



Assessment of carbon leakage by channels: An approach combining CGE model and decomposition analysis

Xiujie Tan^a, Yu Liu^{b,c,*}, Jingbo Cui^d, Bin Su^e

^a Institute for International Studies, CICTSMR, Wuhan University, Wuhan 430072, China

^b Institutes of Science and Development, Chinese Academy of Sciences, Beijing 100190, China

^c School of Public Policy and Management, University of Chinese Academy of Sciences, Beijing 100049, China

^d School of Economics and Management, Wuhan University, Wuhan 430072, China

^e Energy Studies Institute, National University of Singapore, Singapore

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ABSTRACT

As carbon leakage occurs through the channels of competitiveness, demand and energy, a detailed study of leakage channels in a unified framework is clearly warranted. This paper illustrates these three channels by a simplified theoretical general equilibrium model. It confirms the common concern that the competitiveness and demand channels as a whole cause relocation of energy-intensive production, and the energy channel leads to increased carbon-intensity in other regions, resulting in positive leakage. We propose an approach, combining computable general equilibrium (CGE) model and decomposition analysis, to decompose overall carbon leakage into three channels. The numerical simulation using the multi-region CGE model in China to study the carbon leakage from Hubei Pilot ETS is presented. The results show that (a) the competitiveness channel is the main source of carbon leakage, while the demand channel is smallest one; (b) carbon leakage rate through the energy channel is modest due to limited energy price fall. Policy implications of this study are also discussed.

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1. Introduction

The Paris Agreement, reached at 2015 United Nations Climate Change Conference, put forward a global response plan against climate change post-2020. Although the Agreement may be a 'plugging' of carbon leakage (Murphy and McDonnell, 2017), this problem remains one of the most critical environmental issues. According to the Agreement, all parties are required to submit the Nationally Determined Contributions (NDCs). There will be substantial variations in the stringency of climate policies across countries, due to differentiating historical responsibilities, varying capacities for reduction and various stages of development. As a result, carbon leakage will arise when these variations bring about abatement cost differentials (in actual costs or shadow costs). Besides, some sub-national jurisdictions have imposed stringent climate policies with no global policy response. For example, China has launched seven regional Pilot Emissions Trading Schemes (ETS) since 2013. It implies that carbon leakage can happen at different scale levels

(province, state, nation, or world region). Therefore, the Paris Agreement has inherited the carbon leakage issue formerly existed under the Kyoto Protocol,¹ calling for a need for further study.

The Intergovernmental Panel on Climate Change (IPCC) classifies carbon leakage as a spillover effect from climate policies. The leakage process may occur through three different but related channels, including: (a) relocation of energy-intensive production in regions with lax climate policies (competitiveness channel); (b) increased consumption of fossil fuels in these regions through decline in energy price (energy channel); and (c) changes in income thus in demand (demand channel) (IPCC, 1996, 2001, 2007). Some studies investigated theoretical mechanisms of carbon leakage channels using analytical model. For example, Burniaux and Martins (2012) offered a general equilibrium exploration of the key channels: energy and non-energy markets, and captured factors underlying the sizes of carbon leakage. Baylis et al. (2014) built

* Corresponding author at: Institutes of Science and Development, Chinese Academy of Sciences, Beijing 100190, China.

E-mail address: liuyu@casipm.ac.cn (Y. Liu).

¹ Under the Kyoto Protocol, carbon leakage is defined as: the increase in carbon emissions from non-Annex-I countries, divided by the emission reductions from Annex-I countries. Under the Paris Agreement, it is appropriate to revise it into: the increase in carbon emissions from jurisdiction/sector with lax climate policies, divided by the emission reductions from jurisdiction/sector with stringent climate policies.

a simple general equilibrium model and identified the terms-of-trade effect and the abatement resource effect. This latter effect implies that the dirty sector substitutes dirty inputs with clean inputs, so it may absorb resources, shrink the other sector, and lead to negative leakage.

It is not an easy task to estimate carbon leakage, and it is more challenging to further assess the respective sizes of leakage channels. Many studies applied the computable general equilibrium (CGE) model to simulate carbon leakage rates varying between -14% and $+130\%$, depending on the models, assumptions, data and contexts (Babiker, 2005; Sinn, 2008; Alexeeva-Talebi et al., 2012). Other studies researched leakage in some energy-intensive sectors by adopting partial equilibrium models and resulted in high leakage rates (Mathiesen and Mæstad, 2004; Ponssard and Walker, 2008; Lanz et al., 2013). Most literature presented net results about overall carbon leakage and did not identify the magnitude of channels. Besides, there are a few papers attempted to decompose carbon leakage into different driving effects.² For example, Bollen et al. (2000) used the Kaya identity to divide carbon leakage into changes in GDP per capita, energy use per unit GDP and carbon content per unit energy use. Kuik and Hofkes (2010) divided sectoral output changes into changes in internal demand, import and export, and decomposed carbon leakage into the substitution effect and the scale effect.

The simple carbon leakage rate alone cannot capture the changes in trade flows, consumption patterns and energy markets, and fails to investigate the interactions among them. Overall carbon leakage and its regional flows are also insufficient for policymaking. It is essential to understand how different channels cause the leakage for choosing countermeasures. Therefore, a detailed study of leakage channels is clearly warranted. This paper presents an examination of carbon leakage channels, focusing only on competitiveness channel, demand channel and energy channel. Its main contributions are summarized as follows: (a) we employ a two-factor general equilibrium model to illustrate the channels of competitiveness, demand and energy in a unified framework; (b) we propose an approach combining CGE model and decomposition analysis, which enables us to decompose overall carbon leakage into channels; and (c) we apply the suggested approach to numerically simulate the magnitudes of three channels by calibrating CGE model to data from Hubei Pilot ETS in China.

The rest of the paper is organized as follows. Section 2 reviews the literature studying on carbon leakage channels. Section 3 builds the analytical model to sign leakage channels, and describes the approach to decompose carbon leakage. Section 4 outlines the key features of TermCO2 model and scenario design. Section 5 presents the simulation results, and Section 6 concludes.

2. Literature review

There is growing number of literature studying carbon leakage channels, such as competitiveness channel, demand channel, energy channel, technology spillover channel (Maria and Werf, 2008; Gerlagh and Kuik, 2014) and abatement resource effect (Baylis et al., 2013; Carbone, 2013; Winchester and Rausch, 2013). However, this paper only involves former three channels, which are identified by IPCC and widely accepted.

2.1. Competitiveness channel

The competitiveness channel relies on the possibility that stringent climate policy would weaken the competitiveness of carbon-intensive sector in a region (Dissou and Eyland, 2011; Rivers, 2010). In turn, this

² In the literature, two popular decomposition techniques on energy and emissions are index decomposition analysis (IDA) and structural decomposition analysis (SDA). The comparison of these two techniques can be found in Su and Ang (2012). Recently, the traditional temporal decomposition analysis has been further extended to spatial decomposition analysis (Ang et al., 2015; Su and Ang, 2016).

could increase its import or decrease its export (Demailly and Quirion, 2006; Balistreri and Rutherford, 2012), and induce relocation of its production to regions with lax climate policy (Copeland and Taylor, 2004; Reinaud, 2008), thus leading to positive carbon leakage.

The competitiveness channel, as well as its manifestations on trade patterns and capital flows, is always a subject of considerable interests in the literature. Most of them estimated competitiveness channel by numerical modeling. Böhringer et al. (2012a) compared papers published via the Energy Modeling Forum, and discovered the competitiveness channel to be more important than the energy channel. Antimiani et al. (2016) showed that negative effects on competitiveness would be serious in the case of a unilateral EU climate policy. Babiker (2001) noted that carbon leakage would be virtually unaffected by restrictions on capital mobility, and largely originate from the trade flows. Due to the sparse data available, only a few empirical studies exist. Aichele and Felbermayr (2013) found that Kyoto countries' exports could be reduced by 13 to 14% due to Kyoto commitment using matching econometrics. However, critical uncertainties remain in the assessment of competitiveness channel. There are studies that have revealed no strong evidence of competitiveness losses in the energy-intensive sectors such as cement, aluminum and iron & steel (Zhang and Baranzini, 2004; Okereke and McDaniels, 2012; Sartor, 2013).

