 17% and 11%, 14%, 15% from 2015 to 2010 level. Compared with the reduction target set by government of 14.8% for SO_2 and 16.9% for NO_x emissions below the 2010 levels by 2015, it is found that the abatement target of SO_2 emissions will be completed with the help of the climate policy, but the NO_x emission reduction target can't be completed under the carbon cap policy. In addition, from 2010 to 2020, the SO_2 emission will decrease at a higher rate than the NO_x emissions.

Policy instrument to achieve the target

Three policy scenarios are simulated to investigate their effects of reducing carbon intensity. Fig. 3a shows that although the CO_2 emission increases yearly under all scenarios from 2010 to 2020, yet

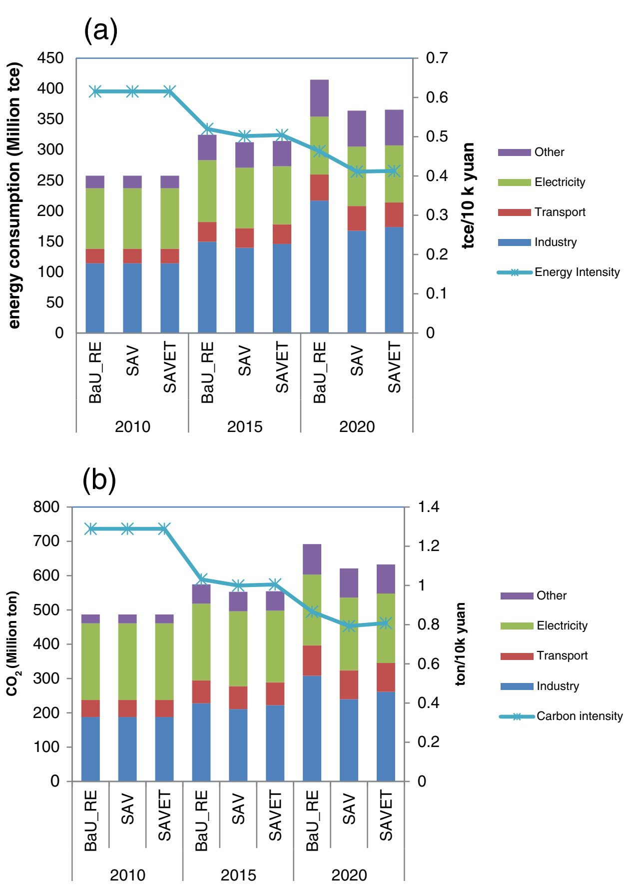

Fig. 3. (a) Trend of sector energy consumption (bar) and energy intensity (line) and (b) carbon emissions (bar) and carbon intensity (line) of Guangdong over 2010–2020.

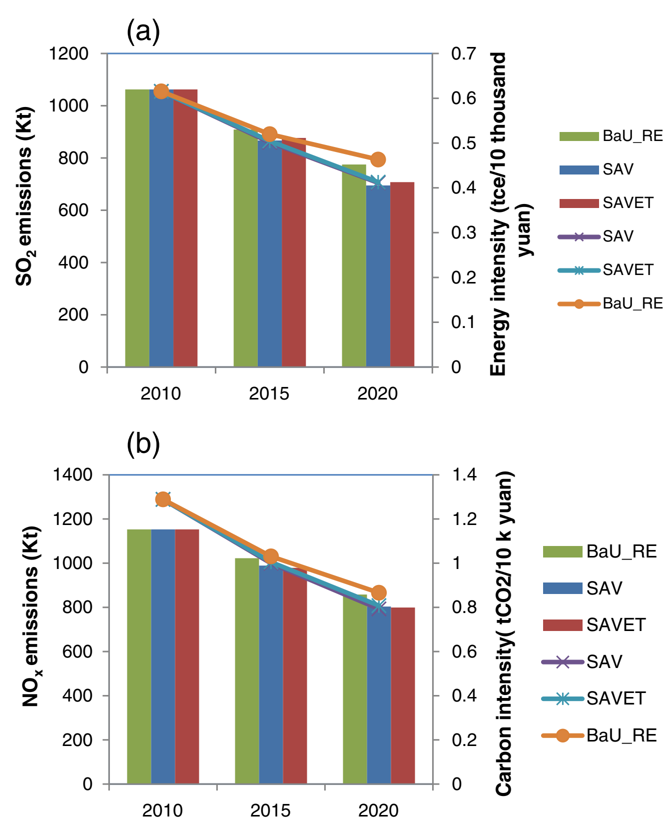

Fig. 4. The trend of SO_2 (a) and NO_x (b) emissions (bar) and energy intensity (line) in 2010–2020.

under the SAV scenario, CO_2 emissions are slightly lower than other scenarios. The carbon intensity reduction in SAV scenario is 33% from 2010 to 2020, which is higher than the BaU_RE (24.7%) and SAVET (32.9%) scenarios over the same period. In addition, the carbon intensity reduces by 38%, 44% and 45% from 2005 to 2020 in BaU_RE, SAVET and SAV scenarios, respectively. This indicates that the Guangdong's carbon intensity reduction target cannot be achieved by developing renewable energy alone without additional carbon cap.

