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Ishikawa, Masanobu
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Economic and environmental impact analysis of carbon tariffs on Chinese exports

Yanli Dong*, Masanobu Ishikawa, Taiji Hagiwara

Graduate School of Economics, Kobe University, Japan

*Corresponding author: Yanli Dong

Postal address: Graduate School of Economics, Kobe University

2-1 Rokkodai-cho, Nada-ku,

Kobe, 657-8501, JAPAN

Tel/Fax: +81-78-803-7247

E-mail address: dongyanli2005@hotmail.com (Yanli Dong)

[Abstract] As an alternative measure for the proposal of border tax adjustments (BTAs) advocated by the countries that seek to abate CO_2 emissions (hereafter referred to as 'abating countries'), export carbon tax (ECT) voluntarily conducted by the developing countries has been widely discussed in recent years. This paper uses the multi-regional and multi-commodity computable general equilibrium (CGE) model and the GTAP8.1 database to investigate the economic and environmental effects of carbon tariffs on Chinese exports. The following three policy scenarios are considered: 1) The abating countries implement cap-and-trade emission programs without BTAs; 2) The unilaterally abating countries levy import tariffs and export subsidies on non-abating countries; and, 3) The abating countries implement unilateral climate policies combined with ECT imposed by China. The ECT policy of China is evaluated with a carbon price set at 17 US$/t-$CO_2$. Results illustrate that the ECT voluntarily implemented by China is ineffective in reducing its domestic CO_2 emissions. Moreover, ECT merely has a minor impact on global emissions. Finally, the competitiveness of China's energy-intensive and trade-exposed (EITE) industries suffers substantial losses if export tariffs are imposed. However, China's gains in terms of welfare and gross domestic product (GDP) would be slightly improved if an ECT policy is implemented, compared to the scenario where China is subjected to BTAs levied by the abating coalition. In the light of the tradeoff between tariff revenue for welfare and competiveness losses of the EITE industries, it is therefore difficult to conclude that carbon tariff on Chinese exports is an alternative policy to BTAs.

Key words: CGE, border tax adjustments, carbon leakage, China

1. Introduction

In recent years, two interrelated problems, carbon leakage and international competitiveness, have become central concerns in the domestic discussions in the major developed countries implementing or proposing to implement unilateral emissions abating policies. To address these issues, a number of academic studies as well as political debate have proposed the use of border tax adjustments (BTAs) (Winchester, 2011; Böhringer et al., 2012b; Antimiani et al., 2013). BTAs could take several forms, such as taxing imports from unregulated countries based on carbon intensities, or requiring importers to surrender emission allowances under domestic emission trading schemes, or rebating the emission payments for exports to unregulated regions (Böhringer et al., 2012; Asselt and Brewer, 2010). In the European Union (EU), the European parliament and the council adopted Directive 2009/29/EC on the revision of the EU emission trading scheme (EU-ETS) in phase Ⅲ in April 2009, which contained several provisions for limiting carbon leakage in EITE sectors. The Directive stipulates that sectors deemed to be exposed to carbon leakage can receive free allocation of allowances. It also allows for some forms of border carbon adjustments to support certain EITE industries, which are identified as being exposed to a significant risk of carbon leakage. Nevertheless, although the revised Directive includes a notion of comparability of mitigation efforts, it does not specify how this comparability is to be determined (European Commission, 2009). Similar proposals are also being discussed in the United States (U.S.). The Waxman-Markey-Bill (H.R.2454) was approved by the House of Representatives in 2009 but it was later defeated in the Senate. The bill includes some provisions on border tariffs for the carbon-intensive products from countries without comparable actions to reduce emissions. However, much like the EU, it does not include a definition of comparable action either. Instead, the bill follows the basic logic from other bills by including the following standards for tariff exemption: 1) a country has an economy-wide emission cap at least as stringent as that of the U.S.; 2) there is a sectoral bilateral or multilateral agreement with the U.S.; or, 3) it has a lower sectoral energy or greenhouse gas intensity than the U.S. (Asselt and Brewer, 2010). The debate on trade-based anti-leakage measures has been echoed by the other abating countries, such as Australia, New Zealand and Canada (Marcu et al, 2013). The motivation behind adopting BTAs by the regulating countries is to induce the major emitting developing countries, especially China and India, to participate in the future climate regime. While BTAs have theoretical appeal on global efficiency grounds, their induced distributional impacts have attracted controversy. BTAs initiated by developed countries are criticized to shift the economic burden of carbon emission reduction from the abating countries to the unregulated countries (Böhringer et al., 2012b).

China has overtaken the U.S. to become the largest emitter of greenhouse gases (GHG) since 2007, yet it is not subject to the quantified emission limitation and reduction commitment under the current international climate framework. Both the international debate on BTAs and their domestic problems relating to environmental and energy security exert pressure on China to take action to reduce emissions (Li et al., 2012). In 2009, the Chinese government pledged to achieve its national target on climate change, which includes a reduction of the intensity of CO_2 emissions per unit of GDP by 40~45% by 2020, compared to the 2005 level. In addition, since 2011, China has initiated carbon-trading pilots in seven provinces and cities. However, unlike most existing 'absolute' cap-and-trading emissions systems, the target adopted by China is a carbon intensity-based one. Moreover, there is lack of market-based instruments for the enforcement of ETS in China. Consequently, it is still unclear whether the total carbon emissions of China will be reduced or not (Han et al., 2012). Since exports have become a major contributor to economic growth of China in recent years (Shan and Sun, 1998; Liu et al., 2002), BTAs imposed by the abating coalition are supposed to directly affect China's international trade and substantially influence the whole economy through decreases in domestic production and consumption (Tang et al., 2013). As a matter of fact, China has implemented restrictive policies on energy-intensive exports in the form of 'export value-added tax refund rebate and export tax' since 2007. In the 2012 report on China's policies and actions for addressing climate change, the government emphasized that it has vigorously controlled the exports of high-energy-consumption products (IOSC, 2012). Although these restrictive export policies have mainly served for China's domestic development strategies so far, some analysts have proposed to implement an explicit export carbon tax (ECT) in China, which will entail advantages at the international level (Andersen and Ekins, 2009; Wang et al., 2012; Hűbler, 2012; Li et al., 2012). First of all, the ECT of China can be seen as an alternative measure to the BTAs levied by the developed countries, in that it may help to lessen the abating countries' concerns about carbon leakage and competitiveness losses. In addition, export tariffs can generate a significant revenue flow for developing countries, thus alleviating the adverse economic impact of the BTAs by the abating coalition.

The literature to date related to BTAs has mainly focused on quantifying the extent of competitiveness effects and the scope of carbon leakage under different implementation scenarios of carbon tariffs in developed countries (e.g., Kuik and Hofkes, 2010; Mckibbin and Wilcoxen, 2009; Takeda et al., 2012; Böhringer et al., 2012). For example, using the GTAP-E model, Kuik and Hofkes (2010) explored the implications of BTAs in the EU-ETS. Their results suggest that the reduction of the overall or macro rate of carbon leakage would be modest. They consequently argued that BTAs would not be a very effective policy to reduce carbon leakage but might mainly be justified in relation to sectoral competitiveness. Mckibbin and Wilcoxen (2009) examined border taxes that exactly offset carbon-cost increases of all EU manufacturing firms. They suggest that the impact of border carbon tariffs on overall import prices in the EU would be relatively small and that the border tax measures would therefore be little effective for EU import-competing industries in general. Takeda et al. (2012) evaluated the BTA policies as carbon regulations in Japan. Their results show that export border adjustments are effective for restoring the competitiveness of Japanese exporters and reducing carbon leakage. In addition, their analysis reveals that BTAs in Japan significantly affect carbon leakage to China on the one hand and the competitiveness of the iron & steel sector on the other. Böhringer et al.

(2012) carried out a survey on the role of BTAs in the unilateral climate policy under an Energy Modeling Forum Study (EMF-29). They find that border carbon adjustment can effectively reduce carbon leakage and ameliorate adverse impacts on the energy-intensive and trade-exposed (EITE) industries of unilaterally abating countries. However, the scope for global cost saving is small. The main effect of border carbon adjustment is to shift the economic burden of emission reduction to non-abating countries through the implicit changes in international prices.

On the other hand, there are few studies that have examined the feasibility of implementing an ECT policy in the developing countries, particularly in China. Wang et al. (2012) proposed that subjecting the energy-intensive sectors to a unique, stable and explicit carbon cost, introduced into the export value-added tax rebate at 20 US$/t-$CO_2$, would be feasible for China, thus resolving both the competitiveness problem and the WTO concerns. Hűbler (2012) analyzed a contraction and convergence type climate regime, using a computable general equilibrium (CGE) model, which includes international capital mobility and technology diffusion. He suggests that if China does not participate in the regime and, instead, a carbon tariff is imposed on its exports, the welfare effects will likely be worse than in the case of participation. This study also casts doubt on the effectiveness of carbon tariffs as a direct instrument for reducing the leakage and emissions in general. Li et al. (2012) use a recursive dynamic CGE model based on China's 2002 input-output table, in order to investigate the economic rationale for directly taxing China's CO_2 emissions of exports. The results suggest that China's ECT has a slightly negative economic impact on its GDP, while the effect on its export structure is significant. The export of major energy-intensive products would decrease. In contrast, the export of labor-intensive and high value-added commodities would increase. The study of Li et al. focuses on examining the effects of different scenarios for redistribution of the ECT revenue. Nevertheless, it is worth pointing out that their analysis, perhaps due to the data constraint, does not take into account the terms-of-trade effects through the competitiveness channel in the international market. This is bound to result in underestimation of the negative impact on both gross domestic product (GDP) and export by EITE industries, the critical parameters in the feasibility study on ECT.

There is still lack of research on the feasibility and design of the ECT policy in China. Therefore, we elaborate on the existing studies, seeking to prove further evidence on the impact of different forms of BTAs. This paper uses a multi-region and multi-sector CGE model in order to derive a quantitative comparison of the economic and environmental impacts between BTAs levied by the abating coalition and ECT voluntarily implemented by China. We address the subsequent key policy questions:

1) How would the international competitiveness of China's EITE industries change under the carbon-based tariff policies?
2) To what extent could the domestic CO_2 emissions of China be reduced through carbon tariff approaches and, how effective are the relevant measures in restraining carbon leakage?
3) Compare the BTAs implemented by the abating countries with ECT conducted by China in order to find out which policy option is preferable for China.

The remainder of this paper is organized as follows. Section 2 describes the modeling framework and the data sources. In section 3, we define the concepts of carbon permit price and border carbon adjustment tax. In sections 4 and 5, we present the different policy scenarios for analysis and the results of our simulation, respectively. Finally, concluding remarks on policy implications are summarized in section 6.

2. Model and data sources

2.1 Modeling framework

In this paper a modified version of the GTAP-EG model is used for the assessment. The GTAP-EG model is based on the GTAP8inGAMs package developed by Thomas Rutherford (2012), and documented for version 4.0 of the Global Trade Analysis project (GTAP) dataset and model in Rutherford and Paltsev (2000). The model is a static multi-sector, multi-regional general equilibrium model which tracks the production and distribution of goods in the global economy. It does not incorporate dynamic responses for technological changes and capital reallocations. As such, our results should be considered as short- to medium-term effects of the concerned climate change policies. The structure of the GTAP-EG model is depicted in Fig. 1.