The following summarize key reasons underlying these divergences. First, assessment is very sensitive to different model settings. Mckibbin et al. (1999) showed that when taking lower Armington elasticity values, there would be fewer opportunities for non-Annex countries to expand their exports. Paroussos et al. (2015) suggested that the size of the economies participating in the emission abating group would be important for the leakage rate. Second, production relocation is more complicated than assumed. Paltsev (2001) found high costs of transportation would render sectoral relocation, thus decreasing competitiveness channel. Sijm et al. (2004) concluded that relocation would not be substantial, because transport costs, local market conditions, product variety and incomplete information all favor local production. Third, mitigation policies may induce technology innovation and spillover.

2.2. Demand channel

The demand channel is a second-order effect of climate policies. Tight mitigation policies would affect income levels and product prices, and indirectly influence domestic and foreign demands, thus resulting in changes of production and emissions.

Given the complexity of the interactions among climate policies, income levels and product prices, the demand channel may manifest in more than one way. Antimiani et al. (2013) proposed that climate policies would lower the price of energy-intensive products, leading to higher demands in regions without abatement policies and therefore to carbon leakage. However, some papers argue for opposite effects in the demand channel. Oliveira-Martins et al. (1992) claimed mechanism to be: mitigation policies reduce demands for energy, which lower the energy-exporting countries income levels, decreasing their demands and emissions. Holladay et al. (2018) developed a two-good (clean and dirty) model and demonstrated that strict regulation would reduce consumers' real wages and domestic demand. As a result, the exports of dirty goods would increase, while the rest of the world's production decreases, leading to negative leakage.

Since it is complicated to measure demand channel, the relevant literature is sparse. Böhringer et al. (2010) simulated the changes of different countries' consumption in three scenarios: implementation of abatement policies only in the US, only in the EU, and a combination of both. They found that consumption in OPEC would decrease due to falling oil prices in all scenarios. Compared to the US-only scenario, the consumption in Russia would perform better under the EU-only scenario, since the former reduces Russia's oil export and the latter

increases its gas export. The EU-only scenario has stronger effects on consumption in other exporters like Brazil, Canada and China, because the EU suffers higher abatement costs than the US, thus lowering EU's imports and other exporters' incomes.

2.3. Energy channel

The energy channel results from reduced use of fossil fuels in emission abating regions, which depresses energy prices and induces larger consumption and thus emissions in other regions (Dröge, 2009; Böhringer et al., 2012b). Böhringer et al. (2014) highlights re-allocation in fossil energy markets; Bauer et al. (2015) focuses on inter-fuel substitution in non-abating countries; and Arroyo-Currás et al. (2015) emphasizes changes of international fossil fuel trade.

Recent work on carbon leakage has increasingly emphasized the role of energy channel. Fischer and Fox (2009) concluded that the energy channel would be the main source of carbon leakage, with the competitiveness channel being the second. Hassler and Krusell (2012) had an even more surprising finding that oil prices lowered by unilateral climate policies could upend the global distribution of oil production and consumption, in which the emission reduction would be entirely offset by the resulting carbon leakage. However, the literature is not conclusive on the importance of energy channel. Arroyo-Currás et al. (2015) argued that energy channel is mainly limited due to trade costs of fossil energy and demand for final energies in non-abating countries.

Researchers further identify factors in the energy channel, including the influence of policy-enforcing countries on energy prices, the response strategies of energy-supplying countries, the elasticity of energy demands, and the elasticity of energy substitution. Criqui and Mima (2012) proposed that the energy channel would be subject to how much influence the reduction-enforcing countries have on energy prices. Böhringer et al. (2012b) suggested the responses to climate policies from OPEC would play a major role in energy channel. Boeters and Bollen (2012) showed that higher elasticity in energy supply would lead to lower leakage rates. Bauer et al. (2015) found that differences in fossil energy trade patterns and energy substitution effects would result in varying leakage rates.

3. Theoretical model and decomposition approach

On the basis of previous studies, we employ a two-factor general equilibrium model to illustrate different channels in a unified framework. Then, we propose an approach to decompose overall carbon leakage into channels.

3.1. Theoretical model

Consider a world with a representative consumer who purchases domestic goods Q and foreign goods Q^* . The utility function preserves the following Cobb-Douglas form:

$$U = Q^\beta (Q^*)^{1-\beta} \tag{1}$$

where β denotes the share of expenditure on the home goods.

Given total income I , the sum of income from factor endowments and potential carbon price (carbon tax or carbon ETS), together with the domestic and foreign goods prices (p, p^*), the utility maximization gives rise to the domestic and foreign demands:

$$Q = \frac{\beta I}{p}; Q^* = \frac{(1-\beta)I}{p^*} \tag{2}$$

Production uses energy-carbon e and capital k , and pays energy-carbon price p_e and capital reward r . Assuming capital does not move across countries, the inelastic supply of capital at the home and foreign

countries are \bar{K} and \bar{K}^* , respectively. We also assume an upward-sloping world supply of energy-carbon $\bar{E}(p_e)$. The constant returns to scale production technologies are provided by the Cobb-Douglas form. Hence home and foreign production functions are:

$$q = Ak^{1-\alpha}e^\alpha; q^* = A^*(k^*)^{1-\alpha^*}(e^*)^{\alpha^*} \tag{3}$$

where (A, A^*) are the respective home and foreign technology coefficients, and (α, α^*) are the respective energy-carbon intensities in home and foreign production technologies.

We assume the home country imposes a carbon price (carbon tax or carbon ETS) t on energy-carbon, while the foreign one does not. Given the factor reward of capital (r, r^*) and the world energy-carbon price p_e , we have the cost functions:

$$c(r, p_e + t) = \frac{W}{A} r^{1-\alpha} (p_e + t)^\alpha; c^*(r^*, p_e) = \frac{W^*}{A^*} (r^*)^{1-\alpha^*} p_e^{\alpha^*} \tag{4}$$

where $W \equiv \alpha^{-\alpha}(1 - \alpha)^{\alpha-1}$, $W^* \equiv \alpha^{*\alpha^*}(1 - \alpha^*)^{\alpha^*-1}$.

Following Shepard Lemma, the home and foreign factor demand of capital and energy-carbon are respectively:

$$e = \frac{\partial c(r, p_e + t)}{\partial p_e} q; e^* = \frac{\partial c^*(r^*, p_e)}{\partial p_e} q^*; k = \frac{\partial c(r, p_e + t)}{\partial r} q; k^* = \frac{\partial c^*(r^*, p_e)}{\partial r^*} q^* \tag{5}$$

Profit maximization yields that marginal costs equal output price, thus, $p = c(r, p_e + t)$ and $p^* = c^*(r^*, p_e)$. Factor market-clearing conditions for world energy-carbon, home capital and foreign capital are:

$$e + e^* = \frac{\partial c(r, p_e + t)}{\partial p_e} q + \frac{\partial c^*(r^*, p_e)}{\partial p_e} q^* = \bar{E}(p_e) \tag{6}$$

$$k = \frac{\partial c(r, p_e + t)}{\partial r} q = \bar{K}; k^* = \frac{\partial c^*(r^*, p_e)}{\partial r^*} q^* = \bar{K}^* \tag{7}$$

Output market-clearing conditions in the home and foreign markets are:

$$Q = \frac{\beta I}{p} = q; Q^* = \frac{(1-\beta)I}{p^*} = q^* \tag{8}$$

where total income is the sum of factor endowment rewards and carbon price, that is, $I = p_e \bar{E} + r \bar{K} + r^* \bar{K}^* + t e$.

Given the home carbon price t , the two-factor equilibrium variables include the home capital reward r , the foreign capital reward r^* , the world energy-carbon price p_e , the home output price p , the foreign output price p^* , the home output q , and the foreign output q^* . The equilibrium conditions are the world energy-carbon market-clearing condition, the home and foreign capital factor market-clearing conditions, the home and foreign output market-clearing conditions, and the home and foreign profit maximization conditions. With the choice of the home capital as the numeraire good, one of the above equilibrium conditions is redundant.

Proposition 1. (competitiveness and demand channels). Given the world supply of energy-carbon $\bar{E}(p_e)$, the increase of the home carbon price t lowers the home output $\frac{\partial q}{\partial t} < 0$, while raising the foreign output $\frac{\partial q^*}{\partial t} > 0$.