The results of sectoral energy consumption (Fig. 3b) reveal that over the periods of 2010–2020 in the SAV scenario, the share of energy consumption by power sector would reduce from 38% to 27%, whereas that of other sectors would increase, for example, industry sector would increase from 44% to 46%, transport sector from 9% to 11% and all other sectors from 8% to 16%. The reason for this trend is greater use of non-fossil energy. Development of nuclear power and renewable energy helps to substitute the coal use and improve the energy efficiency of the power sector. At the same time the demand growth in service and residential sectors leads to increase in energy consumption in other sectors.

Co-benefit of local air pollutant reduction

Fig. 4 shows the SO_2 and NO_x emissions under the SAV and SAVET scenarios. Similar to the carbon intensity reduction in the SAV scenario, the SO_2 and NO_x emissions in the SAVET scenario are lower than BaU_RE scenario.

The SO_2 emissions in 2020 under the BaU_RE scenario are predicted to be 775,000 tons, and in the SAV scenario it will reduce to 695,000 tons, equivalent to a reduction rate of 12%. Under the SAVET scenario with ETS policy, the reduction rate will be 9%. The level of SO_2 emission reduction between scenario is consistent with the change along the time serials.

As a consequence of carbon intensity decreasing by 33% from 2010 to 2020, the SO_2 and NO_x emissions would decrease by 33% and 31% in the SAVET scenario and by 35% and 30% in the SAV scenario.

Generally speaking, the results show that there are correlation and co-benefit between the carbon reduction policy and pollutant emission reduction. Comparing SAV with BaU_RE in Table 4, the annual emissions of CO_2, SO_2 and NO_x in 2020 will be reduced by 621 million tons, 614,000 tons and 722,000 tons, equivalent to reduction rates of 10.2%, 11.3% and 6.7%, respectively. Moreover, Under the SAVET scenario, the annual CO_2, SO_2 and NO_x emissions in 2020 will be reduced by 633 million tons, 625,000 tons and 716,000 tons compared with BAU_RE scenario, equivalent to abatement rates of 8.6%, 9.7% and 7.5%, respectively. In summary, the carbon mitigation policy in the SAV and SAVET scenarios can effectively help to achieve the SO_2 and NO_x reduction targets in 2015.

Interestingly, it is also found that the effect of carbon cap policy on SO_2 emission reduction is slightly stronger than ETS policy. On the contrary, the effect of ETS policy on NO_x emission reduction is more effective than carbon cap policy (SAV). The reason is investigated in the next section.

Reduction in SO_2 and NO_X emissions of ETS participating sectors

For further investigating the emission reduction imposed by ETS participating sectors, the SO_2 and NO_x emissions from fours sectors are showed in Fig. 5.

In Fig. 5, it could be seen that when the carbon emissions decrease 10% in the SAVET scenario, the SO_2 emission would reduce by 12% compared with BaU scenario. On the other hand, the reduction rate of NO_x emissions would be 13.3%.

Although the demand of power and industrial products would be very strong in the last decades, the reduction of SO_2 and NO_x emissions would be achieved mostly by end-of-the-pipe equipments. The most reduction contribution would be attributed to the desulfuration device