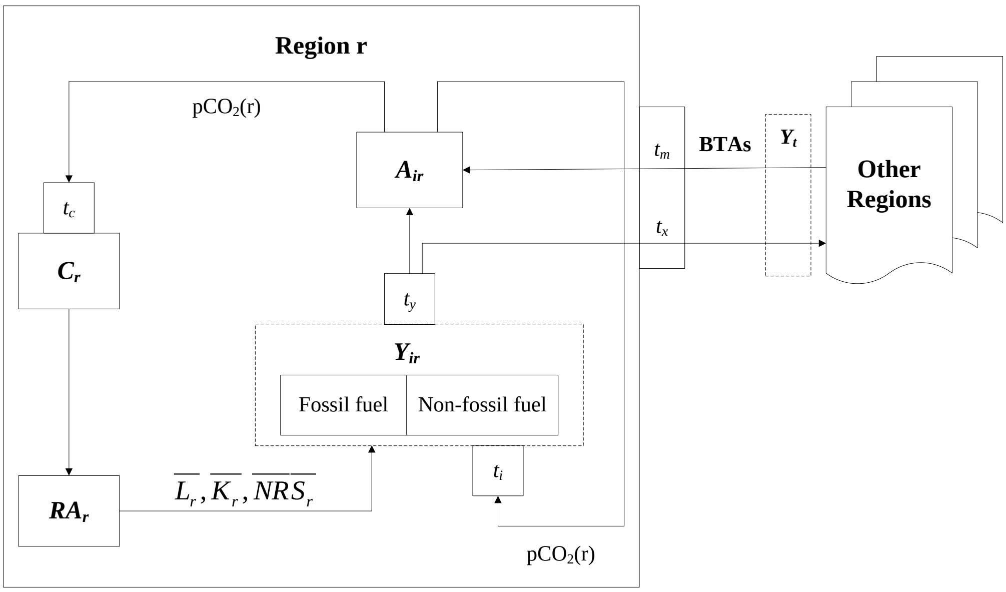

Fig.1: Structure of the GTAP-EG model

In the model, the produced commodities i in region r, are divided into two categories: fossil fuel (i.e., coal, crude oil and gas) and non-fossil fuel commodities. The block Y_{ir} indicates production activities, where fossil fuel production is assumed to have a different structure from other production sectors. All productions are assumed to be subject to constant returns-to-scale technology. Furthermore, the frameworks are represented by multi-level nests of constant-elasticity-of-substitution (CES) functions.

Five energy commodities are identified in the model, i.e., crude oil, gas, coal, petroleum products and electricity. CO_2 emissions result from the usage of crude oil, gas, coal and petroleum products (hereafter referred to as emission-source commodities). No direct CO_2 emission is related to the usage of electricity in order to avoid double counting. After all, electricity is produced from other primary fuels that CO_2 emissions have been accounted for.

Fossil fuel commodities are produced by a CES aggregate of a sector-specific resource and a composite of capital, labor, and the intermediate inputs of emission-source commodities and the other commodities. This structure is shown in Fig.2.

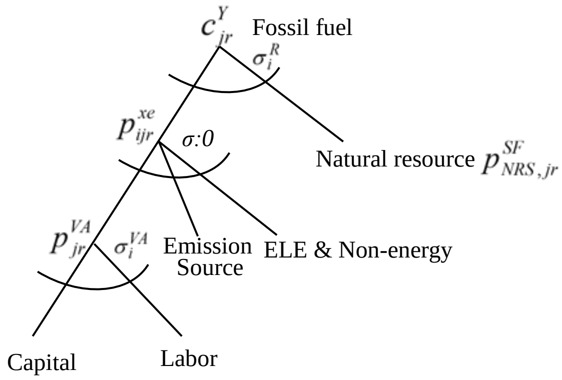

Fig.2: Structure of fossil fuel production

In contrast, as shown in Fig.3, non-fossil fuel production adopts the Leontief form at the first level of production tree, based on the assumption by Hertel and Tsigas (1997) that the mix of intermediate inputs is independent of the prices of primary factors. The energy commodities are transferred to the value added (VA)-energy composite through the CES function.

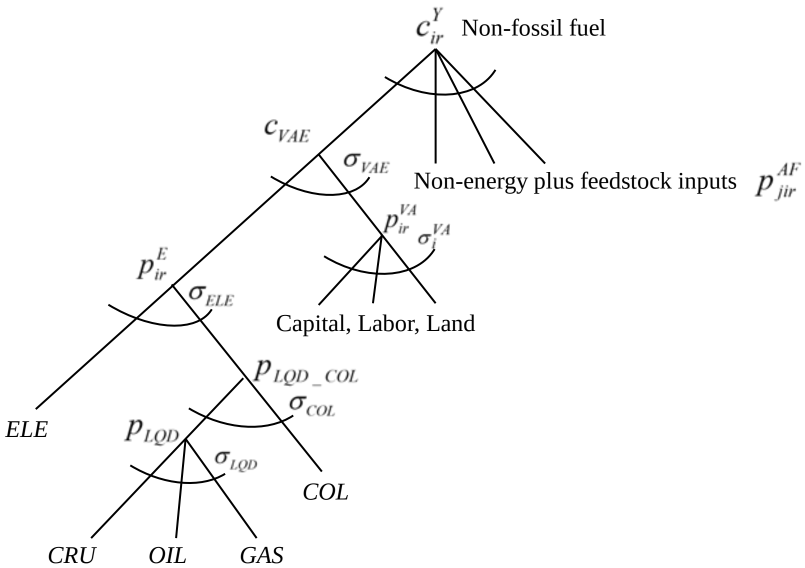

Fig.3: Structure of non-fossil fuel production

To avoid double counting, we assume that all of the crude oil are used as a feedstock, thus treating it as non-energy intermediate input for refined oil production. Moreover, the usage of natural gas and petroleum products in the chemical-rubber-plastics (CRP) sector is divided into feedstock and energy requirements. The relevant ratios of feedstock usage are derived from the energy balance tables by OECD/IEA of 2006 (OECD/IEA, 2006a; OECD/IEA, 2006b).

The model assumes that goods produced in different regions are imperfect substitutes for international trade, following the approach suggested by Armington (1969). As shown in Fig.1, the Armington supply block is described by A_{ir}, representing an aggregation between domestically produced variety Y_{ir} and imports M_{ir} of the same variety from different trading partners. The structure of Armington aggregation is depicted in Fig.4.

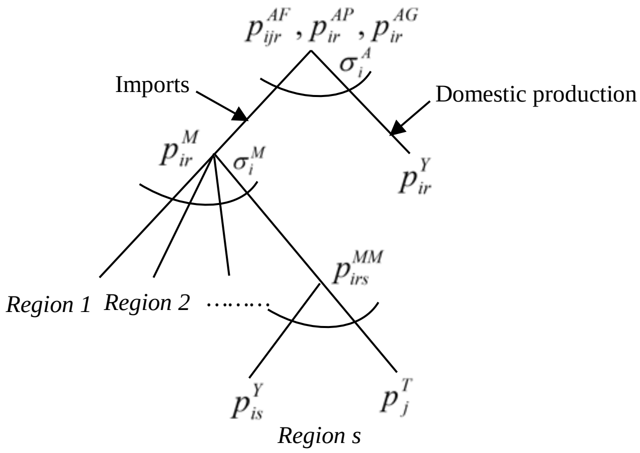

Fig.4: Structure of Armington aggregation

Block Y_t in Fig.1 describes the provision of international transport services. There are three types of global transportation services: air, water and inland transportation. The structure is shown in Fig.5.

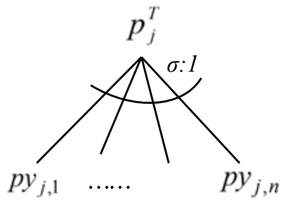

Fig.5: Structure of International transportation services

The final consumption block is described by *C(r)* in Fig.1, which includes private consumption, public expenditure and investment. We assume that government expenditure and investment are held constant at the benchmark values.

The representative agent *RA(r)* in each region *r* is endowed with labor $\overline{L}_r$, capital $\overline{K}_r$, and natural resources. These factors are used for fossil fuel productions. The private household maximizes utility received through consumption of a composite good U_r that combines demands for energy and non-energy commodities at a CES structure. The representative household's utility has the structure depicted in Fig.6.

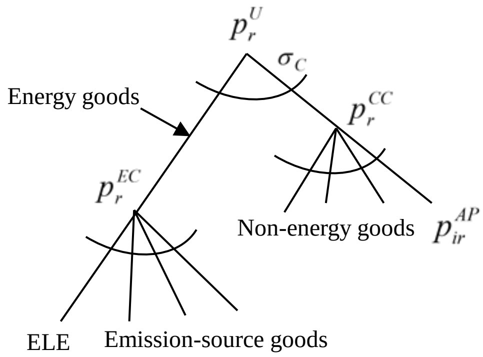

Fig. 6: Structure of private consumption

If the major developed countries implement unilateral carbon constraint policies, a carbon emission permit price, which we depicted as *pco2(r)* in Fig.1, will be induced by their regulation. The border carbon adjustment tariff discussed in this paper is collected from the international trades, hence the arrow with superscript *BTAs* in Fig.1.

The GTAP-EG model is defined in Lars Mathiesen's general equilibrium format (Mathiesen, 1985). There are three types of equations in the definition: 1) zero profit conditions; 2) market clearance conditions; and, 3) an income balance condition stating that net income equals net expenditure. The details of the model are provided in the Appendix.

2.2 Data and parameters

The model is calibrated using the GTAP8.1 database, which includes detailed national input-output tables on production and consumption, together with bilateral trade flows and CO_2 emissions for up to 129 regions and 57 sectors (Narayanan et al., 2012). Specifically, we use the package of GTAP8.1 database with reference year 2004. For elasticity parameters in production functions, we use the values of Fischer and Fox (2007) and GTAP data, whereas for Armington elasticity parameters, we use GTAP values. It is worth mentioning that the carbon leakage rate is sensitive to the values of Armington elasticity and supply elasticity of fossil fuel. The higher the Armington elasticity, the stronger the leakage through the competitiveness channel, whereas the lower the production elasticity of fossil fuel, the higher the leakage rate through the fossil fuel supply channel (Böhringer et al., 2012). We do not check the robustness of results with respect to alternative values of the elasticity parameters in this study, as these have been extensively investigated in Burniaux and Oliveira Martins (2012) and Burniaux et al. (2013).

We aggregated the GTAP-EG database to 23 economic sectors, 10 regions and 4 primary factors.

The economic sectors can be distinguished into three groups: 1) energy goods; 2) EITE industries, which include chemical products (CRP), non-metallic minerals (NMM), iron & steel products (I_S), non-ferrous metals (NFM) and refined oil sectors. These five sectors are the most vulnerable to unilateral emission constraints, as their high emission intensities imply increased production costs and their trade exposure implies limited options for passing on the costs of pricing carbon (Böhringer et al., 2012, Lanzi et al., 2012); and, 3) the other sectors, including other manufacturing, agriculture and service sectors.

The aggregated regions are divided into two categories: the abating coalition and the other regions (the non-abating regions). The abating coalition implements unilateral emission regulations and the other regions do not. The abating coalition includes the EU, the U.S., Japan and Rest of Annex 1 countries (which include Canada, New Zealand and Australia). The non-abating regions include China, India, Russia, energy exporting countries (excl. Mexico), and other middle-income and low-income countries.

The primary factors are labor, capital, natural resources and land.

Table 1 summarizes the sectors and regions for the above aggregation.