Proposition 1 reveals the impact of stringent climate policies on output via the competitiveness and demand channels. The home carbon price lowers down the competitiveness of the home product, thereby

leading to a decrease in demand. On the contrary, the foreign product enjoys a relative increase in demand. The above shows that, through the two channels, the home country output will decrease and the foreign country output will increase due to the climate policies, leading to similar changes in their emissions.

Proposition 2. (energy channel). Given the world supply of energy-carbon $\bar{E}(p_e)$, the increase of the home carbon price t lowers the world energy-carbon price $\frac{\partial p_e}{\partial t} < 0$ and the home energy-carbon per output $\frac{\partial e^*/q^*}{\partial t} < 0$, while raising the foreign energy-carbon per output $\frac{\partial e^*/q^*}{\partial t} > 0$.

Proposition 2 represents the mechanism of the energy channel. The stringent climate policy shifts home demand for energy-carbon input leftward, and thus lowers energy-carbon consumption per unit output. With the fixed world supply of energy-carbon, the energy price would be depressed, which in turn induces larger demand and higher energy-carbon consumption per unit output abroad.

Proposition 3. (carbon leakage). Given the world supply of energy-carbon $\bar{E}(p_e)$, the increase of the home carbon price t lowers the home energy-carbon demand $\frac{\partial e}{\partial t} < 0$, while raising the foreign energy-carbon demand $\frac{\partial e^*}{\partial t} > 0$.

Proposition 3 shows the overall carbon leakage through three channels. The stringent climate policy would result in a decreased production and energy-carbon consumption per unit output of home product, and a reverse situation in the foreign country, as presented in the Proposition 1 and Proposition 2. As a consequence, it will lower domestic energy consumption (i.e. carbon emissions), but raise foreign energy consumption, causing a positive carbon leakage. The proofs of three propositions are given in Appendix A.

3.2. Decomposition approach

This proposed approach combines CGE model and decomposition analysis, which enables us to decompose overall carbon leakage into channels.

Generally speaking, the multi-regional CGE model often assumes two ways to cut carbon emissions: output reduction and energy substitution. Output reduction usually manifests itself in three ways: increased imports, decreased exports and decreased local demands. Both increased import and decreased export suggest an increase in the rest of the world's emissions and thus leakage. Hence, the changes in imports and exports correspond to the competitiveness channel, while the change in demands implies the demand channel. Energy substitution includes: inter-factor substitution and inter-fuel substitution. The CGE model usually incorporates the substitution relationships between factors of production and energy sources (see Fig. 1). Energy substitution effectively changes the carbon intensity of the end products, and translates to the energy channel of carbon leakage.

With the theoretical model and the CGE model, we can decompose the carbon leakage into different channels. The following equation represents the emission change of a given sector before and after stringent climate policies are enforced:

$$\Delta C_i = Q_i^t C_i^t - Q_i^0 C_i^0 \tag{9}$$

where Δ denotes change, Q_i and C_i are the given sector's output and carbon intensity. The superscript 0 and t denotes "before" and "after" stringent climate policies, respectively. The above equation can then be expressed as:

$$\Delta C_i = Q_i^t C_i^t - Q_i^0 C_i^t + Q_i^0 C_i^t - Q_i^0 C_i^0 = \Delta Q_i C_i^t - Q_i^0 \Delta C_i \tag{10}$$

This decomposition analysis is well known as Laspeyres form, which measures changes over time using the "weights" for time 0 (Ang and

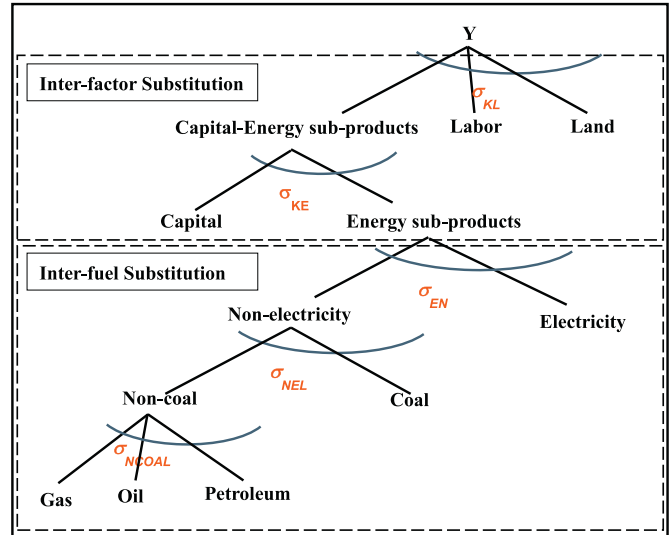


Fig. 1. Substitutions between capital and energy.

Zhang, 2000). In decomposition theory, there is another equivalent form called Paasche form, which uses the weights for time t (Ang and Zhang, 2000). A compromise view, Marshall–Edgeworth form or the average of Laspeyres and Paasche forms, will be adopted in this paper as follows:

$$\Delta C_i = \Delta Q_i (C_i^0 + C_i^t) / 2 + (Q_i^0 + Q_i^t) \Delta C_i / 2 \tag{11}$$

The output change can be divided to analyze the competitiveness and demand channels:

$$\Delta C_i = (\Delta X_i + \Delta D_i - \Delta I_i) (C_i^0 + C_i^t) / 2 + (Q_i^0 + Q_i^t) \Delta C_i / 2 \tag{12}$$

where ΔDE_i , ΔEX_i and ΔIM_i are changes to local demands, exports and imports. Thus, $(\Delta EX_i - \Delta IM_i)(C_i^0 + C_i^t)/2$, $\Delta DE_i(C_i^0 + C_i^t)/2$ and $(Q_i^0 + Q_i^t) \Delta C_i / 2$ can represent the competitiveness channel, demand channel and energy channel, respectively.

According to Fig. 1, the energy channel would be further decomposed, since carbon intensity C_i can be expressed as:

$$C_i = c_i / Q_i = \sum_j^4 \frac{E_i}{Q_i} \frac{F_i}{E_i} \frac{F_{ij}}{F_i} \gamma_j = \frac{E_i}{Q_i} \frac{F_i}{E_i} \sum_j^4 \frac{F_{ij}}{F_i} \gamma_j = N_i S_i \sum_j^4 M_{ij} \gamma_j \tag{13}$$

where N_i is energy intensity (E_i / Q_i), S_i is the fossil fuels (non-electricity) share in energy (F_i / E_i), subscript j denotes different kinds of fossil fuels (coal, gas, oil and petroleum), M_{ij} is the share of fossil fuel j in total fossil fuels (F_{ij} / F_i), and γ_j is the carbon emission coefficient of fossil fuel j , which is supposed to be unchanged.

When there are more than two factors in additive decomposition, the two-factor decomposition form in Eq. (2) can be further extended as the S/S method in IDA (Ang et al., 2003) or D&L method in SDA (Su and Ang, 2012). Besides, there is another decomposition method called the logarithmic mean Divisia index (LMDI) which has been widely used in IDA and recently used in SDA (Su and Ang, 2012; Ang, 2015). Based on the guidelines on LMDI in Ang (2015), the additive LMDI-I method

is a suitable method for our formulation here and the change in carbon intensity can be calculated as:

$$\begin{aligned} \Delta CI_i &= L(\omega^t, \omega^0) \ln\left(\frac{N_i^t}{N_i^0}\right) + L(\omega^t, \omega^0) \ln\left(\frac{S_i^t}{S_i^0}\right) + \sum_j^4 L(\omega^t, \omega^0) \ln\left(\frac{M_{ij}^t}{M_{ij}^0}\right) \\ &= L(\omega^t, \omega^0) \ln\left(\frac{N_i^t}{N_i^0}\right) + L(\omega^t, \omega^0) \ln\left(\frac{S_i^t}{S_i^0}\right) + L(\omega^t, \omega^0) \ln\left(\frac{M_{ic}^t}{M_{ic}^0}\right) \\ &\quad + \sum_j^3 L(\omega^t, \omega^0) \ln\left(\frac{M_{ij}^t}{M_{ij}^0}\right) \\ &= \Delta CI_i^N + \Delta CI_i^S + \Delta CI_i^C + \Delta CI_i^M \end{aligned} \tag{14}$$

where $L(\omega^t - \omega^0) = \frac{CI_i^t - CI_i^0}{\ln(CI_i^t / CI_i^0)}$ is the logarithmic mean function of CI_i^t and CI_i^0 , subscript c denotes coal, ΔCI_i^N is energy intensity effect ($L(\omega^t, \omega^0) \cdot \ln(\frac{N_i^t}{N_i^0})$), reflecting inter-factor substitution, ΔCI_i^S is fossil fuel structural effect ($L(\omega^t, \omega^0) \cdot \ln(\frac{S_i^t}{S_i^0})$), ΔCI_i^C is coal share effect ($L(\omega^t, \omega^0) \cdot \ln(\frac{M_{ic}^t}{M_{ic}^0})$), ΔCI_i^M is other fossil fuel mix effect ($\sum_j^3 L(\omega^t, \omega^0) \cdot \ln(\frac{M_{ij}^t}{M_{ij}^0})$), and $\Delta CI_i^S + \Delta CI_i^C + \Delta CI_i^M$ is inter-fuel substitution.