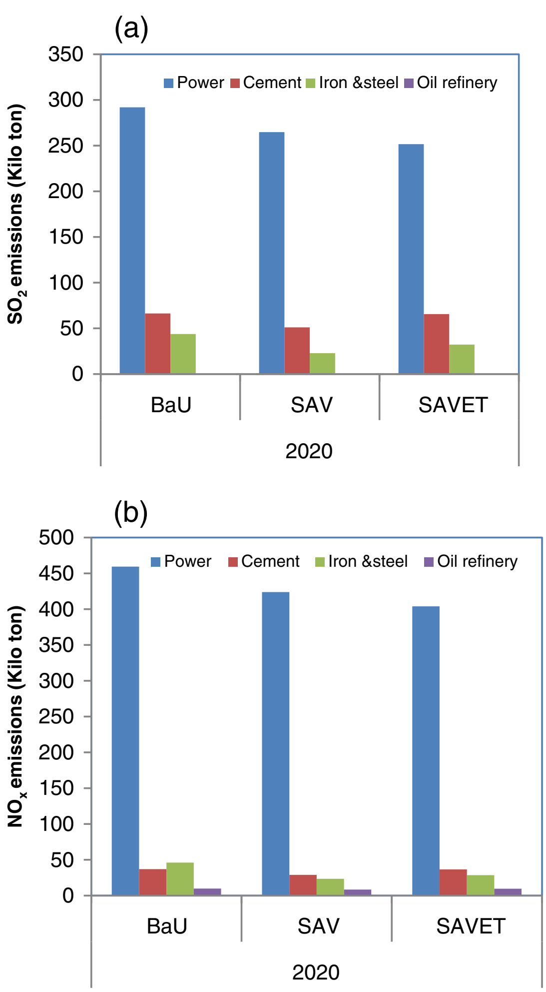

Fig. 5. The SO_2 (a) and NO_x (b) emissions of three scenarios in the carbon limit sector.

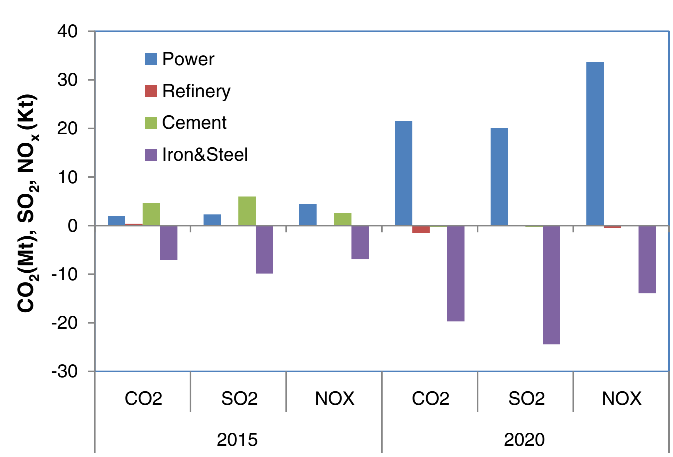

Fig. 6. Trade volume in four emission trading sector (negative value means purchasing emission credit whereas positive value means selling).

installed in the all newly-built and most existing power plants, iron and steel plants, and cement plants.

Undoubtedly, in the next five years, the total amount of carbon control policy will affect the room of industry development from the macro level. Hence, it is reasonable that the related reduction of CO_2, SO_2 and NO_x emissions comes from the four ETS participating sectors, whereas other sectors contribute little to carbon reduction.

Embedded flow of air pollutant

Following the emission trading of CO_2 in the obligated four ETS participating sectors in Guangdong, the embedded emissions of air pollutant are traded at the same time. From Fig. 6 it could be seen that in the SAVET scenario, power sector could be the seller and iron & steel could be the buyer in 2013–2020, refinery and cement could be sellers before 2015 and will change to be buyer in 2016–2020 as the different sectors faced the different CAP.

As a result of the 21 million tons trading volume of carbon allowances in ETS, an embedded trading volume of 24,000 tons SO_2 and 13,900 tons NO_x air pollutants is created in 2020. According to the trade price in the current Guangdong emission pollutant market, the SO_2 price is 1600 yuan/ton and the NO_x price is 20,00 yuan/ton in Guangdong Province that refer to the pollution charges (GAET in reference). This implies that, with ETS implemented a carbon market of around 55 million USD in 2020 would bring some extra 50 million USD of air pollutant trading volume (Table 5).

Negative value means purchasing emission credit whereas positive value means selling. The price of SO_2 and NO_x is pricing by government in realistic case as reference.

Welfare cost of carbon mitigation

Through the implementation of the carbon emission trading (ETS) policy in Guangdong, it is efficient for SAV and SAVET scenarios to achieve carbon and energy intensity targets. However, carbon mitigation will lead to negative impact on the macroeconomic GDP of Guangdong since it needs to pay additional cost to promote the energy structure change, coal substitution, technology upgrade and new capital investment compared with the conventional development pathway in the BaU scenarios. As Table 6 reveals, GDP loss of the SAV scenario in 2020 will reach 1.08% compared with BaU scenario, and it will cause economic impact on the rest of China as well. Nevertheless, it also reveals that the welfare loss would be alleviated through the implementation of ETS, the GDP loss in the SAVET scenario is 0.03% less, equivalent to 427 million USD dollar.