Table 1: Sectors and regions in the model

Symbol	Sectors and commodities	Symbol	Countries and regions
	Energy goods		*Abating coalition (industrialized regions)*
COL	Coal	EUR	Europe Union (EU-27 plus EFTA)
CRU	Crude oil	USA	US−United States of America
GAS	Natural gas	JPN	Japan
OIL	Refined oil products [a]	RA1	Rest of Annex 1 countries
ELE	Electricity		
			Non-abating countries and regions
	Non-energy goods	CHN	China
CRP	Chemical products [a]	IND	India
NMM	Non-metallic minerals [a]	RUS	Russia
I_S	Iron and steel industry [a]	EEX	Energy exporting countries (excl. Mexico)
NFM	Non-ferrous metals [a]	MIC	Other middle-income countries
TEQ	Transport equipment	LIC	Other low-income countries
OME	Other machinery		
OMN	Mining		
FPR	Food products		
PPP	Paper-pulp-print		
LUM	Wood and wood-products		
CNS	Construction		
TWL	Textiles-wearing apparel-leather		
OMF	Other manufacturing		
AGR	Agricultural products		
TRN	Transport		
ATP	Air transport		
SER	Commercial and public services		
DWE	Dwellings		

[a] Sectors included in the category of energy-intensive and trade-exposed (EITE) industries.

2.3 Embodied CO_2 emission intensity

The carbon tariff rate is determined based on the CO_2 emission intensity embodied in the traded goods. When calculating the embodied CO_2 emission intensity, we took into account both direct CO_2 emissions from the combustion of emission-source commodities and indirect emissions associated with sectoral electricity consumption. Based on empirical data, Böhringer et al. (2011) suggested that indirect emissions from electricity cover the bulk of total indirect emissions in the absence of detailed input-output accounting under a CGE analysis. For the direct CO_2 emission data, we use the combustion-based CO_2 emissions data included in the GTAP8.1 database, which is presented as $eco2_{ijr}$ in the equation below. Since all CO_2 emissions related to the production process of all intermediate inputs are taken into account when applying BTAs, the embodied carbon emission accounting approach seems to be the most promising from an environmental point of view. However, due to the complexity of calculating measures and limited availability of data, this approach may lead to substantially high difficulties and costs when implementing the policy (Antimiani et al., 2012; Böhringer et al., 2011).

The embodied CO_2 emission intensities, ξ_{ir}, engendered by the export of sector i in region r, can be calculated using equation (1):

$$\xi_{ir} = \left(\sum_{j \in EN} eco2_{jir} + \frac{vdfm_{ELE,i,r}}{vom_{ELE,r}} \times \sum_{j \in EN} eco2_{j,ELE,r}\right) / vom_{ir} \qquad (1)$$

The first summation term inside the parentheses represents the direct CO_2 emissions of sector i in region r, where $eco2_{jir}$ denotes the volume of CO_2 emissions of the jth type of emission-source commodity for sector i. The second term inside the parentheses represents the indirect CO_2 emissions caused by the consumption of electricity in sector i in region r, where $vdfm_{ELE,i,r}$ denotes the domestic intermediate input of electricity for the production of sector i, and $vom_{ELE,r}$ indicates the total electricity supply in region r. Thus, the term ($vdfm_{ELE,i,r}/vom_{ELE,r}$) represents the share of electricity used in sector i. Consequently, the CO_2 content of 1 unit of commodity i (ξ_{ir}) can be obtained by dividing the total amount of embodied CO_2 emissions by the total volume of the ith sector output (vom_{ir}).

Fig.7 illustrates the values of the embodied CO_2 emission intensities by region for the benchmark year 2004. The figure shows that the CO_2 intensity of the products from Russia is the highest in the world, on average about 1.94 t-CO_2/US\$1000 (tons of CO_2 per thousand US\$ of output). China has the second highest CO_2 emission intensity, on average about 1.77 t-CO_2/US\$1000. In contrast, Japan has the lowest CO_2 emission intensity with an average of 0.29 t-CO_2/US\$1000. As expected, commodities produced in non-abating regions have much higher carbon intensities (with a mean value of 1.30

t-CO_2/US\$1000) than those produced in the abating coalition (with a mean value of 0.57 t-CO_2/US\$1000). This difference reflects the gap in carbon tariff rates in the later simulation.

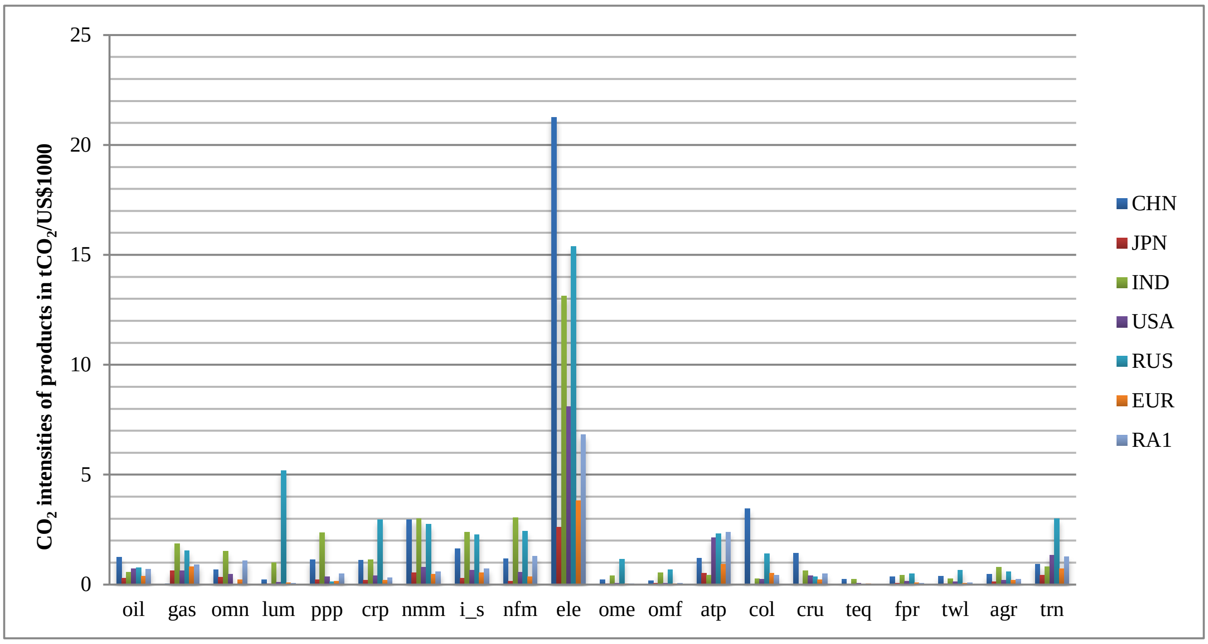

Fig.7: Regional carbon intensity factors of commodities in 2004

3. Calculation of CO_2 emission permit price and border adjustment tax

3.1 CO_2 emission permit price

The CO_2 emission permit price is primarily correlated with the magnitude of the unilateral emission reduction targets. The more stringent the reduction targets, the higher the prospected emission levels, and hence the higher the CO_2 emission prices. In our simulation, the regional emission reduction targets are roughly set in accordance with the post-Kyoto reduction pledges of Annex 1 countries during the 15th Conference of Parties (COP15) of the United Nations Framework Convention on Climate Change (UNFCC) at Copenhagen in 2009. They are expressed as reductions from historical emission levels in 1990 or 2005 but apply to 2020. As described in World Energy Outlook 2009 (OECD/IEA, 2009), the targets set by the abating countries are: the EU will reduce its emissions by 20% by 2020 relative to 1990 levels; the U.S. proposed a 17% cut by 2020 relative to 2005 levels; Japan announced a target to reduce GHG emissions by 25% by 2020 relative to 1990 levels; the average reduction target for remaining Annex 1 countries (including Canada, Australia and New Zealand) is an approximate cut of 13% relative to 2000 or 2006 levels.

We assume that the coalition countries impose a domestic carbon tax applied to fossil fuels' consumption through a cap-and-trade emission program so as to fulfill their emission reduction commitments. Firms within the coalition can trade the domestic emission allowance subsequently. At equilibrium, the carbon tax is equal to the emission permit price. We do not consider the possibility of allowance trading outside of the region in the model.

3.2 Border carbon adjustment tax

As mentioned above, the carbon tariff rate in the international trade is set according to the embodied CO_2 emission intensities. There is a major practical design issue for the BTA policy by the abating coalition. We considered two possibilities for the determination of the required amount of allowance per unit of imported goods from non-abating countries. One is based on the embodied CO_2 emission intensities of comparable domestic goods and is applied in scenario S2-d below. The other is based on the embodied CO_2 emission intensities of the exporting countries and applies to scenario S2-f below. Under the scenario S2-d, the carbon tariff rate τ_{isr}^{M} assigned to 1 unit of the commodity *i* imported in region *r* from region *s* is defined as equation (2):

$$\tau_{isr}^{M} = p_r^{CO2}\xi_{ir} \qquad (2)$$

In this equation, p_r^{CO2} denotes the CO_2 emission permit price in region *r*, and ξ_{ir} denotes the embodied CO_2 emission intensity of region *r*. On the other hand, under the scenario S2-f, the carbon tariff rate τ_{isr}^{M} based on the embodied CO_2 emission intensity of the region of origin of the imported good (denoted by ξ_{is}) is defined as equation (3):

$$\tau_{isr}^{M} = p_r^{CO2}\xi_{is} \qquad (3)$$

The export subsidy rate, τ_{ir}^{X} , which applies to 1 unit of the commodity *i* exported by region *r* can be calculated by equation (4):

$$\tau_{ir}^{X} = p_r^{CO2}\xi_{ir} \qquad (4)$$

When the border carbon tariff is considered in the international trade, the CIF price of imports in region *r*, p_{irs}^{MM} , can be calculated by equation (5):

$$p_{isr}^{MM} = p_{is}^{Y} + \sum_j p_j^T \tau_{jisr} + \tau_{isr}^{M} - \tau_{is}^{X} \qquad (5)$$

In this equation, p_{is}^{Y} denotes the output price of commodity *i* in region *s*, p_j^T denotes the price of the *j*th type of transportation service, and τ_{jisr} describes a ratio of global transportation service *j* in the bilateral trade between region *r* and region *s*.

3.3 Definition of carbon leakage

In our simulations, we take the IPCC definition of carbon leakage, which is defined as the ratio of the change of CO_2 emissions in non-abating countries to the reduction of CO_2 emissions in the unilaterally abating regions (IPCC, 2007). For instance, a leakage rate of 50% means that a decrease of 100 million tons of carbon emissions by the abating coalition will lead to an increase of 50 million tons of carbon emissions by the non-abating regions (Rutherford and Paltsev, 2000). The formula for the leakage rate (LR) is given as equation (6).

$$LR = 100 * \frac{\sum_{n} (Carb_{1,n} - Carb_{0,n})}{\sum_{ac} (Carb_{0,ac} - Carb_{1,ac})} \qquad (6)$$

In this equation, the subscript *n* and *ac* represent, respectively, the non-abating countries and the abating regions, $Carb_0$ is the level of CO_2 emissions in the benchmark, and $Carb_1$ denotes CO_2 emissions in a counterfactual scenario. However, we note that this definition ignores the fact that CO_2 emissions in non-abating countries may raise for other reasons than the implementation of unilateral reduction measures in abating regions, e.g., change in real exchange rate or other labor costs, etc. Thus, this definition is highly dependent on model assumptions (Peters and Hertwich, 2007).