4. Numerical model and scenarios

We simulate the magnitudes of three channels by calibrating TermCO2 model with data from Hubei Pilot ETS. This section outlines the key features of TermCO2 model and scenario design.

4.1. TermCO2 model

The TermCO2 model is a multi-region CGE model developed by the Institutes of Science and Development, Chinese Academy of Sciences, and the Cops Center of Victoria University in Australia. This model is based on the provincial-level input/output table of China, with the following features: (a) it is a bottom-up multi-regional general equilibrium model that treats each province as a separate economy, connected to each other by trade, investment and labor mobility; (b) compared to the conventional top-down model, it has the advantage of simulating regional supply-side shocks in addition to the demand-side ones; and (c) for the impact of climate policies, the model incorporates a carbon tax/ETS module, allowing us to conduct and decompose carbon leakage caused by Hubei Pilot ETS.

In the carbon tax/ETS module, the carbon tax is implemented as the changes in the indirect tax rate on fossil energy consumption. Since the carbon tax is levied as a non-*ad valorem* duty, in the first place it is converted into an *ad valorem* duty before its addition into the model, using the following equation:

$$P_{co2} \times C_i = BASE_i \times T_i \tag{15}$$

where P_{co2} , as an exogenous policy variable, is the carbon tax in RMB/t. C_i is the carbon emissions measured in tonne. $BASE_i$ denotes the tax base, provided by the TermCO2 economic database. T_i represents the indirect tax rate increase in fossil energy. This allows us to transform the carbon tax from the non-*ad valorem* P_{co2} to *ad valorem*, i.e. $T_i = (P_{co2} \times C_i) / BASE_i$.

With carbon tax introduced, the TermCO2 model could provide a comprehensive assessment of the economic impacts of carbon tax or ETS, using mechanisms shown in Fig. 2. In the case of carbon tax, an exogenous carbon tax rate variable T_i could be added to the model to simulate post-impact emissions C_i , allowing us to draw a marginal abatement cost (MAC) plot. The impact of ETS is simulated by an inverse process: an emission cap CAP_i is introduced to obtain a corresponding shadow carbon price P_i , i.e., the carbon allowance price which equals

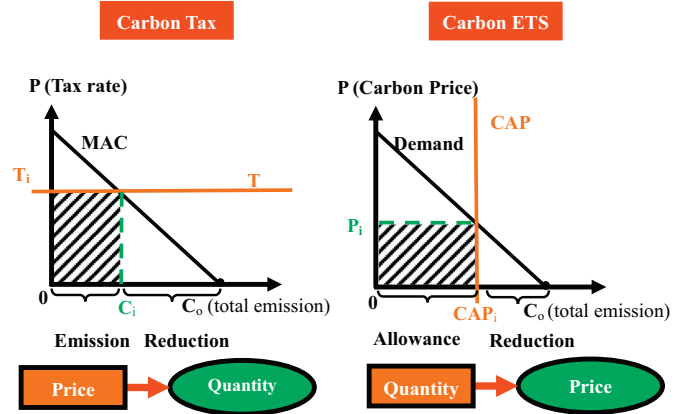


Fig. 2. Schema of the carbon tax/ETS module.

the carbon tax rate at the cap level. The MAC plot can be obtained similarly. Based on this module, the TermCO2 model could simulate how carbon tax or ETS would affect macro-economy, sectoral output and carbon leakage.

The social accounting matrix data in the TermCO2 model are derived from the input/output tables of 42 sectors among 31 provinces of China, published by the National Bureau of Statistics, and the provincial trade and tariff data provided by China Customs, both data starting from year 2007. The energy data in CO2 emissions database are obtained from *China Energy Statistical Yearbook 2008*, and the carbon emission factor is retrieved from the IPCC. Data on substitution elasticity among different types of energy is from GTAP-E model database. The values of Armington elasticity are taken from the 9th Version of GTAP database. The TermCO2 model is a static CGE model with 6 layers of production, most of which are nested in Constant Elasticity of Substitution form. In this paper, we use a short-run closure which means sticky wage and constancy of regional industrial capital stocks. Moreover, there are some additional hypotheses: the labor force can flow freely within a province but cannot flow between provinces; regional total consumption depends on regional workers' income, while the government expenditure is fixed; and regional industrial return of capital and workforce keep changing, while industry investment level depends on industry return of capital.

4.2. Scenario design

The simulation is conducted using the Hubei Pilot ETS as an example. This ETS is chosen for the following reasons: First, there is not enough literature studying on carbon leakage caused by sub-national climate-change policies in one country. Second, the implementation of carbon trading across provinces in China has not been cooperated and coordinated, providing a good scenario for the simulation of carbon leakage across sub-national regions. Third, among seven regional Pilot ETSs in China, Hubei Pilot ETS makes for a particularly representative example in a developing country with stable and active trading, and substantial abatement effect (Qi et al., 2014).

Two scenarios of interests are proposed for this study. The first one is the reference scenario, in which no abatement policies are enforced. The other is the Hubei Pilot ETS scenario, which assumes Hubei as the only Pilot ETS set in effective. Then, we can simulate the magnitude of carbon leakage and its channels. It is worth noting that other six ETS Pilots do not appear in our model. This simplifying assumption shuts down interactions among different carbon leakages from multi-regions, which is important but not the focus of this paper. Therefore, we can analyze carbon leakage caused by Hubei Pilot ETS and its channels with greater clarity.

The key issue in setting up the policy scenario is to determine the abatement target of each sector based upon the *Interim Regulations on Carbon Emissions Trading in Hubei Province*. According to its provisions,