Discussions

Recently, the trading market of SO_2 and chemical oxygen demand (COD) emission allowances in Guangdong is also being built, which will involve more than 900 enterprises into the market. The involved companies are similar to the carbon ETS participating sectors as simulated in our study, namely from the sector of power, petrochemical, iron and steel, cement and other industrial enterprises.

ETS could promote the enterprises to choose a cost-effective way to realize the emission reduction, which is more efficient than the non-market pollution control policies based on the government command. Through the communication and cooperation between the government and the enterprises, the companies can make the emission reduction behavior together in the business operation, which can improve the management capacity and reach a minimum cost of implementation of pollutant emission reduction in the whole society. Finally, with implementation of the emission trading markets, the external costs would be internalized.

In addition to the co-benefits of reducing air pollutant, ETS can inspire the enterprises to upgrade the emission reduction technology and equipment, and reduce the government's administrative costs and subsidies burden.

Especially, ETS policy would incentive the enterprises to invest new technologies and form the new low carbon industries, except the industrial upgrading of the economy itself. The future new industries are implicitly captured in the CGE model. In the case of new industries related to solar PV, since power generation technologies are explicitly represented, development of solar PV power generation requires huge investment in this sector, which in return drives the upstream industry chain related to solar PV. This kind of co-benefits in various terms needs to be considered in the policy making process.

Conclusions

This study estimates the impacts of carbon emission trading scheme (ETS) policy on air pollutant emission reduction in Guangdong (GD) Province, especially with respect to the embedded air pollutant emission flow caused by carbon ETS. A Computable General Equilibrium (CGE) model is constructed to project the local emission trajectory of CO_2 and air pollutants under business as-usual (BaU) and policy scenarios in GD province and the rest of China from 2007 to 2020. To achieve the energy and carbon intensity targets, the carbon constraint and ETS policy are employed to promote energy saving and CO_2 emission reduction. The simulation results reveal that in the BaU scenario, the emissions of SO_2 and NO_x in 2020 would be 0.81, 0.91 million ton, respectively. Air pollutants are mainly emitted from industry, power generation and transport sectors.

The policy instruments implemented in the BaU_RE, SAV, and SAVET scenarios can all help to reduce the energy and carbon intensities, and bring co-benefits of reducing local air pollutants. Among these policy instruments, carbon cap and ETS are the two most promising instruments for achieving Guangdong's energy and carbon intensity targets that are in line with Copenhagen commitment.

The results also indicate that the ETS policy would bring benefits of reducing SO_2 and NO_x emissions in 2020 by 33% and 31% from 2010 level. Furthermore, with ETS implemented in SAVET scenario, there is an embedded trade amount of 38,000 tons of air pollutants. When creating a carbon market of around 55 million USD in 2020, it brings some extra 50 million USD air pollutant trading volume.

Although the ETS policy brings extra benefits for air pollutant reduction, it still will cause the gross domestic production (GDP) loss to be 1.05%, or about 15 billion USD due to carbon emission cap. However, this loss is lower than that the scenario without ETS. The abatement rate of SO_2 in the model is higher than the NO_x. With implementation of new standard of controlling air pollutant and with the help of carbon mitigation policy, the SO_2 emission reduction target could be achieved, but the NO_x target will not. It implies that more stringent policy is needed for cutting NO_x emissions. Based on the assessment of co-benefits in terms of reduction in air pollutant and reducing mitigation cost, this analysis indicates that evaluation of the co-benefits of carbon mitigation policy needs to be considered in the policy making process.