4. Simulation scenarios

4.1 Reference scenario

In this study, we compare the economic impact of BTAs imposed by the abating coalition on the one hand with an ECT policy implemented by China on the other, through simulations against the reference scenario where no explicit climate policies have been undertaken. Since most Annex 1 countries made 2020 the target year for compliance with unilateral emission reduction pledges, we accordingly adopt 2020 as the target year in our economic impact analysis. The reference scenario is labeled as the business-as-usual (BAU) scenario, which hypothesizes that current laws and policies will remain unchanged by 2020. The projections of macroeconomic growth in the BAU scenario are obtained from the database of International Energy Outlook 2009 (IEO2009) (EIA, 2009). From the statistics by the World Bank, it is evident that China's economic growth shows signs of slowdown in 2012 and 2013, both years displaying an average annual growth rate of 7.7% (World Bank: http://data.worldbank.org/indicator/GDP). However, due to the macroeconomic stability of China, as well as increases in exports as the economies of China's major trading partners experience recovery, IEO2013 remains projecting an average annual growth rate of approximately 8.7% for China's economy from 2005 to 2020 in the reference case (EIA, 2013). Since the shutdown period of Japan's nuclear power plants is extended following the March 2011 disaster in northeastern Japan, the projection for Japan's energy-related CO_2 emissions by IEO2013 declines by an average of 0.1% per year from 2010 to 2040 in the reference case, which is lower than the IEO2009 estimates (EIA, 2009; EIA, 2013). We assume that there is an annual autonomous energy efficiency improvement (AEEI), as well as a productivity efficiency improvement across all regions in the model. Thus, the carbon intensity of each region will decrease versus the level of 2004 by 2020, taking into account these efficiency gains.

For the cross-comparison of alternative carbon tariff measures, we follow the example of most of the existing literature (Winchester, 2011; Böhringer et al., 2012), in holding the global CO_2 emissions constant at the level achieved under the reference scenario. This allows us to assume that the gross benefits of reduced emissions are separable from the welfare derived from private consumption. Accordingly, we do not need to estimate the external cost generated by CO_2 emissions in the subsequent welfare analysis.

Table 2 provides a summary of the regional projected annual growth rates under the BAU scenario.

Table 2: Regional annual growth rate under BAU scenario (2004-2020, %)

	Population ①	GDP ②	CO_2 emissions ③	Efficiency parameters	
				Labor (②-①)	AEEI (②-③)
CHN	0.79	8.30	3.64	7.51	4.66
JPN	-0.13	0.98	-0.16	1.11	1.14
IND	1.47	6.77	3.01	5.30	3.76
USA	0.93	2.31	-0.19	1.38	2.50
RUS	-0.14	3.52	0.10	3.66	3.42
EUR	-0.06	1.89	-0.37	1.95	2.26
RA1	1.04	2.43	-0.13	1.39	2.56
EEX	2.88	4.44	2.88	1.56	1.56
MIC	1.61	4.28	1.80	2.67	2.48
LIC	2.98	4.48	1.90	1.5	2.58

4.2 Policy scenarios

We assume the following three counterfactual policy scenarios according to alternative implementation methods for the carbon limitation policy.

Scenario S1: In this case, the abating coalition is assumed to implement unilateral climate policy such as cap-and-trade emissions system, without BTAs, in order to realize their national emission reducing targets in the medium-term. Non-abating countries are assumed not to undertake any carbon pricing policy. The detailed reduction targets for each abating region are described in section 3.1.

Scenario S2: In this scenario, the abating coalition is assumed to go ahead with stringent carbon emission legislation, imposing carbon tariff on imports from non-regulating regions and rebating emission payments for exports to non-regulating countries. However, exports from the abating countries are relieved of the burden of carbon tariffs associated with their production. As mentioned in section 3.2, this scenario is further split up into two cases, which are denoted as S2-d and S2-f, respectively. The difference between these two sub-scenarios lies in the determination method of the carbon tariff ratio to be imposed on the imported goods.

Scenario S3: In this scenario, the abating coalition is assumed to implement unilateral emission reducing measures combined with an ECT policy conducted by China. On the other hand, the rest of the world will not adopt any BTA approaches in the international trade. For the analysis, we considered an equilibrium allowance price of 17 US$/t-$CO_2$ as carbon price on Chinese exports. This price is the CO_2 emission permit price of the U.S. under the cap-and-trade emission scheme estimated by this study. It is also near the illustrative price (20 US$/t-$CO_2$) for the EU-ETS in the Impact Assessment of the European Commission after considering Joint Implementation and the Clean Development Mechanism (Kuik and Hofkes, 2010). We adopted this price because the export carbon price in China's ECT policy should be high enough in order to be recognized by the abating countries as a comparable action to BTAs. In order to determine which level of carbon prices is affordable for the industries of China, Liu et al. (2013) carried out a survey among Chinese enterprises on energy cost increases due to the introduction of market-based climate policies. Their results indicate that the acceptable carbon price is 12 US$/t-$CO_2$ for the chemical industry and 6 US$/t-$CO_2$ for iron & steel and cement sectors. Therefore, a modestly higher carbon price, 17 US$/t-$CO_2$, is reasonable for our analysis of China's ECT policy. In the sensitivity analysis, we investigate how the CO_2 emission permit prices adopted in the ECT measures affect China's economy.

5. Results and discussions

We present the simulation results from four major angles: carbon leakage, welfare changes, GDP impacts and international competitiveness of EITE industries. The environmental and economic impacts of policies under scenarios S1 to S3 are reported in percentage changes relative to the BAU scenario where no climate policy is conducted.

5.1 CO_2 emission permit prices, carbon leakage rates and CO_2 emissions effects

The simulation results for the CO_2 prices in the abating coalition are listed in Table 3. The CO_2 permit price is the highest in Japan (75 US$/t-$CO_2$), followed by the EU and the U.S. (34 and 17 US$/t-$CO_2$, respectively). The price in the rest of Annex 1 countries is much lower (11 US$/t-$CO_2$). The variation reveals a substantial difference in marginal reduction cost across the abating coalition due to the stringency of the carbon reduction target that applies to regulated economic activities. As the BTA approach encourages energy-intensive production in the coalition countries (see Table 9 for details), the CO_2 permit price (marginal reduction cost) for both scenario S2 and S3 increases to some extent, so as to achieve the emission reduction target.

Table 3: Simulation results of CO_2 prices in the abating coalition (US$/t-$CO_2$)

Scenario	JPN	USA	EUR	RA1
S1	75.2	16.7	34.0	11.7
S2-d	77.3	17.2	36.2	12.5
S2-f	78.1	17.5	37.1	12.8

S3	75.3	16.8	34.1	11.8

The results for the carbon leakage rate are listed in Table 4. In scenario S1 with unilateral emission pricing only, the carbon leakage rate is roughly 4.7%. In contrast, in scenarios S2-d and S2-f with imposition of BTAs by the abating coalition, the leakage rates fall to 2.1% and -1.3%, respectively. In scenario S3 with ECT implemented by China, the leakage rate is 3.0%. Thus, no matter whether the carbon tariff revenues are collected by the abating regions or China, both of the carbon adjustment measures are effective in reducing carbon leakage. In particular, the leakage rate becomes negative in scenario S2-f, where the carbon tariff rate is determined based on embodied CO_2 emission intensities of the non-regulated countries. This implies that, when a high carbon tariff is imposed in the international trade, the reducing legislation of the abating coalition not only causes reduced emissions in regulating countries but also leads to large emission drops in non-abating countries.

Table 4: Simulation results of carbon leakage rate (%)

Scenario	S1	S2-d	S2-f	S3
Carbon leakage rate	4.7	2.1	-1.3	3.0

The change rates of the CO_2 emissions relative to the BAU scenario are summarized in Table 5. In scenario S2-d and S2-f, CO_2 emissions in China range from 0.07% to -0.15% relative to the BAU level. However, in scenario S3 there is only a change to a lesser extent in China's CO_2 emissions compared to S2-f scenario. This confirms that border carbon tariff is a very weak instrument to reduce China's domestic CO_2 emissions due to lack of direct pricing incentives to reduce the fossil fuel inputs. There is also little difference in global carbon emissions across all scenarios, which suggests the fact that global emissions may not be reduced significantly through carbon-based tariff policies.

Table 5: Simulation results of CO_2 emissions (% change from BAU)

Scenario	CHN	JPN	IND	USA	RUS	EUR	RA1	EEX	MIC	LIC	World
S1	0.27	-24.82	0.42	-16.33	0.30	-16.74	-11.73	0.53	0.82	0.54	-6.13
S2-d	0.07	-24.82	0.30	-16.33	0.02	-16.74	-11.73	0.34	0.40	0.01	-6.29
S2-f	-0.15	-24.82	-0.003	-16.33	-1.22	-16.74	-11.73	-0.18	0.22	-0.03	-6.51
S3	-0.14	-24.82	0.36	-16.33	0.33	-16.74	-11.73	0.54	0.77	0.61	-6.23

5.2 Welfare changes

The economic cost of implementing CO_2 emission regulations is represented by changes in utilitarian social welfare, which is measured in terms of Hicksian equivalent variation (HEV). As defined in Varian (1992), HEV is the amount of income that needs to be taken away from consumers to enjoy a utility level equal to the one in the counterfactual policy scenario on the basis of ex-ante relative prices. The global gross economic cost is simply the add-up of all changes in money-metric utility in income across all regions. Given the high level of uncertainty in predicting climate change, as well as the difficultly to quantify the region-specific monetary costs arising both in market (e.g., productivity changes, capital depreciation) and non-market sectors in the long term (e.g., biodiversity losses, natural disasters) (Maslin, 2013; Manne et al., 1995), the welfare effect does not incorporate the benefits (in terms of reduced damages) resulting from emission abatement, which are more uncertain and only occur in the long term.

Table 6 presents the simulation results for the HEV under each scenario compared to the BAU level. The results suggest that the unilateral regulation by the abating coalition induces not only direct welfare decreases in regulating countries as a consequence of the additional costs of reducing emissions, but also substantial welfare losses or gains in non-regulating countries due to the reduced economic activity in abating countries and terms-of-trade changes. Terms-of-trade presents the ratio of export prices to import prices. The reduced energy demand in abating countries will bring a downward pressure on prices of fossil fuel in the international market and, as a consequence, lead to decreased revenues for all non-regulating regions, particularly Russia and the energy exporting countries (EEX). However, a modest welfare gain is experienced by India which is a net importer of fossil fuels, and thus benefits from the decline in price of the imported commodities.

Compared with scenario S1 with unilateral carbon emission pricing, China encountered more pronounced welfare losses in scenarios S2-d and S2-f, where the abating countries introduce BTAs. Conversely, China's welfare slightly increases in scenario S3, compared to scenarios S2-d and S2-f, due to the revenue generated by the ECT tariff. It is worth noting that the ECT policy implemented by China also indirectly affects other countries as a result of adverse terms-of-trade effects.

Table 6: Simulation results of HEV (% change from BAU)

Scenario	CHN	JPN	IND	USA	RUS	EUR	RA1	EEX	MIC	LIC	World
S1	-0.06	-1.82	0.04	0.06	-1.14	-0.53	-0.43	-0.95	-0.12	-0.35	-0.30
S2-d	-0.14	-1.40	0.05	0.21	-1.56	-0.38	-0.44	-1.20	-0.21	-0.46	-0.28
S2-f	-0.42	-0.78	-0.11	0.58	-2.54	-0.21	-0.57	-1.69	-0.37	-0.53	-0.30
S3	-0.09	-1.91	0.02	0.13	-1.19	-0.54	-0.48	-1.01	-0.19	-0.42	-0.32

5.3 GDP impacts

Table 7 shows the impacts on GDP in terms of percentage change relative to the BAU scenario. In scenario S1 with unilateral climate policy, both regulating and non-regulating regions suffer from GDP losses ranging from 0.1% to 1.03%. Like the economic impacts reported in terms of HEV, the changes of GDP also indicate that the climate policies implemented in the abating countries indirectly affect non-abating countries through the international fossil fuel markets and terms-of-trade changes.

In scenarios S2-d and S2-f, the imposition of BTAs by the regulating coalition leads to substantial GDP losses in the unregulated regions, especially in scenario S2-f, where the carbon tariff rate is based on the embodied carbon content of non-abating regions. In particular, China's GDP will decrease by about 0.91% and 1.87% with respect to the BAU scenario, in scenarios S2-d and S2-f respectively. This is due to decreased exports in unregulated countries in the light of a deterioration of their terms-of-trade. In particular, their EITE sectors are affected, with losses in both exports and output resulting from the relatively high embodied carbon intensities. In scenario S3, China's GDP losses are slightly offset by the revenue from ECT accrued to China.