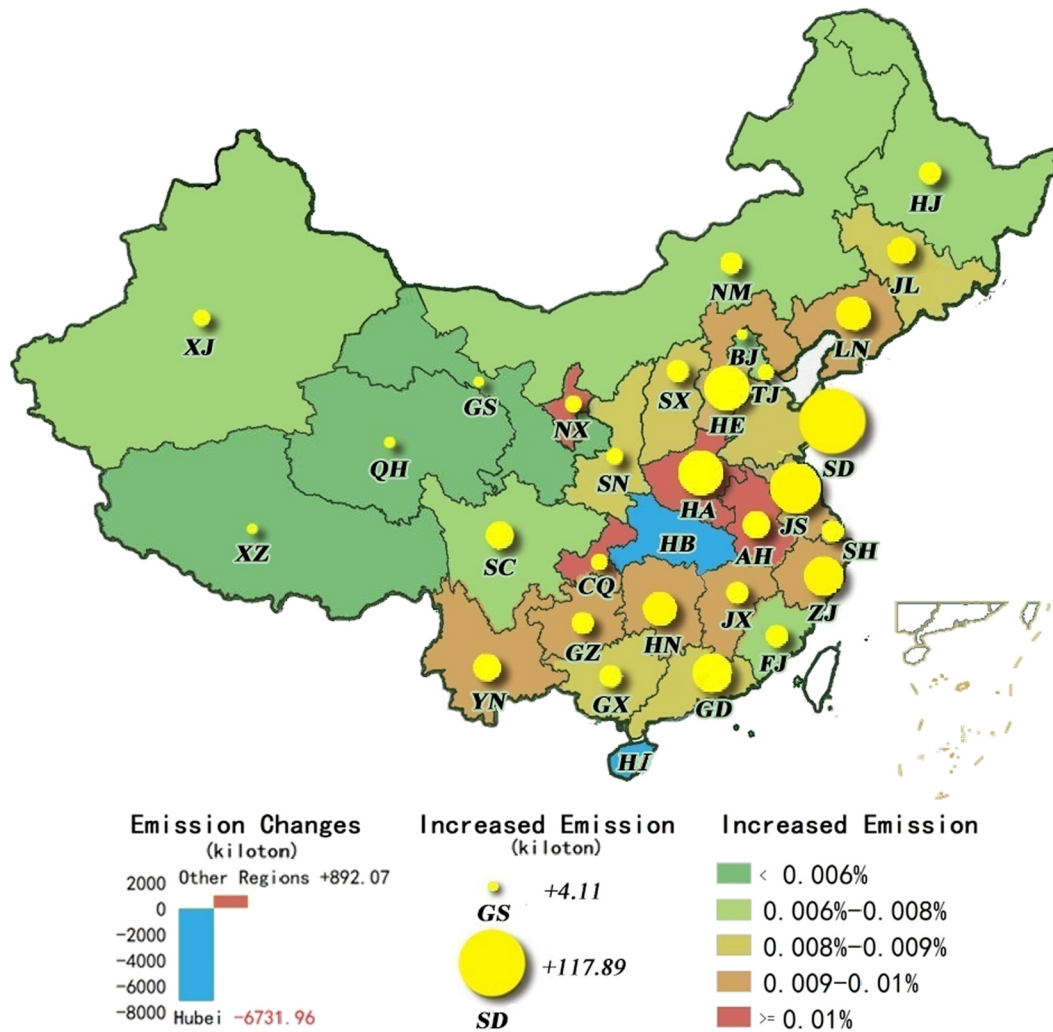


Fig. 3. Carbon emission changes and change rates by province NOTE: AH – Anhui, BJ – Beijing, FJ – Fujian, GS – Gansu, GD – Guangdong, GX – Guangxi, GZ – Guizhou, HI – Hainan, HE – Hebei, HA – Henan, HJ – Heilongjiang, HB – Hubei, HN – Hunan, JL – Jilin, JS – Jiangsu, JX – Jiangxi, LN – Liaoning, NM – Inner Mongolia, NX – Ningxia, QH – Qinghai, SD – Shandong, SX – Shanxi, SN – Shaanxi, SH – Shanghai, SC – Sichuan, TJ – Tianjing, XZ – Tibet, XJ – Xinjiang, YN – Yunnan, ZJ – Zhejiang, CQ – Chongqing.

the Hubei Pilot ETS covers all firms with total consumption above 60,000 t of coal equivalent.³ The free allowances of each covered firm is set to 97% of its historical emissions, that is to say, each firm is required to reduce its emissions by 3% (Liu et al., 2017). Since not every firm in these sectors is covered by the ETS, the abatement target of each sector would also multiply the reduction rate with the share of the covered firms in its sector.

5. Simulation results

This section presents simulation results of carbon leakage, its regional flows, and the magnitude of channels.

³ In 2013, 138 firms in 10 sectors meet the criterion. In 2014 and 2015, the Hubei Pilot ETS had respectively categorized its covered firms into 12 and 15 sectors. For this study, we devised our own division based on the 42-sector input/output table of the National Bureau of Statistics. Covered sectors in our division include: oil & natural gas extraction; food & tobacco processing; papermaking, printing & stationery manufacturing; petroleum processing, coking & nuclear fuel processing; chemical industries; non-metallic mineral products; smelting; general & special-purpose equipment manufacturing; transport equipment manufacturing; and power & heat.

5.1. Carbon leakage rates and regional flows

Fig. 3 shows that carbon emissions in Hubei have decreased by about 0.97%, or 6731.96 kt, while total emissions in other provinces have increased slightly by 0.01%, or 892.07 kt. Carbon emissions increase in most provinces, except a slight decrease in Hainan Province. This is consistent with Proposition 3, indicating that the ETS could lead to carbon leakage, with a leakage rate of 13.25%.

The IPCC indicates a leakage rate of 5% to 20% (IPCC, 2007). The leakage rate of Hubei Pilot ETS is in the medium-to-higher range for the following reasons: First, without tariffs or other trade barriers, the inter-provincial trade competition in China is even fiercer than international trade, as the model shows Hubei suffering a far greater decrease in its export to other provinces (−0.18%) than to foreign markets (−0.07%). Second, power and heat are mobile across regions in China, turning the power & heat sector into a major source of carbon leakage. Lastly, some model assumptions have boosted the leakage rate, e.g., only Hubei Pilot ETS appears in our model; only short-term shocks are considered; no technological progress is assumed.

Fig. 3 also depicts the regional flows of carbon leakage, including emission changes and change rates by province. The ratios of increases are greater in provinces nearer to Hubei, with the top five regions being Chongqing, Ningxia, Anhui, Henan, and Jiangxi. And the ratios

are smaller in more distant provinces, with the lowest five being Gansu, Beijing, Tibet, Qinghai, and Shanghai. In terms of absolute changes, Shandong is the only province with an increase over 100 kt, while Jiangsu, Henan, Hebei, Zhejiang, and Guangdong each has an increase over 50 kt. It can be explained by high historical emissions in these provinces and their sectoral structures. Both these provinces and Hubei enjoy competitive advantages in non-metallic mineral products, smelting, and power & heat.

5.2. Decomposition of carbon leakage by sector

Table 1 presents the simulated results of carbon leakage decomposed by sector and channel. It is generally recognized that the risk of carbon leakage may be higher in certain energy-intensive industries, such as the smelting, non-metallic mineral products, and chemical industries. Table 1 indicates that Hubei cuts 5490.14 kt of emissions in these three sectors, about 81.55% of total reduction. In other provinces, these sectors also account for 517.28 kt of increased emissions, or 57.99% of the overall growth. The results confirm that conventional energy-intensive sectors are the main source of leakage.

Generally speaking, the power & heat sector is not a notable leakage source, as it is largely immobile across countries. An interesting finding in this paper is that the power & heat sector has the greatest emission growth in other provinces, with a total of 393.82 kt. From another perspective, the power & heat sector has a high leakage rate of 42.62%, while the rates are 6.99%, 12.98% and 9.29% for smelting, non-metallic products and chemical industries, respectively. This can be attributed to facts that increased output in other provinces further rise the demand for electricity, and the power & heat sector occupies the large share in the final energy consumption.

It should be noted that carbon leakage does not occur in some covered sectors. Carbon emissions do not increase in other provinces for the petroleum processing, coking & nuclear fuel processing, and the transport equipment manufacturing sectors, but rather decrease by 1.33 and 0.07 kt, respectively. A channel-based analysis shows that the reduction in the former is largely due to a 10.53 kt decrease via the competitiveness channel, which ultimately results from the reduced consumption of fossil energy in Hubei. Meanwhile, the latter sector has a 0.95 kt decrease in the demand channel, because of less demand for transport equipment caused by the decline in inter-provincial and international trade.

5.3. Competitiveness and demand channels

The competitiveness channel originates from changes in import and export, while the demand channel results from local demand changes, both related to outputs. Through competitiveness channel (or demand channel), Hubei reduces emissions by 1151.00 kt (or 1209.81 kt), while

other regions increase emissions by 483.24 kt (or 75.21 kt). Therefore, the competitiveness channel is the main source of carbon leakage with a leakage rate of 41.98%, and the demand channel is smaller than the other two channels with the lowest rate of 6.21%. Overall, the competitiveness channel and demand channel lead to a positive leakage, which is consistent with the Proposition 1. And the reduction in Hubei far surpasses the increase in other provinces, indicating a total output decline in the carbon-intensive sectors.