Acknowledgments

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Appendix A

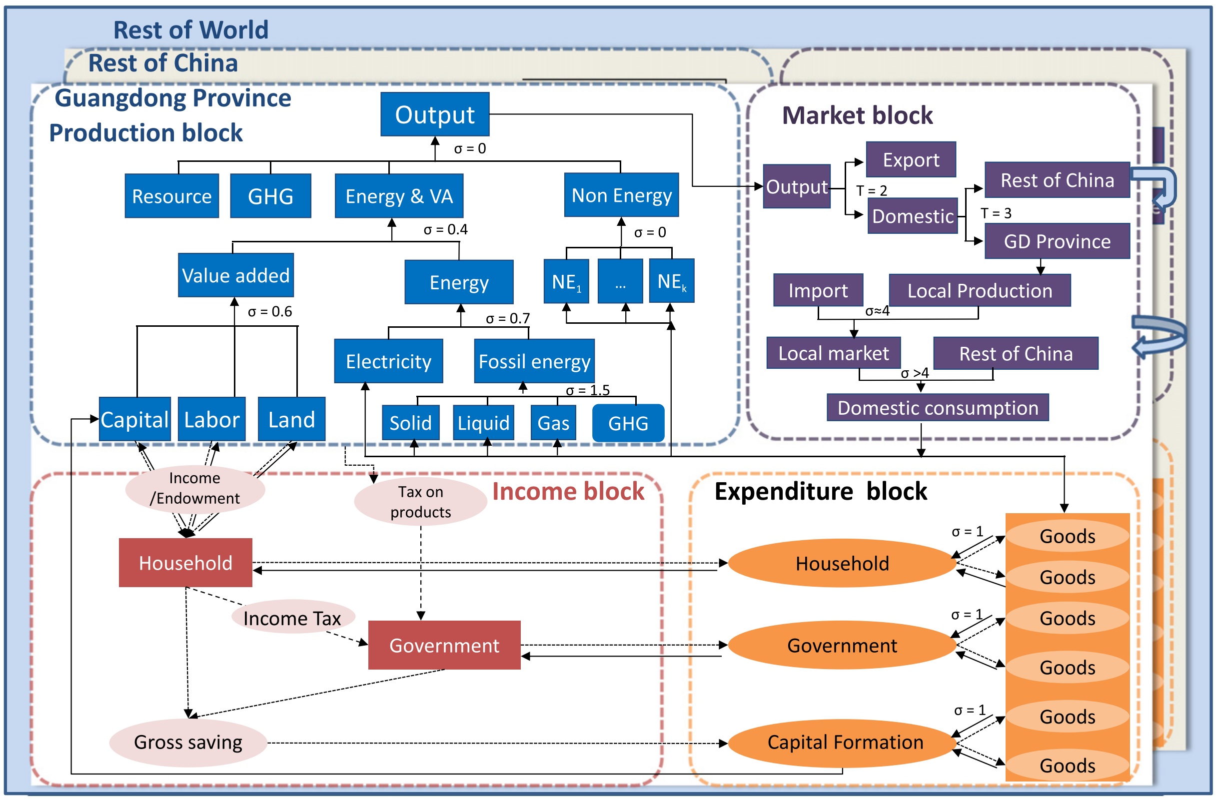

Fig. A1. The structure of two-region GD_CGE model for Guangdong Province (solid arrow: physical flow; dashed arrow: monetary flow).

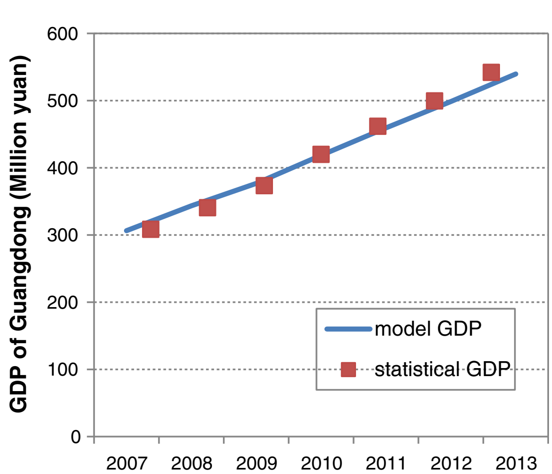

Fig. A2. The comparison of model GDP with statistical data.

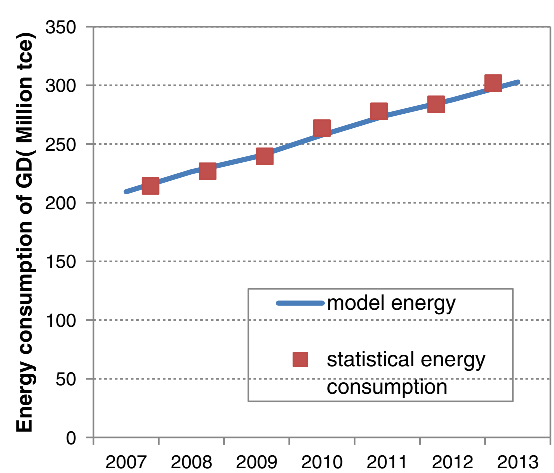

Fig. A3. The comparison of model energy consumption with statistical data.

The appendix provides a technical description of the CGE model based on Dai (2012) and Wang et al. (2015).