Table 7: Simulation results of GDP impacts (% change from BAU)

Scenario	CHN	JPN	IND	USA	RUS	EUR	RA1	EEX	MIC	LIC	World
S1	-0.19	-0.36	-0.18	-0.11	-1.03	-0.24	-0.43	-0.66	-0.23	-0.41	-0.25
S2-d	-0.91	-0.23	-0.84	-0.20	-2.10	-0.36	-0.61	-1.74	-1.01	-1.24	-0.58
S2-f	-1.87	-0.24	-1.84	-0.31	-4.01	-0.45	-0.92	-3.02	-1.63	-1.85	-0.94
S3	-0.74	-0.42	-0.24	-0.12	-1.07	-0.28	-0.47	-0.72	-0.29	-0.49	-0.34

5.4 Effects on competitiveness of EITE commodities

The competitiveness effects on the EITE industries are measured as a percentage change of the EITE exports relative to the BAU scenario. The results for exports and output of EITE commodities in each scenario are illustrated in Table 8 and 9, respectively. In order to illustrate the comparison between different scenarios more clearly, we also present the exports and output impacts on China's EITE industries in Fig.8.

In scenario S1 with unilateral carbon pricing policy, EITE sectors in the abating coalition are particularly affected, with decreases in both exports and output. In general, these effects are a compound result of changes in competitive position with respect to the main trading partners and domestic demand changes (Lanzi et al., 2012). The decrease is large for Japan, the U.S. and the EU. However, the exports and output of CRP, NMM and I_S sectors increase slightly in RA1 countries since their main trading partners are the U.S. and the EU, and the carbon price is relatively lower than in the other abating countries. In contrast, the exports of China's EITE commodities rise in a range of 0.55% to 2.51% relative to the BAU scenario, since they benefit from the fall in output of the EITE industries in regulating regions. However, in scenarios S2-d and S2-f with BTAs implemented by the abating coalition, China's EITE commodities suffer serious losses in exports and output due to the deterioration of terms-of-trade relative to the industrialized countries. More specifically, obligatory purchases of allowances based on carbon-intensities associated with emissions in the source regions in scenario S2-f would cause more costs than in scenario S2-d where the tariff rate is based on embodied carbon intensities of the abating coalition. The volume of EITE exports of China decreases by 6.41% to 19.83% in scenario S2-f. In scenario S3 with unilateral ECT policy applied by China, exports of EITE commodities in China will decrease by 4.88% to 15.18% relative to the BAU scenario, whereas EITE exports in all other regions make significant improvements beyond the levels in scenario S1. The non-metallic minerals (NMM) industry of China will be particularly adversely affected by the implementation of BTAs or ECT regulation, because it has the highest carbon intensity among all

EITE sectors. As a consequence, substitution of NMM production is taking place, through shifting from China to other countries.

We notice that there is a rather large difference in terms of negative impact for China between scenario S2-d on the one hand, where the carbon tariff rate is based on embodied CO_2 intensities of the abating coalition and scenario S2-f on the other hand, where the tariff rate is based on embodied CO_2 intensities of the non-abating regions (See Fig.8). The reason is that emission intensities in regulating countries are significantly lower than those in non-regulating countries. As for the impacts on the competitiveness of the EITE sectors, if the carbon tariff rate is determined based on the embodied CO_2 intensity of China, its output and exports of EITE sectors encounter larger losses in both scenario S2-f and S3 compared to scenario S2-d, no matter who retains the carbon tariff revenues. Therefore, Chinese government should seriously consider which concern should be addressed if an ECT were to be introduced: export tariff revenue for welfare or the competitiveness losses of EITE sectors.

Table 8: Simulation results of exports of EITE commodities (% change from BAU)

Scenario	Sector	CHN	JPN	IND	USA	RUS	EUR	RA1	EEX	MIC	LIC
S1	oil	-0.71	-10.77	-3.20	-3.94	0.70	-3.28	-1.02	1.05	-1.19	-1.99
	crp	0.55	-3.31	1.25	-1.07	2.38	-0.53	0.68	2.50	0.57	0.69
	nmm	2.32	-7.64	1.60	-1.50	2.38	-0.74	1.59	2.28	2.18	1.25
	i_s	2.51	-8.16	2.60	-1.06	4.24	-1.30	0.07	3.91	2.28	2.62
	nfm	1.66	-2.31	0.94	-1.64	4.03	-1.51	-2.65	3.51	1.59	2.09
S2-d	oil	-2.60	-3.17	-3.55	0.65	2.87	6.22	3.78	-0.42	-1.77	-3.40
	crp	-1.73	-1.72	-0.40	-0.84	1.30	-0.15	0.68	1.47	-0.89	-1.06
	nmm	-3.92	3.55	-3.68	1.51	-0.23	3.29	3.95	-0.42	-2.41	-2.12
	i_s	-1.90	-5.39	-2.46	0.28	0.52	2.94	1.92	0.36	-1.49	-1.38
	nfm	-2.13	-2.63	-1.16	0.31	0.28	1.14	0.85	1.16	-1.55	-1.62
S2-f	oil	-11.15	-8.92	-5.91	-2.29	-0.91	2.30	0.91	-6.47	-5.82	-5.48
	crp	-6.93	-4.37	-2.86	-0.98	-9.00	0.24	1.10	-3.68	-1.35	-2.66
	nmm	-19.83	2.31	-17.05	4.31	-2.78	6.37	8.48	-0.74	-8.86	-4.27
	i_s	-7.49	-8.81	-12.01	-0.29	-3.57	4.47	2.98	-3.26	-3.40	-6.83
	nfm	-6.41	-8.01	-3.56	1.38	-16.40	3.09	2.79	-1.48	-1.75	-0.83
S3	oil	-7.93	-12.72	-4.13	-5.11	-0.26	-4.05	-1.88	-0.08	-2.64	-2.33
	crp	-5.30	-3.42	1.42	-0.98	2.41	-0.29	1.02	2.73	0.41	1.16
	nmm	-15.18	-5.07	4.55	1.42	5.53	1.22	5.15	5.37	5.12	3.84
	i_s	-7.48	-7.38	3.52	-0.03	5.31	-0.77	1.00	4.67	2.90	3.51
	nfm	-4.88	-1.96	1.43	-0.96	4.71	-0.96	-2.17	4.17	1.96	2.82

Table 9: Simulation results of output of EITE commodities (% change from BAU)

Scenario	Sector	CHN	JPN	IND	USA	RUS	EUR	RA1	EEX	MIC	LIC	World
S1	oil	-0.42	-14.73	-0.77	-3.82	1.52	-4.60	-1.85	4.29	1.63	1.05	-2.01
	crp	0.09	-1.21	0.13	-0.46	1.43	-0.42	0.46	1.29	0.36	0.14	-0.15
	nmm	0.16	0.56	0.05	0.15	0.11	0.28	0.48	0.25	0.51	0.12	0.29
	i_s	0.15	-0.06	0.44	-0.01	2.28	-0.38	0.49	1.95	1.16	1.74	0.33
	nfm	0.22	-0.75	0.84	-0.26	2.91	-0.98	-2.25	2.60	1.18	1.25	0.07
S2-d	oil	-1.79	-9.51	-1.81	-3.90	1.15	-4.37	-2.30	1.85	-0.46	-1.12	-2.55
	crp	-0.82	-0.44	-0.77	-0.46	0.49	-0.24	-0.09	0.43	-0.64	-0.79	-0.48
	nmm	-1.22	2.63	-1.23	0.44	-1.00	0.95	0.20	-0.89	-1.08	-0.84	0.05
	i_s	-0.66	0.61	-1.04	-0.15	0.01	1.50	0.43	0.23	-0.58	-0.69	0.03
	nfm	-0.67	-1.02	-0.84	-0.41	0.21	0.71	1.92	0.74	-1.01	-1.46	-0.27
S2-f	oil	-3.78	-2.08	-3.00	-4.48	-1.28	-4.17	-3.33	-2.40	-2.23	-3.47	-3.32
	crp	-2.01	-0.63	-1.69	-0.54	-5.40	0.22	0.08	-2.03	-0.93	-1.53	-0.82
	nmm	-3.92	4.81	-3.70	1.23	-2.16	2.27	1.09	-1.52	-2.56	-1.51	-0.13
	i_s	-1.58	1.13	-3.50	-0.19	-2.29	2.80	0.82	-0.98	-1.37	-3.62	-0.23
	nfm	-1.46	0.82	-1.82	-0.31	-10.93	2.59	3.46	-1.02	-1.09	-1.18	-0.48
S3	oil	-2.14	-14.13	-0.61	-3.74	1.63	-4.61	-1.89	3.90	2.11	1.15	-2.11
	crp	-1.14	-1.15	0.28	-0.35	1.48	-0.25	0.69	1.48	0.39	0.40	-0.29
	nmm	-3.07	1.46	0.61	0.97	0.62	0.89	1.54	1.39	1.60	1.03	0.23
	i_s	-1.31	0.18	0.65	0.19	2.86	-0.06	0.99	2.32	1.76	2.68	0.19
	nfm	-1.12	-0.47	1.16	-0.13	3.40	-0.57	-1.78	3.08	1.66	1.77	-0.10

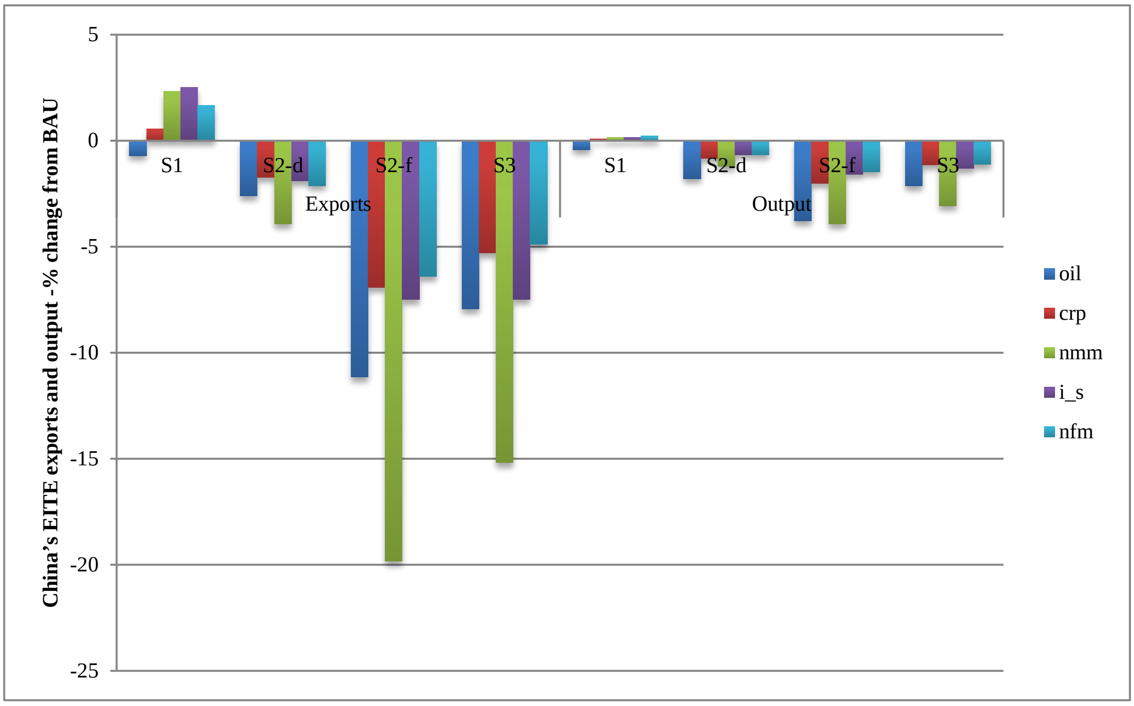

Fig.8: Impacts on the exports and output of China's EITE sectors (% change from BAU).