The increased costs caused by Pilot ETS would lower exports and local demands, and raise imports in Hubei, thus reducing its emissions. The simulation results show that the product prices in 8 out of the 10 covered sectors increase, with the top three by ratio being non-metallic mineral products (0.25%), smelting (0.14%) and chemical industries (0.14%). As a result, Hubei cuts emissions by 1209.81 kt because of declining local demand. The decrease through export changes is 1121.68 kt, accounting for the vast majority of the competitiveness channel. By comparison, the decrease via import reaches only 29.32 kt. It implies that Hubei Pilot ETS leads to a big decline in export, instead of a significant import substitution effect. This also suggests that a carbon tariff on imports will have an extremely limited effect in Hubei.

The Hubei Pilot ETS could increase the competitiveness in other provinces, but its influences on their local demands are less certain. Fig. 4 shows that other provinces increase emissions by 256.28 kt caused by decline in import from Hubei, indirectly reflecting loss of Hubei's export competitiveness. This largely occurs in provinces near Hubei: Hunan, Zhejiang, Guangdong, Shandong, Henan, and Anhui. What's more, other provinces with an improvement in their terms of trade would take over market shares from Hubei, increasing emissions by 226.96 kt. This largely happens in Shandong, Jiangsu, Hebei, Guangdong, Liaoning and Zhejiang. The demand channel leads to 75.21 kt of increased emissions in other provinces as a whole. However, 15 provinces contribute to the increase, while the other 15 provinces show decline in the demand channel. It implies that the effect of the demand channel may be less predictable.

5.4. Energy channel

Hubei performs major abatement through substitution of energy, adding up to 4386.60 kt, or 65.16% of the overall reduction. On the other hand, the substitution effects are very weak in other provinces, which only increase 333.62 kt of emissions, or 33.08% of total emissions increase. As a consequence, the energy channel has a leakage rate of 7.61%, though significantly lower than that of the competitiveness channels.

Carbon leakage rate through energy channel is modest due to limited energy price fall. Table 2 shows that the price levels decline in all four fossil energy-related sectors, which supports Proposition 2. Among the 10 covered sectors, only two oil-related sectors show price

Table 1
Decomposition of carbon leakage by sector.

Sector	Carbon leakage (kiloton)		Leakage rate* (%)	Comp. & demand channel (kiloton)		Energy channel (kiloton)	
	Others	Hubei		Others	Hubei	Others	Hubei
Oil & gas extraction	0.31	-0.69	45.11	0.11	-0.11	0.20	-0.58
Food & tobacco processing	7.95	-79.62	9.99	4.58	-0.83	3.38	-78.82
Papermaking, printing & stationery manufacturing	7.26	-87.72	8.28	3.90	-6.08	3.36	-81.68
Petroleum processing, coking & nuclear fuel	-1.33	-14.89	-8.96	-2.58	-10.01	1.25	-4.86
Chemical industries	101.05	-1088.30	9.29	66.04	-366.08	35.01	-724.04
Non-metallic mineral products	235.38	-1813.32	12.98	167.90	-744.86	67.48	-1073.22
Smelting	180.85	-2588.52	6.99	117.47	-907.25	63.38	-1689.00
General & special purpose equipment	0.11	-63.40	0.18	-1.07	-11.53	1.18	-51.92
Transport equipment	-0.07	-31.57	-0.23	-0.42	-3.89	0.35	-27.68
Power & heat	393.82	-923.93	42.62	241.08	-271.31	152.74	-653.56
Uncovered sectors	-33.26	-40.00	-83.15	-38.54	-38.86	5.28	-1.24
All sectors	892.07	-6731.96	13.25	558.45	-2360.81	333.62	-4386.60

NOTE: * A sector's carbon leakage rate is its carbon emissions increase in other provinces, divided by its emissions decrease in Hubei.

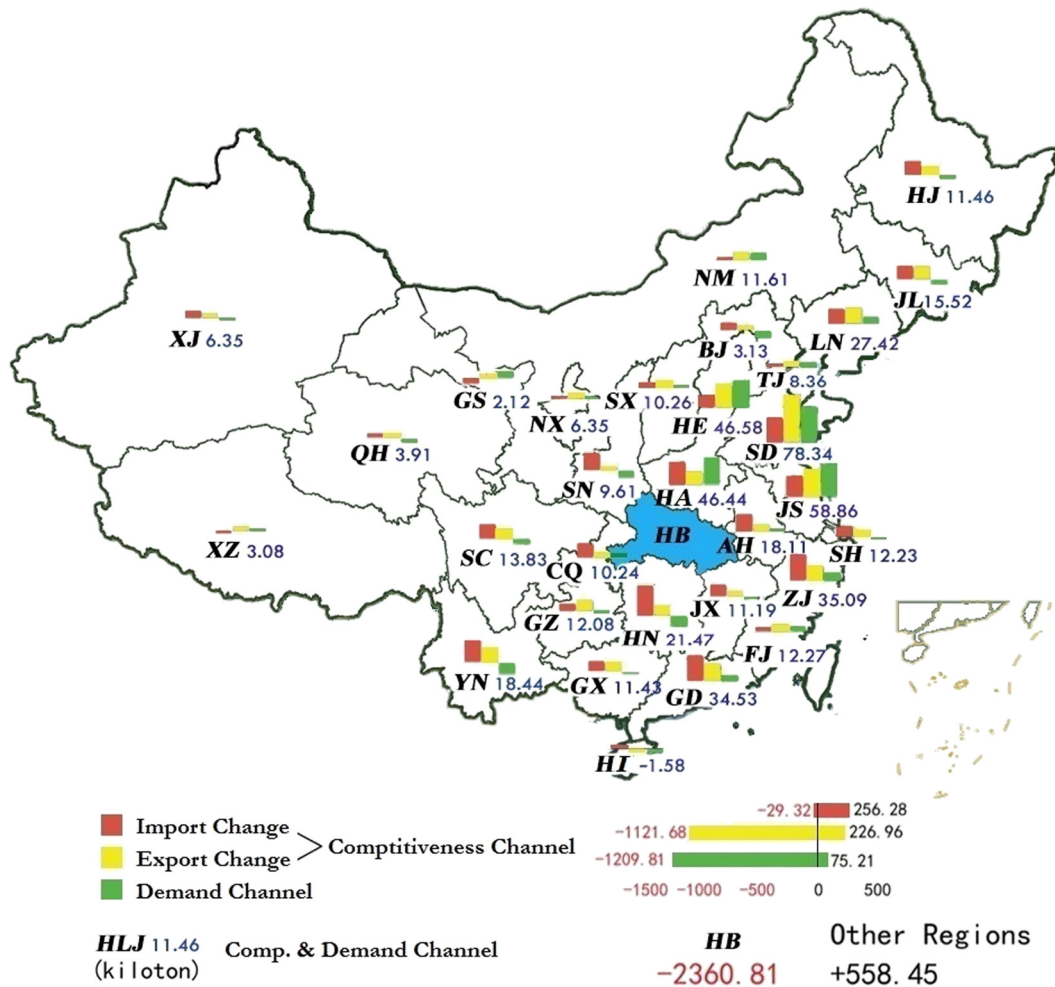


Fig. 4. Carbon leakage via the competitiveness and demand channels by province.

fall; their outputs in Hubei also decrease. Coal extraction & dressing sector undergoes the biggest price drop, as coal has the highest carbon emission per unit of heat content. However, the price level of this sector only experiences a 0.11% decrease, which does not substantially spur other provinces to substitute other factors for fossil energy. Because Hubei is the only province adopting the ETS assumed in the policy scenario, with only little influence on energy prices. Other reasons are attributed to the high costs of transportation for fossil energy, and addition technical and capital investment required in switching energy sources.

The TermCO₂ model simulates energy channel as inter-factor substitution and inter-fuel substitution, as shown in Fig. 5. Hubei pilot TES incurs an additional cost to fossil energy and in turn leads to decline in demand for them. Energy channel causes an emission reduction of 4386.60 kt in Hubei, which is nearly twice of the competitiveness and demand channels combined. Inter-factor substitution reduces 1993.68 kt of emissions, accounting for 45.45% of the energy channel, highlighting the significance of increased capital and other factors in achieving emission reduction (energy intensity effect). Inter-fuel substitution accounts for

the remaining 54.55%, which is explained by the relative low costs of switching energy sources. Specifically, 1301.78 kt of emission reduction are from fossil fuel structural effect, 986.54 kt are from coal share effect, and 104.6 kt are from other fossil fuel mix effect.