A. Production

Each producer maximizes profit subject to the production technology. Activity output of each sector follows a nested constant elasticity of substitution (CES) production function. Each sector has two types of production function; one uses the existing capital stock, and another uses new investment (Masui et al., 2011). The difference between these two subsectors is the efficiency and mobility of capital among the sectors. Inputs are categorized into material commodities, energy commodities, land, labor, capital and resource. The producer maximizes its profit by choosing its output level and input use, depending on their relative prices subject to its technology. The producer's problem can be expressed as:

$$\max\pi_{r,j} = p_{r,j}\cdot Z_{r,j} - \left(\sum_{i=1}^{N} p_{r,j}\cdot X_{r,i,j} + \sum_{i=1}^{N}\omega_{r,j}\cdot V_{r,f,j}\right) \qquad (A-1)$$

Subject to:

$$Z_{r,j} = \upsilon_{r,j}\left[X_{r,1,j}, X_{r,2,j}, \ldots, X_{r,N,j};\ \ V_{r,F,j}, \ldots, V_{r,F,j}\right] \qquad (A-2)$$

where

$\pi_{r,j}$ profit of j-th producers in region r,
$Z_{r,j}$ output of j-th sector in region r,
$X_{r,i,j}$ intermediate inputs of i-th goods in j-th sector in region r,
$V_{r,f,j}$ f-th primary factor inputs in j-th sector in region r,
$p_{r,j}$ price of the j-th composite commodity,
$\omega_{r,j}$ f-th factor price in region r,
$\upsilon_{r,j}$ share parameter in the CES production function.

B. Household consumption

Household and government are final consumers. The representative household endows primary factors to the firms and receives income from the rental of primary factors (labor and capital), rents from fixed factors (land and natural resources) and lump-sum transfer from the government (e.g. carbon tax revenue of government). The income is then used for either investment or final consumption. The objective of household consumption is to maximize utility by choosing levels of goods consumption following Cobb–Douglas preferences, subject to commodity prices and budget constraint. The agent's problem is expressed as:

$$\max\ u_{r,h}\left[X^p_{r,1}, \ldots, x^p_{r,i}\right] = A^p_r \cdot \coprod_{i=1}^{N}\left(X^p_{r,i}\right)^{a^p_{r,i}} \qquad (B-1)$$

s.t

$$EH_r = \sum_i p^q_{r,j}\cdot X^p_{r,i} = \sum_{f=1}^{F}\omega_{r,f} + \sum_j pld_r\cdot QLAND_{r,j} + \sum_{res,j} p^{res}_{r,j}\cdot QRES_{r,j} + T^{cab}_r - T^d_r - S^p_r \qquad (B-2)$$

$$T^{cab}_r = pghg_{r,\text{"}CO2\text{"}}\cdot TEMS_{r,\text{"}CO2\text{"}} \qquad (B-3)$$

$$T^d_r = \tau^d_r \cdot \sum_f \omega_{r,f}\cdot V_{r,f} \qquad (B-4)$$

$$S^p_r = sr^p_r \cdot \sum_f \omega_{r,f}\cdot V_{r,f} \qquad (B-5)$$

where

$u_{r,h}$ utility function of households,
EH_r household expenditure,
$X^p_{r,1}$ household consumption of i-th commodity,
$V_{r,f}$ f[th] primary factor endowment by household,
S^p_r household savings,
$TEMS_r$, "$CO2$" CO_2 emissions in region r,
$pghg_r$, "$CO2$" carbon price,
T^d_r direct tax,
τ^d_r direct tax rate,
sr^p_r average propensity to save by the household,
$\omega_{r,f}$ price of the f-th primary factor,
A^p_r scaling parameter in Cobb–Douglas function,
$a^p_{r,i}$ share parameter in Cobb–Douglas function, $0 \le \alpha^p_{r,i} \le 1$, $\sum_i \alpha^p_{r,i} = 1$.

C. Government

The government is assumed to collect taxes, including direct tax on household income, ad valorem production tax (indirect tax) on gross domestic output, ad valorem import tariff on imports and carbon tax. Based on a Cobb–Douglas demand function (Hertel and Tsigas, 2004), the government spends its revenue on public services which are provided to the whole society and on the goods and services which are provided to the households free of charge or at low prices (NBS, 2006). The model assumes that the revenue from carbon tax is recycled to the representative agent as a lump-sum transfer.

$$\max\ u_{r,g}\left[x^g_{r,1}, \ldots, x^g_{r,i}\right] = A^g_r \cdot \prod_{i=1}^{N}\left(x^g_{r,i}\right)^{a^g_{r,i}} \qquad (C-1)$$

s.t.