5.5 Sensitivity analysis

We performed sensitivity analysis with respect to the important uncertainty in the choice of CO_2 emission permit price for the ECT policy of China. We multiply the CO_2 price (17 US$/t-$CO_2$) by 0.5 and 2 times to test the robustness of our central simulation results. Table 10 illustrates how these changes result in alternative policy design of China's ECT. As the CO_2 emission price applied to China's ECT policy increases, the carbon leakage rate drops, whereas the CO_2 emissions of China changes slightly relative to the BAU level. This reveals how the ECT policy has a limited potential for reducing Chinese CO_2 emissions. On the other hand, China's HEV and GDP are worse off under the ECT regulation with higher CO_2 permit prices. This is due to increased losses of exports and output of China's EITE sectors, with higher additional cost under the ECT legislation. This confirms the insight that, although China's welfare benefits from the revenue generated by the ECT tariff, it is not sufficient in itself to alleviate the adverse terms-of-trade effects for the EITE sectors.

Table 10: Sensitivity analysis of CO_2 emission permit price to policy design in China's ECT

		S3 with CO_2 price at 8.5 US$/t-$CO_2$	S3 in the central simulation with CO_2 price at 17 US$/t-$CO_2$	S3 with CO_2 price at 34 US$/t-$CO_2$
Carbon leakage rate (%)		3.80	3.00	1.58
CO_2 emissions of China (% change from BAU)		0.05	-0.14	-0.50
HEV of China (% change from BAU)		-0.07	-0.09	-0.13
GDP of China (% change from BAU)		-0.47	-0.74	-1.28
Exports of EITE sectors of China (% change from BAU)	oil	-4.38	-7.93	-14.63
	crp	-2.41	-5.30	-10.84
	nmm	-6.88	-15.18	-29.46
	i_s	-2.61	-7.48	-16.47
	nfm	-1.66	-4.88	-11.05

6. Conclusions

In this study, we employed a multi-region multi-commodity static CGE model, using GTAP8.1 data to compare the economic implications of BTAs levied by the abating coalition with those generated by an ECT voluntarily implemented by China. We found that both approaches are effective in reducing carbon leakage and preserving the competitiveness of the EITE industries in unilaterally regulated countries. However, either of the approaches is a weak instrument to reduce Chinese domestic CO_2 emissions due to lack of direct abating incentives for energy inputs. Moreover, the border tax measures have virtually no impact on global carbon emissions.

The results show that China's gains in terms of welfare and GDP that can be attributed to the tariff revenues could be improved to a lesser extent if the ECT policy implemented by China, compared to the scenario where China is subjected to BTAs imposed by the abating coalition. However, the ECT policy will cause severe competitiveness losses for the EITE industries in the international trade. Since most of Chinese exports are much more carbon-intensive than those of developed countries, Chinese policy-makers should be aware that, whether the border tariff is retained by China or not, the policy option with a high carbon tariff rate would put China's EITE industries at a significant risk of competitiveness losses. As a consequence, it is difficult to conclude that a carbon tariff on Chinese exports is an alternative policy to BTAs imposed by the abating coalition when the tradeoff between tariff revenue for welfare and competiveness losses of EITE industries is balanced. Moreover, in terms of economic efficiency, the trade-based carbon reduction measures are regarded as the second best solutions to combat climate change. Thus, as a policy recommendation, it is important for China to accumulate experience from the on-going carbon emissions trading pilots at the local level and implement a nation-wide GHG ETS earlier for achieving the carbon intensity reduction goals. Otherwise, the other proper market-based instruments shall be investigated as comparable countermeasures.

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Appendix:

A.1 Model structures

A.1.1 Notation for variables and parameters

The notation for variables and parameters used in this analysis is listed in Table A1 to Table A9. All of the functions are described in calibrated share form. Due to notational simplicity, all taxes and reference prices are omitted in the following equations.

Table A1: Energy goods

Symbol	Description
COL	Coal
CRU	Crude oil
GAS	Gas
OIL	Petroleum and coal products
ELE	Electricity

Table A2: Sets

Symbol	Description
i, j	Sectors and goods
r,s	Regions

CGD	Index of investment goods
EG	All energy goods: CRU, GAS, COL, OIL, and ELE
EN	Emissions source: CRU, GAS, COL and OIL
FF	Primary fossil fuels: CRU, GAS, COL
LQD	Liquid fuels: GAS, OIL and CRU
MF	Mobile factors: labor and capital
NRS	Index of nature resources
SF	Sluggish factors: land and natural resources

Table A3: Activity variables

Symbol	Description
G_r	Government expenditure in region *r*
INVr	Investment in region *r*
M_{ir}	Aggregate imports of goods *i* in region *r*
T_{fr}^{SF}	Allocation of sluggish factors in region *r* ($f \in SF$)
U_r	Household utility in *r*
Y_{ir}	Production in sector *i* and region *r*
Y_i^T	Global transport services
A_{jir}^F	Armington aggregate demand for goods *j* used for sector *i* in region *r*
A_{ir}^P	Armington aggregate demand for goods *i* used for private consumption in region *r*
A_{ir}^G	Armington aggregate demand for goods *i* used for government expenditure in region *r*
A_{ir}^{INV}	Armington aggregate demand for goods *i* used for investment in region *r*
A_{fir}^F	Primary factor demand for production of sector *i* in region *r*
d_{jr}^T	Demand of transportation service *j* from region *r*
da_{ir}	Aggregate demand of domestic output for Armington supply of goods *i* in region *r*
d_CO2_r	Total demand of CO_2 emissions in region *r*
dm_{ir}	Aggregate demand of imports for Armington supply of goods *i* in region *r*
d_m_{isr}	Bilateral trade demand of goods *i* from region *r* to region *s*
$dtwr_{jisr}$	Demand of transportation service *j* from region *r* to region *s*

Table A4: Benchmark parameters

Symbol	Description
$vafm_{ijr}$	Benchmark values of Armington supply for intermediate inputs
vca_{ir}	Benchmark values of Armington supply for private consumption
$vdfm_{ijr}$	Benchmark values of domestic goods for intermediate inputs
vfm_{fjr}	Benchmark endowment of primary factors
vga_{ir}	Benchmark values of Armington supply for public expenditure
vgm_r	Benchmark values of aggregate public demand
$vifm_{ijr}$	Benchmark values of imported goods for intermediate inputs
vim_{ir}	Benchmark values of aggregate imports
$vinv_r$	Benchmark value of investment
vom_{ir}	Benchmark values of total supply
vpm_r	Benchmark values of aggregate private demand

vst_{ir}	Benchmark values of exports for international transportation
$vtwr_{ijrs}$	Benchmark marginal values for international transportation
vtw_j	Aggregate international transportation services
$vxmd_{irs}$	Benchmark values of bilateral exports at market prices

Table A5: Unit cost and price variables

Symbol	Description
c_{ir}^{Y}	Unit cost of goods *i* produced in region *r*
p_{ijr}^{AF}	Price of Armington goods *i* used for sector *j* in region *r*
p_{ir}^{AG}	Price of Armington goods *i* used for government expenditure in region *r*
p_{ir}^{AP}	Price of Armington goods *i* used for private consumption in region *r*
p_{r}^{CC}	Price of aggregate household non-energy consumption in region *r*
p_{r}^{CO2}	Price of emissions permit for region *r*
p_{ir}^{E}	Price of aggregate energy for sector *i* in region *r* ($i \notin FF$)
p_{r}^{EC}	Price of aggregate household energy consumption in region *r*
p_{jir}^{EF}	Price of energy intermediate goods *j* for sector *i* in region *r* ($j \in EN$, $i \notin FF$)
p_{ir}^{EP}	Price of energy consumption goods *i* in region *r*
p_{fr}^{F}	Price of primary factor *f* in region *r*
p_{r}^{G}	Price index of government expenditure in region *r*
p_{r}^{INV}	Price index of investment in region *r*
p_{ir}^{M}	Import price aggregate for goods *i* imported to region *r*
p_{irs}^{MM}	CIF price of goods *i* imported from region *r* to region s
p_{fir}^{SF}	Price of sluggish factor *f* for sector *i* in region *r*
p_{i}^{T}	Price of global transport service *i*
p_{r}^{U}	Price of household utility in region *r*
p_{ir}^{VA}	Price index of VA for sector *i* in region *r* ($i \notin FF$)
p_{jir}^{xe}	Price of composite of VA and Armington intermediate goods *j* for sector *i* in region *r* ($i \in FF$)
p_{ir}^{Y}	Output price of goods *i* produced in region *r*

Table A6: Cost shares

Symbol	Description
θ_{jir}	Share of intermediate goods *j* for sector *i* in region *r* ($i \notin FF$)
θ_{ijr}^{AF}	Share of domestic variety in Armington goods *i* used for sector *j* of region *r*
θ_{ir}^{AG}	Share of domestic variety in Armington goods *i* for government expenditure in region *r*
θ_{ir}^{AP}	Share of domestic variety in Armington goods *i* for private consumption in region *r*
θ_{r}^{C}	Share of composite energy input in household consumption in region *r*
θ_{r}^{CC}	Share of non-energy goods *i* in non-energy household consumption demand in region *r*
θ_{ir}^{COL}	Share of coal in fossil fuel demand by sector *i* in region *r* ($i \notin FF$)
θ_{ir}^{E}	Share of energy in the VAE aggregate for sector *i* in region *r* ($i \notin FF$)
θ_{ir}^{EC}	Share of energy goods *i* in energy household consumption demand in region *r*

θ_r^{EI}	Share of energy for investment in region *r*
θ_{ir}^{ELE}	Share of electricity in overall energy demand by sector *i* in region *r*
θ_{fir}^{F}	Share of primary factor *f* in VA composite for sector *i* in region *r* ($i \notin FF$)
θ_{fir}^{FF}	Share of primary factor *f* for sector *i* in region *r* ($i \in FF$)
θ_{ir}^{G}	Share of Armington goods *i* in government expenditure in region *r*
θ_{jir}^{LQD}	Share of liquid fossil fuel *j* in liquid energy demand by sector *i* in region *r* ($i \notin FF$), ($j \in LQD$)
θ_{isr}^{M}	Share of imports of goods *i* from region *s* to region *r*
θ_{jir}^{NR}	Share of non-resource intermediate inputs *j* for sector *i* in region *r* ($i \in FF$)
θ_{ir}^{R}	Share of natural resources for sector *i* in region *r* ($i \in FF$)
θ_{fir}^{SF}	Share of sluggish factor *f* for sector *i* in region *r*
θ_{ir}^{T}	Share of supply from region *r* in global transport sector *i*
θ_{ir}^{VAE}	Share of VAE aggregate for sector *i* in region *r* ($i \notin FF$)

Table A7: Income and policy variable

Symbol	Description
H_r	Household income in region *r*
T_r	Tax revenue in region *r*
V_r^R	Value of carbon permits in region *r*

Table A8: Endowments and emissions coefficients

Symbol	Description
a_{jir}^{CO2F}	Carbon emissions coefficient for fossil fuel *i* used for sector *j* in region *r* ($i \in FF$)
a_{ir}^{CO2P}	Carbon emissions coefficient for fossil fuel *i* used for private consumption in region *r* ($i \in FF$)
$\overline{B}_r$	Balance of payment deficit or surplus in region *r* ($\sum_r \overline{B}_r = 0$)
$\overline{CO2}_r$	Carbon emission limit for region *r*
$\overline{E}_{fr}$	Aggregate endowment of primary factor *f* for region *r*
τ_{jirs}	Amount of global transport service *j* required for the shipment of goods *i* from *r* to *s*

Table A9: Elasticities

Symbol	Description	Values
σ_C	Substitution between the fossil fuel composite and the non-fossil fuel consumption aggregate in household consumption	0.5
σ_{COL}	Substitution between coal and gas& the liquid fossil fuel composite in production	0.5
σ_{ELE}	Substitution between electricity and emission source goods aggregate in production	0.1
σ_{LQD}	Substitution between gas and the liquid fossil fuel composite in production	2
σ_i^A	Substitution between the import aggregate and the domestic input	GTAP values
σ_i^M	Substitution between imports from different regions	GTAP values
σ_i^R	Substitution between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticity μ_{FF}	$\mu_{COA} = 2$ $\mu_{OIL} = 2$ $\mu_{GAS} = 2$

σ_i^{VA}	Substitution between primary factors in VA composite of production in sector *i*	GTAP values
σ_{VAE}	Substitution between energy and VA in production	0.5
η_f	Elasticity of transformation for sluggish factor allocation	$\eta_{NRS} = 0.0001$ $\eta_{LND} = 1$

A.1.2 Zero profit conditions

In the model, all of the markets are assumed to be operated competitively with free entry and exit. As a consequence, equilibrium profits are driven to zero and the price of output reflects the marginal cost of inputs.