For other provinces, their demands for fossil energy are on the rise due to the reduced prices. The carbon leakage via the energy channel reaches 333.62 kt in other provinces. Geographically, the top five provinces are Shandong, Jiangsu, Henan, Hebei, and Zhejiang, which are proximate to the coal-producing region in Northern China. Within the channel, 43.88%, or 146.38 kt of emissions are increased due to inter-factor substitution (energy intensity effect). Inter-fuel substitution is more prominent, specifically, 129.06 kt of emissions from fossil fuel structural effect, 38.58 kt from coal share effect, 19.60 kt from other fossil fuel mix effect.

6. Conclusion

This paper assesses carbon leakage by the channels of competitiveness, demand and energy in a unified framework. We first employ a

Table 2
Effects of Hubei ETS market on outputs and prices of energy sectors.

Covered sectors	Output (%)	Price (%)	Uncovered sectors	Output (%)	Price (%)
Oil & natural gas extraction	-0.03	-0.01	Coal extraction & dressing	-0.11	-0.11
Petroleum processing, coking & nuclear fuel processing	-0.13	-0.03	Fuel gas production & supply	-0.02	-0.02

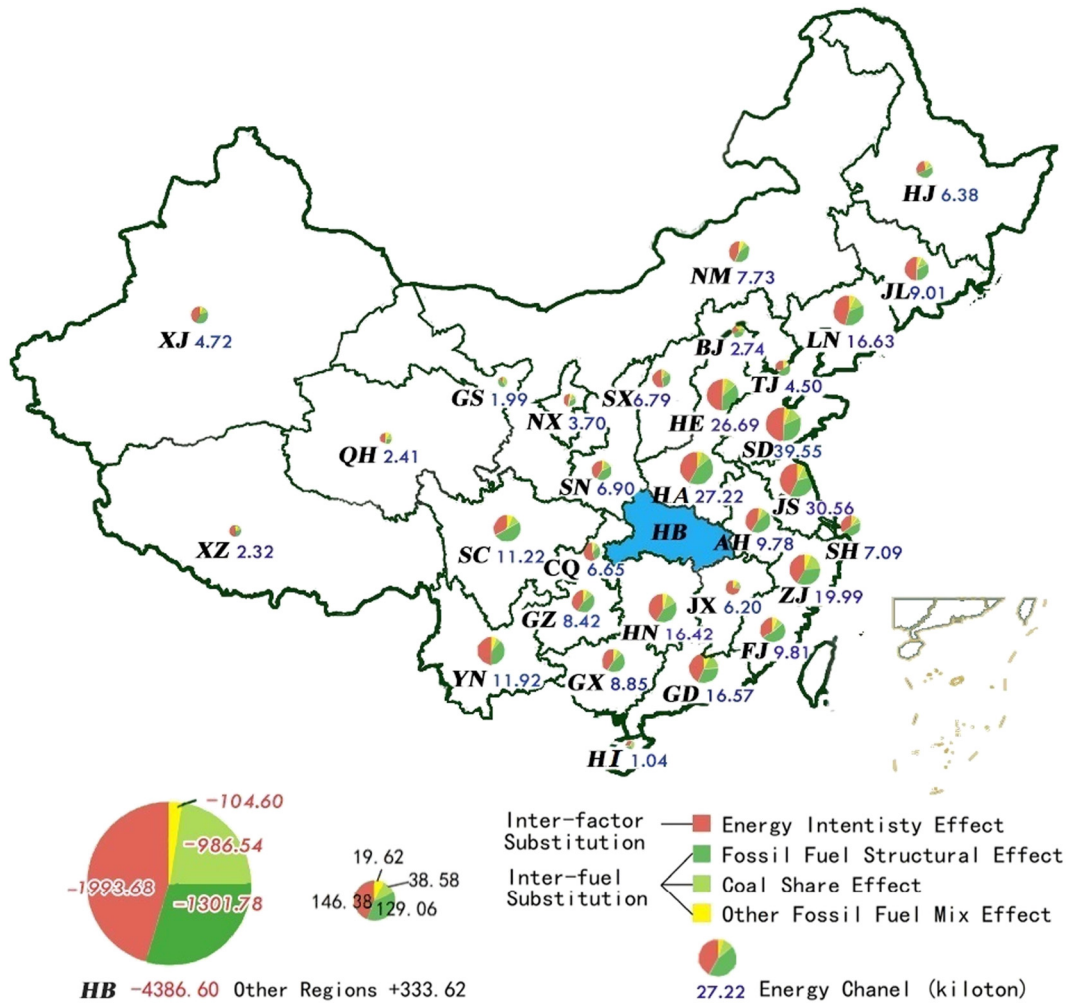


Fig. 5. Carbon leakage via the energy channel by province.

two-factor general equilibrium model to illustrate different channels. This model confirms the common concern that competitiveness and demand channels as a whole cause relocation of energy-intensive production, and energy channel leads to increased carbon-intensity in other regions, resulting in positive leakage.

Then, we propose an approach combining CGE model and decomposition analysis, to decompose overall carbon leakage into the channels of competitiveness, demand and energy. To further identify sizes of these channels, we apply the suggested approach to numerically simulate the magnitudes of three channels, by calibrating CGE model to data from Hubei Pilot ETS in China. The results demonstrate these theoretical propositions discussed above. And we find that:

First, Hubei cuts carbon emissions by 6731.96 kt, while other provinces increase emissions by 892.07 kt, leading to a leakage rate of 13.25%. The leakage is higher in provinces nearer to Hubei, and largely concentrated in conventional energy-intensive sectors and power & heat industry.

Second, the competitiveness channel is the main source of carbon leakage with a leakage rate of 41.98%, while the demand channel with the lowest rate of 6.21%. Overall, the reduction in Hubei far surpasses the increase in other provinces, indicating a total output decrease in the carbon-intensive sectors.

Lastly, the energy channel has a leakage rate of 7.61%, significantly lower than that of the competitiveness channel due to limited energy price fall. Within the energy channel, inter-fuel substitution is more prominent than inter-factor substitution.

On the basis of the aforementioned analyses, this study offers the following suggestions. First, carbon reduction targets proposed by NDCs are very disparate in ambition level, thus indicating potential to carbon leakage. This highlights the significance of counter measures, such as border carbon adjustment (BCA), and free allowance allocation. Second, BTA may alleviate carbon leakage by applying carbon price on import, as the competitiveness channel is the main source. However, BTS is only a partial remedy because of its ineffectiveness for other channels. Third, free allowance allocation may be useful to minimize competitiveness channel and demand channel. But it is more challenging to reduce the energy channel.

However, it is important to bear in mind that our paper only involves one ETS for simplicity. Other six Pilot ETSs are not present in our theoretical model and numerical model. For this reason, the interaction among carbon leakages from different ETSs are indistinguishable. Future work should address how to conduct the analysis with multiple ETSs using the proposed decomposition approach.

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Appendix A. Proposition 1: competitiveness and demand channels

Based on the conditions of domestic and foreign output market-clearing, and profit maximization, one derives that,

$$\frac{Q}{Q^*} = \frac{\beta}{1-\beta} \frac{p^*}{p} = \frac{q}{q^*}$$

Using the conditions of domestic and foreign capital factor market-clearing, it yields,

$$\frac{\beta}{1-\beta} \frac{p^*}{p} = \frac{q}{q^*} = \frac{\bar{K} \frac{\partial c^*(r^*, p_e)}{\partial r^*}}{\bar{K}^* \frac{\partial c(r, p_e + t)}{\partial r}} \Rightarrow \frac{\beta}{1-\beta} \frac{r^*}{r} = \frac{1-\alpha^* \bar{K}}{1-\alpha \bar{K}^*}$$

Given the choice of domestic capital as the numeraire good, $r = 1$, the capital reward in the home and foreign countries are irrelevant to carbon price. The domestic capital market-clearing condition yields,

$$(1-\alpha) \left(\frac{p_e + t}{r} \right)^\alpha \frac{q}{A} = \bar{K} \Rightarrow \left(\frac{p_e + t}{r} \right)^\alpha = \frac{A \bar{K}}{1-\alpha} \frac{1}{q}$$

$$(1-\alpha^*) \left(\frac{p_e}{r^*} \right)^\alpha \frac{q^*}{A^*} = \bar{K}^* \Rightarrow \left(\frac{p_e}{r^*} \right)^\alpha = \frac{A^* \bar{K}^*}{1-\alpha^*} \frac{1}{q^*}$$