$$\sum_i p_{r,i}\cdot x^g_{r,i} = T^d_r + \sum_j T^z_{r,j} + \sum_j T^m_{r,j} - S^g \qquad (C-2)$$

$$T^z_{r,j} = \tau^z_{r,j}\cdot p_{r,j}\cdot Z_{r,j} \qquad (C-3)$$

$$T^m_{r,i} = \tau^z_{r,i}\cdot pm_{r,i}\cdot M_{r,i} \qquad (C-4)$$

$$S^g_r = sr^g_r\cdot\left(T^d_r + \sum_j T^z_{r,j} + \sum_j T^m_{r,j}\right) \qquad (C-5)$$

where

$u_{r,g}$ utility function of government,
$x^g_{r,i}$ government consumption of i-th commodity,
S^g_r government savings,
$T^z_{r,j}$ production tax on the j-th commodity,
$T^m_{r,j}$ import tariff on the j-th commodity,
$\tau^z_{r,j}$ production tax rate on the j-th commodity,
$\tau^m_{r,i}$ import tariff rate on the i-th commodity,
sr^g_r average propensity to save by the government,
$Z_{r,j}$ gross domestic output of the j-th commodity,
$M_{r,j}$ import of the i-th commodity,
$pm_{r,i}$ price of the i-th imported commodity,
A^g_r scaling parameter in Cobb–Douglas function,
$a^g_{r,i}$ share parameter in Cobb–Douglas function, $0 \le \alpha^g_{r,i} \le 1$, $\sum_i \alpha^g_{r,i} = 1$.

D. Investment and savings

Investment is an important part of final demand. In the CGE model a virtual agent is assumed for investment which receives all the savings from the household, government and the external sector to purchase goods for domestic investment. The virtual investment agent is assumed to maximize the utility based on a Cobb–Douglas demand function subject to its (virtual) income constraint. Mathematically, the investment problems can be described as follows:

$$\max\ u_{r,v}\left[x^v_{r,1}, \ldots, x^v_{r,i}\right] = A^v_r \cdot \coprod_{i=1}^{N}\left(x^v_{r,i}\right)^{a^v_{r,i}} \qquad (D-1)$$

s.t.

$$\sum_i p_{r,i} \cdot x^v_{r,i} = S^p_r + S^g_r + \varepsilon \cdot S^f_r \quad (D-2)$$

where

$u_{r,v}$ utility of virtual investment agent,
S^f_r current account deficits in foreign currency terms (or alternatively foreign savings),
ε foreign exchange rate,
$x^v_{r,i}$ demand for the i-th investment goods,
A^v_r scaling parameter in Cobb–Douglas function,
$a^v_{r,i}$ share parameter in Cobb–Douglas function, $0 \le \alpha_{r,i}^{v} \le 1$, $\sum_i \alpha^v_{r,i} = 1$.

E. International transaction

The model is an open economy model that includes interaction of commodity trade with the rest of the world. Like most other country CGE models, this model assumes the small open economy, meaning that an economy is small enough for its policies not to alter world prices or incomes. The implicit implication of small-country assumption is that export and import prices are exogenously given for the economy. In this study, future international prices are fixed to be the same level for non-energy commodities whereas increase by 3% yearly for energy commodities compared to the 2005 level. Two types of price variables are distinguished. One is prices in terms of the domestic currency p^e_i and p^m_i; the other is prices in terms of the foreign currency p^{We}_i and p^{Wm}_i. They are linked with each other as follows:

$$p^e_i = \varepsilon \cdot p^{We}_i \quad (E-1)$$

$$p^m_i = \varepsilon \cdot p^{Wm}_i. \quad (E-2)$$

Furthermore, it is assumed that the economy faces balance of payment constraints, which is described with export and import prices in foreign currency terms:

$$\sum_i p^{We}_i \cdot E_{r,i} + S^f_r = \sum_i p^{Wm}_i \cdot M_i \quad (E-3)$$

where

$E_{r,i}$ export of i-th commodity in region r,
$M_{r,i}$ import of i-th commodity in region r,
p^{We}_i export price in terms of foreign currency,
p^e_i export price in terms of domestic currency,
p^{Wm}_i import price in terms of foreign currency,
p^m_i import price in terms of domestic currency.

F. Inter-provincial trade

An important feature of this model is that it is a two-region country model in which inter-provincial trade is treated. Similar to the case of international trade, Armington assumption is adopted to distinguish between locally produced commodity and commodity produced by firms in other provinces, and CES and CET functions are employed to describe commodity inflow from and outflow to all provinces, respectively.