A.1.2.1 Production

(a) Fossil fuel production

The output of fossil fuel production is exhaustible energy, including crude oil, gas and coal.

As shown in Fig.2, the value-added factors are assumed as a Cobb-Douglas (σ_i^{VA}=1) composite of labor and capital based on benchmark year value shares:

$$p_{ir}^{VA} = \prod_{j \in MF} (p_{fr}^{F})^{\theta_{fir}^{F}} \qquad \text{(A1)}$$

The unit cost for intermediate inputs of emission-source commodities ($i \in EN$) gross of carbon tax are given by:

$$p_{ijr}^{EF} = p_{ijr}^{AF} + p_r^{CO2} a_{ijr}^{CO2F} \qquad \text{(A2)}$$

The unit cost for non-resource input is a Leontief (linear) composite of the costs of value-added factors, Armington aggregation inputs (including energy and non-energy commodities), based on benchmark year value shares:

$$p_{ijr}^{xe} = \theta_{fjr}^{VA} p_{jr}^{VA} + \sum_{i \notin EN} \theta_{ijr}^{AF} p_{ijr}^{AF} + \sum_{i \in EN} \theta_{ijr}^{NR} p_{ijr}^{EF} \qquad \text{(A3)}$$

A CES cost function then describes the minimum cost of a bundle of natural resource input $p_{NRS,jr}^{SF}$ and a non-resource input composite to production, based on benchmark value shares and an elasticity of substitution σ_i^R,

$$c_{ir}^{Y} = (\theta_{ir}^{R} (p_{NRS,ir}^{SF})^{1-\sigma_i^R} + (1-\theta_{ir}^{R})(p_{ijr}^{xe})^{1-\sigma_i^R})^{1/(1-\sigma_i^R)} \qquad \text{(A4)}$$

Compensated demand functions related to c*y(i,r)* for production of fossil fuel include Armington supply of non-energy goods, sluggish primary factor (natural resource) input, mobile primary factors (including labor and capital) and energy intermediate goods:

Armington supply of non-energies: $A_{jir}^{F} = Y_{ir} vafm_{jir} (\frac{c_{ir}^{Y}}{p_{jir}^{xe}})^{\sigma_i^R}$ $(j \notin EN,\ i \in FF)$ (A5)

Natural resource input: $A_{NRS,ir}^{SF} = Y_{ir} vfm_{fir} (\frac{c_{ir}^{Y}}{p_{NRS,ir}^{SF}})^{\sigma_i^R}$ $(f \in SF,\ i \in FF)$ (A6)

VA factors input: $A_{fir}^{MF} = Y_{ir} vfm_{fir} (\frac{c_{ir}^{Y}}{p_{jir}^{xe}})^{\sigma_i^R} (\frac{p_{ir}^{VA}}{p_{fr}^{F}})$ $(f \in MF,\ i \in FF)$ (A7)

Energy intermediate input: $A_{jir}^{F} = Y_{ir} vafm_{jir} (\frac{c_{ir}^{Y}}{p_{jir}^{xe}})^{\sigma_i^R}$ $(j \in EN,\ i \in FF)$ (A8)

(b) Non-fossil fuel production

Non-fossil fuel production includes agriculture, refined oil, electricity and other goods productions. The production structure is illustrated in Fig.3.

Output is produced with fixed-coefficient (Leontief) inputs of intermediate non-energy goods and an energy-primary composite. The energy and value-added primary factors are composited through CES function. The energy composite is a nested CES function of electricity versus other energy inputs, coal versus liquid fuels, and gas versus oil (or crude oil).

The unit cost for emission-source commodities ($i \in EN$) gross of carbon tax are defined in the same way as equation (A2).

Sector-specific energy aggregate *($i \notin FF$)*:

$$p_{LQD} = (\sum_{j \in LQD} \theta_{jir}^{LQD} {p_{jir}^{EF}}^{1-\sigma_{LQD}})^{1/(1-\sigma_{LQD})} \quad \text{(A9)}$$

$$p_{LQD\_COL} = (\theta_{ir}^{COL} {p_{COL,ir}^{EF}}^{1-\sigma_{COL}} + (1-\theta_{ir}^{COL}) {p_{LQD}}^{1-\sigma_{COL}})^{1/(1-\sigma_{COL})} \quad \text{(A10)}$$

$$p_{ir}^{E} = (\theta_{ir}^{ELE} {p_{ELE,ir}^{AF}}^{1-\sigma_{ELE}} + (1-\theta_{ir}^{ELE}) {p_{LQD\_COL}}^{1-\sigma_{ELE}})^{1/(1-\sigma_{ELE})} \quad \text{(A11)}$$

Price index of primary factors *($i \notin FF$)*:

$$p_{ir}^{VA} = \left[\sum_{f \in MF} \theta_{fir}^{F} {p_{fr}^{F}}^{1-\sigma_i^{VA}} + \sum_{f \in SF} \theta_{fir}^{F} {p_{fir}^{SF}}^{1-\sigma_i^{VA}} \right]^{1/(1-\sigma_i^{VA})} \quad \text{(A12)}$$

Allocation of sluggish factor ($f \in SF$):

$$p_{fr}^{F} = (\sum_{i} \theta_{fir}^{SF} p_{fir}^{SF\,1+\eta_f})^{\frac{1}{1+\eta_f}} \quad (A13)$$

The unit cost of energy-primary factor composite is given by:

$$c_{VAE} = \left[\theta_{ir}^{E} p_{ir}^{E\,1-\sigma_{VAE}} + (1-\theta_{ir}^{E}) p_{ir}^{VA\,1-\sigma_{VAE}}\right]^{1/(1-\sigma_{VAE})} \quad (A14)$$

The unit cost of production of non-fossil fuel goods c_{ir}^{Y} ($i \notin FF$) is given by:

$$c_{ir}^{Y} = \sum_{j \notin EG} \theta_{jir} p_{jir}^{AF} + \theta_{ir}^{VAE} p_{VAE} \quad (A15)$$

The zero profit condition for firms in each region is expressed as the marginal cost of supply equals to the market price net of output taxes:

$$c_{ir}^{Y} = p_{ir}^{Y}(1 - t_{ir}^{o}) \quad (A16)$$

The compensated demand functions for non-fossil fuel production ($i \notin FF$) related to Armington supply of non-energy inputs, each primary factor and energy inputs are given by:

Armington supply of non-energies: $A_{jir}^{F} = Y_{ir} vafm_{jir}$ ($j \notin EG, i \notin FF$) (A17)

Mobile primary factors input: $A_{fir}^{MF} = Y_{ir} vfm_{fir} (\frac{c_{VAE}}{p_{ir}^{VA}})^{\sigma_{VAE}} (\frac{p_{ir}^{VA}}{p_{fr}^{F}})^{\sigma_i^{VA}}$ ($f \in MF$) (A18)

Sluggish primary factor input: $A_{fir}^{SF} = Y_{ir} vfm_{fir} (\frac{c_{VAE}}{p_{ir}^{VA}})^{\sigma_{VAE}} (\frac{p_{ir}^{VA}}{p_{fir}^{SF}})^{\sigma_i^{VA}}$ ($f \in SF$) (A19)

Energy intermediate inputs are given by:

Electricity: $A_{ELE,ir}^{F} = Y_{ir} vafm_{ELE,ir} (\frac{c_{VAE}}{p_{ir}^{E}})^{\sigma_{VAE}} (\frac{p_{ir}^{E}}{p_{ELE,ir}^{AF}})^{\sigma_{ELE}}$ (A20)

Coal: $A_{COL,ir}^{F} = Y_{ir} vafm_{COL,ir} (\frac{c_{VAE}}{p_{ir}^{E}})^{\sigma_{VAE}} (\frac{p_{ir}^{E}}{p_{LQD\_COL}})^{\sigma_{ELE}} (\frac{p_{LQD\_COL}}{p_{COL,ir}^{EF}})^{\sigma_{COL}}$ (A21)

Liquid fuels: $A_{LQD,ir}^{F} = Y_{ir} vafm_{LQD,ir} (\frac{c_{VAE}}{p_{ir}^{E}})^{\sigma_{VAE}} (\frac{p_{ir}^{E}}{p_{LQD\_COL}})^{\sigma_{ELE}} (\frac{p_{LQD\_COL}}{p_{LQD}})^{\sigma_{COA}} (\frac{p_{LQD}}{p_{jir}^{EF}})^{\sigma_{LQD}}$ (A22)

A.1.2.2 Armington supply

Armington aggregation activity generates intermediate demand for production and final demand for consumption as a mix of domestic and imported goods as imperfect substitutes. The structure is depicted in Fig.4.

The unit cost of Armington aggregate for intermediate inputs is given by:

$$p_{ijr}^{AF} = (\theta_{ijr}^{AF} p_{ir}^{Y\,1-\sigma_i^A} + (1-\theta_{ijr}^{AF}) p_{ir}^{M\,1-\sigma_i^A})^{1/(1-\sigma_i^A)} \tag{A23}$$

The unit cost of Armington aggregate for private consumption is given by:

$$p_{ir}^{AP} = (\theta_{ir}^{AP} p_{ir}^{Y\,1-\sigma_i^A} + (1-\theta_{ir}^{AP}) p_{ir}^{M\,1-\sigma_i^A})^{1/(1-\sigma_i^A)} \tag{A24}$$

The unit cost of Armington aggregate for government consumption is given by:

$$p_{ir}^{AG} = (\theta_{ir}^{AG} p_{ir}^{Y\,1-\sigma_i^A} + (1-\theta_{ir}^{AG}) p_{ir}^{M\,1-\sigma_i^A})^{1/(1-\sigma_i^A)} \tag{A25}$$

The unit cost of aggregate imports across import regions:

$$p_{ir}^{M} = (\sum_s \theta_{isr}^{M} p_{isr}^{MM\,1-\sigma_i^M})^{1/(1-\sigma_i^M)} \tag{A26}$$

The calculation of CIF price p_{isr}^{MM} of imported goods is represented by equation (5) in Section 3.2. The aggregate demand of domestic output for Armington supply is given by:

$$da_{ir} = \sum_j A_{ijr}^{F} (\frac{p_{ijr}^{AF}}{p_{ir}^{Y}})^{\sigma_i^A} + A_{ir}^{P} (\frac{p_{ir}^{AP}}{p_{ir}^{Y}})^{\sigma_i^A} + A_{ir}^{G} (\frac{p_{ir}^{AG}}{p_{ir}^{Y}})^{\sigma_i^A} + A_{ir}^{INV} (\frac{p_{ijr}^{AF}}{p_{ir}^{Y}})^{\sigma_i^A} \tag{A27}$$