The above two equations together give rise to,

$$r^* \left(\frac{A^* \bar{K}^*}{1-\alpha^*} \frac{1}{q^*} \right)^{\frac{1}{\alpha}} + t = r \left(\frac{A \bar{K}}{1-\alpha} \frac{1}{q} \right)^{\frac{1}{\alpha}}$$

Using the world energy-carbon market-clearing condition,

$$e + e^* = \alpha \left(\frac{r}{p_e + t} \right)^{1-\alpha} \frac{q}{A} + \alpha^* \left(\frac{r^*}{p_e} \right)^{1-\alpha^*} \frac{q^*}{A^*} = \bar{E}(p_e)$$

Using the domestic capital market-clearing condition, further simplification yields,

$$\alpha \left(\frac{\bar{K}}{1-\alpha} \right)^{\frac{\alpha-1}{\alpha}} \left(\frac{q}{A} \right)^{\frac{1}{\alpha}} + \alpha^* \left(\frac{\bar{K}^*}{1-\alpha^*} \right)^{\frac{\alpha^*-1}{\alpha^*}} \left(\frac{q^*}{A^*} \right)^{\frac{1}{\alpha^*}} = \bar{E}(p_e)$$

$$\bar{K} \frac{\alpha}{1-\alpha} \left(\frac{A \bar{K}}{1-\alpha} \frac{1}{q} \right)^{-\frac{1}{\alpha}} + \bar{K}^* \frac{\alpha^*}{1-\alpha^*} \left(\frac{A^* \bar{K}^*}{1-\alpha^*} \frac{1}{q^*} \right)^{-\frac{1}{\alpha^*}} = \bar{E}(p_e)$$

Given the price of the numeraire good $r = 1$ and foreign capital reward $r^* = \frac{1-\alpha^*}{1-\alpha} \frac{1-\beta}{\beta} \frac{\bar{K}}{\bar{K}^*} r$, define $V \equiv \left(\frac{A \bar{K}}{1-\alpha} \frac{1}{q} \right)^{\frac{1}{\alpha}}$ and $V^* \equiv \left(\frac{A^* \bar{K}^*}{1-\alpha^*} \frac{1}{q^*} \right)^{\frac{1}{\alpha^*}}$, and the above two equations yield,

$$r^* V^* + t = V$$

$$\frac{\alpha \bar{K}}{1-\alpha} \frac{1}{V} + \frac{\alpha^* \bar{K}^*}{1-\alpha^*} \frac{1}{V^*} = \bar{E}(p_e)$$

From the above two equations together we derive,

$$\frac{\alpha \bar{K}}{1-\alpha} \frac{1}{r^* V^* + t} + \frac{\alpha^* \bar{K}^*}{1-\alpha^*} \frac{1}{V^*} = \bar{E}(p_e)$$

Using total differentiation with respect to t , we could derive that

$$-\frac{\alpha \bar{K}}{1-\alpha} \frac{1}{(r^* V^* + t)^2} \left(r^* \frac{\partial V^*}{\partial t} + 1 \right) - \frac{\alpha^* \bar{K}^*}{1-\alpha^*} \frac{1}{V^{*2}} \frac{\partial V^*}{\partial t} = \bar{E}'(p_e) \frac{\partial p_e}{\partial t}$$

The foreign capital market-clearing condition is $\left(\frac{p_e}{r^*} \right)^\alpha = \frac{A^* \bar{K}^*}{1-\alpha^*} \frac{1}{q^*}$ and $V^* \equiv \left(\frac{A^* \bar{K}^*}{1-\alpha^*} \frac{1}{q^*} \right)^{\frac{1}{\alpha^*}}$, and we know $\frac{\partial p_e}{\partial t} = r^* \frac{\partial B^*}{\partial t}$. Thus, the above equation gives rise to,

$$-\frac{\alpha \bar{K}}{1-\alpha} \frac{1}{(r^* V^* + t)^2} \left(r^* \frac{\partial V^*}{\partial t} + 1 \right) - \frac{\alpha^* \bar{K}^*}{1-\alpha^*} \frac{1}{V^{*2}} \frac{\partial V^*}{\partial t} = \bar{E}'(p_e) r^* \frac{\partial V^*}{\partial t}$$

$$\frac{\partial V^*}{\partial t} = \frac{-\alpha \bar{K}}{1-\alpha} \frac{1}{(r^* V^* + t)^2} \left[\frac{\alpha \bar{K}}{1-\alpha} \frac{r^*}{(r^* V^* + t)^2} + \frac{\alpha^* \bar{K}^*}{1-\alpha^*} \frac{1}{V^{*2}} + \bar{E}'(p_e) r^* \right] < 0$$

We know that $\frac{\partial V^*}{\partial t} < 0$, henceforth $\frac{\partial V}{\partial t} > 0$. Given $V \equiv \left(\frac{A \bar{K}}{1-\alpha} \frac{1}{q} \right)^{\frac{1}{\alpha}}$ and $V^* \equiv \left(\frac{A^* \bar{K}^*}{1-\alpha^*} \frac{1}{q^*} \right)^{\frac{1}{\alpha^*}}$, one derives $\frac{\partial q}{\partial t} < 0$ and $\frac{\partial q^*}{\partial t} > 0$.

Appendix B. Proposition 2: energy channel

Using the foreign capital market-clearing condition, $(1-\alpha^*) \left(\frac{p_e}{r^*} \right)^\alpha \frac{q^*}{A^*} = \bar{K}^* \Rightarrow \left(\frac{p_e}{r^*} \right)^\alpha = \frac{A^* \bar{K}^*}{1-\alpha^*} \frac{1}{q^*}$. Given the numeraire good nature of domestic capital, $r = 1$, and foreign capital reward $r^* = \frac{1-\alpha^*}{1-\alpha} \frac{1-\beta}{\beta} \frac{\bar{K}}{\bar{K}^*} r$, together with $\frac{\partial q^*}{\partial t} > 0$, one could derive $\frac{\partial p_e}{\partial t} < 0$.

The domestic and foreign energy-carbon consumptions per output unit are $\frac{e}{q} = \frac{\alpha \bar{K}}{1-\alpha} \left(\frac{A \bar{K}}{1-\alpha} \right)^{-\frac{1}{\alpha}} q^{\frac{1}{\alpha}-1}$, $\frac{e^*}{q^*} = \frac{\alpha^* \bar{K}^*}{1-\alpha^*} \left(\frac{A^* \bar{K}^*}{1-\alpha^*} \right)^{-\frac{1}{\alpha^*}} q^{*\frac{1}{\alpha^*}-1}$ respectively. Given $\alpha < 1$, $\alpha^* < 1$, together with $\frac{\partial q}{\partial t} > 0$ and $\frac{\partial p_e}{\partial t} < 0$, one could derive $\frac{\partial e/q}{\partial t} < 0$, $\frac{\partial e^*/q^*}{\partial t} > 0$.

Appendix C. Proposition 3: carbon leakage

From Shepard Lemma, one derives the foreign energy-carbon demand $e^* = \alpha^* \left(\frac{r^*}{p_e} \right)^{1-\alpha^*} \frac{q^*}{A^*}$. Given the domestic capital market-clearing condition, $\left(\frac{p_e}{r} \right)^\alpha = \frac{A \bar{K}}{1-\alpha} \frac{1}{q}$, we have $e^* = \bar{K}^* \frac{\alpha^*}{1-\alpha^*} \left(\frac{A \bar{K}}{1-\alpha} \frac{1}{q} \right)^{-\frac{1}{\alpha}}$. Similarly, one could derive the domestic energy-carbon demand $e = \bar{K} \frac{\alpha}{1-\alpha} \left(\frac{A \bar{K}}{1-\alpha} \frac{1}{q} \right)^{-\frac{1}{\alpha}}$. Using $\frac{\partial q}{\partial t} > 0$ and $\frac{\partial p_e}{\partial t} < 0$, we have $\frac{\partial e}{\partial t} < 0$, $\frac{\partial e^*}{\partial t} > 0$.

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