Substitution commodity between local market and inflow from other provinces

This section describes the top-level nesting of inter-provincial inflow of commodity. By this stage the commodity in the local market is an aggregation of locally produced and imported goods, which needs to be further aggregated with goods produced in other provinces to form the final Armington composite goods to be consumed by final consumers and firms. The treatment is similar to import:

$$\text{Max } \pi^{dd}_{r,i} = p^a_{r,i} \cdot Q^{dd}_{r,i} - \left[p^{md}_{r,i} \cdot Q^{md}_{r,i} + \sum_{rr} p^{inf}_{rr,i} \cdot D^{inf}_{rr,r,i}\right] \quad (F-1)$$

s.t.

$$Q^{dd}_{r,i} = \alpha^{dd}_{r,i} \cdot \left(\delta^{md}_{r,i} \cdot Q^{md}_{r,i}{}^{-\rho^{dd}_{r,i}} + \sum_{rr} \delta^{inf}_{rr,r,i} \cdot D^{inf}_{rr,r,i}{}^{-\rho^{dd}_{r,i}}\right)^{-\frac{1}{\rho^{dd}_{r,i}}} \quad (F-2)$$

where

$\pi^{dd}_{r,i}$ profit of the firm producing the i-th Armington composite goods of local market and inflow from other provinces,
$Q^{dd}_{r,i}$ Armington composite goods,
$D^{inf}_{rr,r,i}$ the i-th goods inflowing from region rr to region r,
$p^{\alpha}_{r,i}$ Armington price taken by the final consumers and firms,
$p^{inf}_{rr,i}$ price of the i-th goods inflowing from province rr to region r,
$\alpha^{dd}_{r,i}$ shift (or efficiency) parameter in the Armington composite goods production function,
$\delta^{md}_{r,i}$, $\delta^{inf}_{rr,r,j}$ input share parameters in the Armington composite goods production function ($0 \le \delta^{md}_{r,i} \le 1$, $0 \le \delta^{inf}_{rr,r,j} \le 1$, $\delta^{md}_{r,i} + \sum_{rr}\delta^{inf}_{rr,r,i} = 1$).
$\rho^{dd}_{r,i}$ the CES substitution parameter, in which the elasticity of substitution between imported and domestic goods, σ, equals $\frac{1}{1+\rho}$.

Transformation between goods sold in local market and outflowing to other provinces

Goods supplied to the domestic market, $D^s_{r,i}$, will be further distributed to local market and market in other provinces through, similar to the treatment of export, a CET function as follows:

$$\text{Max } \pi^{pp}_{r,i} = \left(p^d_i \cdot D^{local}_{r,i} + \sum_{rr} \rho^{out}_{rr,i} \cdot D^{out}_{r,rr,i}\right) - p^{dd}_{r,i} \cdot D^s_{r,i} \quad (F-3)$$

s.t.

$$Q^{pp}_{r,i} = \alpha^{pp}_{r,i} \cdot \left(\delta^{local}_{r,i} \cdot D^{local}_{r,i}{}^{\rho^{pp}_{r,i}} + \sum_{rr} \delta^{out}_{r,rr,i} \cdot D^{out}_{r,rr,i}{}^{\rho^{pp}_{r,i}}\right)^{\frac{1}{\rho^{pp}_{r,i}}} \quad (F-4)$$

where

$\pi^{pp}_{r,i}$ profit of the firm engaged in the i-th transformation,
$Q^{pp}_{r,i}$ out of the i-th goods supplied to local and other provinces' markets,
$D^{local}_{r,i}$ i-th goods supplied to local market,
$D^{out}_{r,rr,i}$ i-th goods outflowing from region r to other province rr,
$p^{out}_{rr,i}$ price of the i-th goods outflowing to other province rr,
$\alpha^{pp}_{r,i}$ shift (or efficiency) parameter in the transformation function,
$\delta^{local}_{r,i}$, $\delta^{out}_{r,rr,i}$ share parameters in the transformation function ($0 \le \delta^{local}_{r,i} \le 1$, $0 \le \delta^{out}_{r,rr,j} \le 1$, $\delta^{local}_{r,i} + \sum_{rr}\delta^{out}_{r,rr,i} = 1$).
$\rho^{pp}_{r,i}$ transformation elasticity parameter, in which the elasticity of substitution between imported and domestic goods, σ, equals $\frac{1}{\rho-1}$.

G. Market clearance conditions

The above sections describe the behavior of economic agents such as the households, firms, government, investment agents and the interactions with other provinces and the rest of the world. The final step is to impose the market-clearing conditions to all commodities and factor markets as follows:

$$Q_{r,i} = x^p_{r,i} + x^g_{r,i} + x^v_{r,i} + \sum_j x_{r,i,j} \quad (G-1)$$

$$\sum_j v_{r,f,j} = V_{r,f}. \quad (G-2)$$

H. Macro closure

In a CGE model, the issue of macro closure is the choice of exogenous variables among all variables in the model, mainly including investment and saving macro closure, and current account balance macro closure. In this model, investment is exogenously assumed. In addition, foreign exchange rate is fixed and thus balanced of payment is an endogenous variable.

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