The aggregate demand of imports for Armington supply is given by:

$$dm_{ir} = \sum_j A_{ijr}^{F} (\frac{p_{ijr}^{AF}}{p_{ir}^{M}})^{\sigma_i^A} + A_{ir}^{P} (\frac{p_{ir}^{AP}}{p_{ir}^{M}})^{\sigma_i^A} + A_{ir}^{G} (\frac{p_{ir}^{AG}}{p_{ir}^{M}})^{\sigma_i^A} + A_{ir}^{INV} (\frac{p_{ijr}^{AF}}{p_{ir}^{M}})^{\sigma_i^A} \tag{A28}$$

The bilateral trade demand of goods *i* from region *r* to region *s* is given by:

$$d\_m_{isr} = M_{ir} vxmd_{isr} (\frac{p_{ir}^{M}}{p_{isr}^{MM}})^{\sigma_i^M} \tag{A29}$$

The demand of transportation service *j* from region *r* to region *s* is given by:

$$dtwr_{jisr} = M_{ir} vtwr_{jisr} (\frac{p_{ir}^{M}}{p_{isr}^{MM}})^{\sigma_i^M} \tag{A30}$$

A.1.2.3 International transport

The unit cost of a transportation service depends on the benchmark value shares of region-specific services through a Cobb-Douglas cost function. The structure is described in Fig.5.

$$p_j^T = \prod_r (p_{jr}^Y)^{\theta_{jr}^T} \tag{A31}$$

The unit cost of demand for transportation service *j* from region *r* can be written as a closed-form function of relative prices and the aggregate provision of those services:

$$d_{jr}^{T} = Y_j^T vst_{jr} \frac{p_j^T}{p_{jr}^Y} \qquad \text{(A32)}$$

A.1.2.4 Private consumption

The structure of private consumption is illustrated in Fig.6. Private consumption in region *r* is characterized by activity *U(r)*, which is a constant elasticity composite of energy and non-energy consumptions. The non-energy composite is in turn a Cobb-Douglas aggregate of different goods, while energy composite is a Cobb-Douglas aggregation of electricity and emission-source commodities. The permit price for carbon emissions is applied to private household as well.

The unit cost of consumption of emission-source commodities is Armington price indices gross of carbon tax.

$$p_{ir}^{EP} = p_{ir}^{AP} + p_r^{CO2} a_{ir}^{CO2P} \qquad \text{(A33)}$$

The consumer price of aggregate energy supply is defined by a Cobb-Douglas price index over unit cost of consumption of emission-source goods.

$$p_r^{EC} = (p_{ELE,r}^{AP})^{\theta_{ELE,r}^{EC}} \prod_{i \in EN} (p_{ir}^{EP})^{\theta_{ir}^{EC}} \qquad \text{(A34)}$$

The consumer price of aggregate non-energy supply is also defined by a Cobb-Douglas price index over unit cost of consumption of Armington aggregation supply p_{ir}^{AP} .

$$p_r^{CC} = \prod_{i \notin EG} (p_{ir}^{AP})^{\theta_{ir}^{CC}} \qquad \text{(A35)}$$

The unit cost of household indirect utility can be expressed over price indices of energy and non-energy goods, based on benchmark value shares and an elasticity of substitution.

$$e(p_r^{EC}, p_r^{CC}) = p_r^U = (\theta_r^C p_r^{EC^{1-\sigma_C}} + (1-\theta_r^C) p_r^{CC^{1-\sigma_C}})^{1/(1-\sigma_C)} \qquad \text{(A36)}$$

Household demands for Armington aggregate of non-energy goods, and each energy goods can be expressed as:

Demands of non-energy goods: $A_{ir}^P = U_r vca_{ir} (\frac{p_r^U}{p_r^{CC}})^{\sigma_C} (\frac{p_r^{CC}}{p_{ir}^{AP}}) \quad (i \notin EG)$ (A37)

Demand of electricity: $A_{ELY,r}^P = U_r vca_{ELE,r} (\frac{p_r^U}{p_r^{EC}})^{\sigma_C} (\frac{p_r^{EC}}{p_{ELE,r}^{AP}})$ (A38)

Demand of cru, oil, gas and coal: $A_{ir}^P = U_r vca_{ir} (\frac{p_r^U}{p_r^{EC}})^{\sigma_C} (\frac{p_r^{EC}}{p_{ir}^{EP}}) \quad (i \in EN)$ (A39)

A.1.2.5 Government consumption

Public expenditure is a fixed-coefficient (Leontief) aggregate of Armington composite goods. The structure is shown is Fig.9.

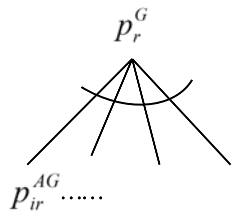

Fig.9: Structure of government expenditure

The price index of public services (p_r^G) is defined by Leontief cost function:

$$p_r^G = \sum_i \theta_{ir}^G p_{ir}^{AG} \tag{A40}$$

Government demand for Armington aggregate goods is written as:

$$A_{ir}^G = G_r vga_{ir} \tag{A41}$$

A.1.2.6 Investment

The investment activity in region *r* is a Leontief aggregation of energy and non-energy composite. The structure is shown in Fig.10.

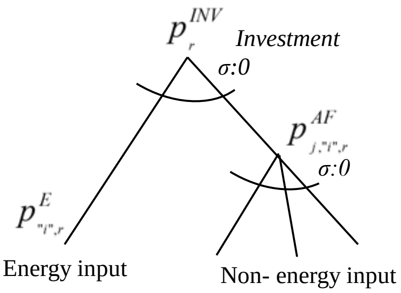

Fig. 10: Structure of investment

The price index of investment in region *r* is given as:

$$p_r^{INV} = \theta_r^{EI} p_{"i",r}^E + (1-\theta_r^{EI}) \sum_{j \notin EG} \theta_{j,"i",r} p_{j,"i",r}^{AF} \tag{A42}$$

The compensated demand functions for investment related to Armington supply of non-energy goods and energies are given by:

Armington supply of non-energies: $A_{jr}^{INV} = INV_r vafm_{j,"i",r} \quad (j \notin EG)$ (A43)

Electricity: $A_{ELE,r}^{INV} = INV_r vafm_{ELE,"i"r} (\frac{p_{"i",r}^{E}}{p_{ELE,"i"r}^{AF}})^{\sigma_{ELE}}$ (A44)

Coal: $A_{COL,r}^{INV} = INV_r vafm_{COL,ir} (\frac{p_{ir}^{E}}{p_{LQD\_COL}})^{\sigma_{ELE}} (\frac{p_{LQD\_COL}}{p_{COL,"i",r}^{EF}})^{\sigma_{COL}}$ (A45)

Liquid fuels: $A_{LQD,r}^{INV} = INV_r vafm_{LQD,ir} (\frac{p_{ir}^{E}}{p_{LQD\_COL}})^{\sigma_{ELE}} (\frac{p_{LQD\_COL}}{p_{LQD}})^{\sigma_{COA}} (\frac{p_{LQD}}{p_{j,"i"r}^{EF}})^{\sigma_{LQD}}$ (A46)

A.1.2.7 Carbon emissions limit for region *r*

Carbon emissions come from the combustion of fossil-fuel for production and private consumption. The total amount of carbon emissions is given by:

$$d\_CO2_r = \sum_{i \in EN} \sum_{j \in FF} A_{ijr}^{F} a_{ijr}^{CO2F} + \sum_{i \in EN} A_{ir}^{P} a_{ir}^{CO2P} \quad \text{(A47)}$$

A.1.3 Market clearance conditions

A.1.3.1 Primary factors

We assume that the endowment of primary factors is exogenously constant. Labor is mobile within domestic borders but cannot move between regions. Capital can be global or region-specific. The aggregate supply of mobile primary factor *f* ($f \in MF$) in region *r* is $\overline{E}_{fr}$, which is equal to the aggregate demand of production in equilibrium.

$$\overline{E}_{fr} = \sum_{i \in FF} A_{fir}^{MF} + \sum_{i \notin FF} A_{fir}^{MF} \quad (f \in MF) \quad \text{(A48)}$$

In the case of sluggish primary factors *f* ($f \in SF$), the endowment is equal to the allocation of sluggish factors in region *r* in equilibrium.

$$\overline{E}_{fr} = \overline{E}_{fr} T_{fr}^{SF} \quad (f \in SF) \quad \text{(A49)}$$

Land and natural resources are portrayed as sector-specific factors of production supplied through constant-elasticity-of-transformation (CET) production function allocate composite factors to sectoral market. In equilibrium, the supply of sectoral factors of production is equal to the demand of sector-specific primary factors, which is described as:

$$T_{fr}^{SF}\theta_{fir}^{SF}(\frac{p_{fir}^{SF}}{p_{fr}^{F}})^{\eta_f} = vfm_{fir}(\frac{p_{fir}^{SF}}{p_{fr}^{F}})^{\eta_f} = A_{fir}^{SF} \quad (f \in SF) \tag{A50}$$

A.1.3.2 Firm output

The supply of goods *i* in region *r* is denoted by $y_{ir}vom_r$. The aggregate demand of goods *i* in region *r* includes domestic demand, imports demand from region *s*, and inputs demand from global transportation sector. The relationship is described as:

$$Y_{ir}vom_r = da_{ir} + \sum_s d\_m_{isr} + d_{ir}^T \tag{A51}$$

A.1.3.3 Composite imports

The aggregate value of imports of goods *i* in region *r* in the reference equilibrium is *vim(i,r)*. The total demand is to satisfy intermediate inputs for production and final consumption.

$$M_{ir}vim_{ir} = dm_{ir} \tag{A52}$$

A.1.3.4 Transport service

The aggregate demand for transport service *j* in the benchmark equilibrium is *vtw(j)*:

$$Y_j^T vtw_j = \sum_{i,s,r} dtwr_{jisr} \tag{A53}$$

A.1.3.5 Final consumption

There are three types of final consumption in the model, which are household consumption, government expenditure and investment. In the reference equilibrium, consumer demand in region *r* is *vpm(r)*, government demand is *vgm(r)*, and investment is *vinv(r)*. Since government expenditure and investment are assumed to be held constant at the benchmark levels, the activity variables for the behaviors G_r and INV_r are expressed as 1 in the definition.

$$U_r vpm_r + G_r vgm_r + INV_r vinv_r = RA_r \tag{A54}$$

A.1.3.6 Carbon limitations

In the equilibrium, the total demand of carbon dioxide emissions in region *r* should meet an exogenous reduction constraint from the domestic combustion of fossil fuel regulated by the government. The amount of CO_2 limitation in region *r* is denoted by $\overline{CO2}_r$. The price of CO_2 emissions permit P_r^{CO2} is determined by this condition:

$$\overline{CO2}_r = d\_CO2_r \tag{A55}$$

A.1.4 Household income

Each region's representative agent is endowed with primary factors, capital inflows, revenue of carbon permits and tax revenue. The tax revenue T_r, consist of output taxes, intermediate demand taxes, factor taxes, final demand taxes, import tariffs and export subsidies.

The budget of household consumption is given by:

$$H_r = \sum_f p_{fr}^F \overline{E}_{fr} - p_r^{INV} vinv_r - p_r^G vgm_r + p_{USA}^c \overline{B}_r + T_r + V_r^R + BTA \;\; revenue \qquad \text{(A56)}$$

V_r^R represents the revenue from carbon emissions permit, which is given by:

$$V_r^R = p_r^{CO2} \overline{CO2}_r \qquad \text{(A57)}$$

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