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Intermediate input linkage and carbon leakage

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ABSTRACT. Climate regulations tend to target energy-intensive sectors whose products are widely used in industrial production as intermediate inputs, and carbon abatement may be partially offset by intermediate input-led leakage. This paper aims to examine the impact of intermediate input linkages on carbon leakage both theoretically and empirically. The theoretical part develops a Harberger-type model with an input-output linkage structure, identifies four leakage effects and derives closed-form solutions for these leakage effects. Its empirical part builds a computable general equilibrium model of China's economy and introduces structural decomposition analysis to link the theoretical and empirical models. When imposing a carbon price on the electricity generation sector, our results show significant sectoral carbon leakage. Our decomposition analysis further suggests that such leakage is mainly through the production substitution effect and the multiplier effect. Our results highlight the importance of sectoral linkage when discussing the carbon leakage issue of climate policies.

1. Introduction

After two weeks of hard work and concerted efforts by all the parties involved, the landmark Paris Agreement was reached in December 2015, charting a clear course for global cooperation on fighting climate change

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to hold the average rise in global temperature well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C (UNFCCC, 2015). For governments around the world, the most urgent task of implementing the details of the agreement is to prepare plans and actions in line with their national priorities to achieve the goals set in their nationally determined contributions. Because energy-intensive sectors are major carbon emitters, it should come as no surprise that climate policies will target these sectors. This will lead to carbon leakage across sectors, given that the products of the regulated sectors are widely used in industrial production as intermediate inputs, such as electricity, and the share of intermediate inputs per unit of outputs increases gradually (Xu and Dietzenbacher, 2014). This domestic leakage may in turn offset the carbon reduction of the regulated sectors (Zhang, 2012; Baylis *et al.*, 2014; World Bank, 2015). This situation highlights that intermediate input linkage may be an important influencing factor of carbon leakage. Böhringer *et al.* (2014) found that domestic industries may suffer rather than benefit from anti-leakage measures under the consideration of an intermediate input structure. The purpose of this study is to clarify the relation between the intermediate input linkage and carbon leakage and to evaluate the leakage effects of China's climate regulations on the electricity generation sector.

The theoretical model of this study builds on a Harberger (1962) type general equilibrium model aimed at studying the effects of climate policies (e.g., Fullerton and Heutel, 2007; Fullerton and Monti, 2013; Lanzi and Wing, 2013; Baylis *et al.*, 2014; Elliott and Fullerton, 2014; Rausch and Schwarz, 2016). However, these studies mainly adopt the assumption of an independent sector or vertical sectoral linkage (e.g., Bushnell and Mansur, 2011; Baylis *et al.* 2014; Sen, 2015), and a systematic study on the effect of sectoral linkage on carbon leakage is lacking. To capture the impact of sectoral linkage on carbon leakage, we extend the two independent sector model of Baylis *et al.* (2014), by introducing an intermediate input linkage structure. This study disentangles four leakage effects[1] and derives closed-form solutions for these effects. All these effects are related to the intermediate input linkage either directly or indirectly.

We find that the intermediate input linkage has important implications for assessing the carbon leakage problem. First, the change in gross output and emissions due to consumption change is influenced by the

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[1] The literature presents different leakage channels, such as a fossil fuel channel (e.g., Dröge *et al.*, 2009), competitiveness channel (e.g., Bruvoll and Fæhn, 2006; Zhang, 2012), terms-of-trade effect (e.g., Di Maria and van der Werf, 2008; Baylis *et al.*, 2014), technology channel (e.g., Golombek and Hoel, 2004; Sijm *et al.*, 2004; Dröge *et al.*, 2009; Gerlagh and Kuik, 2014), abatement resource effect (Baylis *et al.*, 2014), intertemporal channel (e.g., Michielsen, 2014; Eichner and Pethig, 2015) and scale channel (e.g., Kuik and Gerlagh, 2003; Karp, 2013). The Harberger-type model is applicable for discussing the short-term effects of climate policies; therefore, this study does not consider the technology development and intertemporal channel of carbon leakage. In addition, similar to Baylis *et al.*'s (2014) study, this study omits the fossil fuel channel.

intermediate input linkage structure directly, which is known as the multiplier effect (ME). Secondly, producers would adjust the intermediate input structure because climate policies result in higher price levels of the energy-intensive products, which is closely related to the production substitution effect (PSE). Thirdly, the intermediate input linkage has an indirect impact on the magnitude of the scale and consumption substitution effects. For instance, close industrial linkage means that the relative price change is small, and the consumption substitution effect (CSE), which reflects the environmental impact of consumption structure adjustment due to relative price change, would be relatively small.

The empirical study of this paper focuses on the effect of climate regulations on the electricity generation sector in China using a computable general equilibrium (CGE) model of China's economy. Electricity not only accounts for the largest share of direct emissions but is also a crucial intermediate input used in most production activities. China's carbon emissions trading pilots pay special attention to the impact of intermediate input linkage on the environmental effect of climate regulations. One key feature of China's carbon trading pilots is the regulation of both direct and indirect emissions from electricity generation (Zhang, 2015a, 2015b). Previous studies (e.g., Bernstein *et al.*, 1999; Babiker, 2001; Kuik and Gerlagh, 2003; Mathiesen and Mæstad, 2004; Barker *et al.*, 2007; Antimiani *et al.*, 2013; Meunier *et al.*, 2014; Böhringer *et al.*, 2016) have focused mainly on the developed regions' regulations and on leakages between developed and developing countries. Our study focuses on the carbon leakage of China's climate regulations between a regulated sector and unregulated sectors, and thus will broaden our understanding of carbon leakage and enrich the policy relevance of existing studies.

There is a close relationship between the Harberger-type model and the CGE model, which are adopted for the theoretical and numerical studies of this paper, respectively. Chumacero and Schmidt-Hebbel (2004) classify the Harberger-type model as a CGE model. Kortum (2011) states that the Harberger-type model can be observed as a simpler version of the CGE model. The previous literature links these two models by changing the key parameters of the CGE model (Carbone, 2013) or by inserting parameters taken from a CGE model to the theoretical results (Lanzi and Wing, 2013). Adopting structural decomposition analysis (Hoekstra and van den Bergh, 2003), this study proposes another method to link the theoretical and numerical models, and we quantitatively evaluate the magnitude of four leakage effects. The simulation results show that China's climate regulations on the electricity generation sector would generate negative sectoral leakage, which is mainly determined by the PSE and the ME, both of which have a close relation with the sectoral linkage.

This study contributes to the literature in several ways. First, this study clarifies the direct and indirect impacts of intermediate input linkage on carbon leakage of sectoral climate regulations from the perspectives of four different leakage effects. Secondly, the study develops a Harberger-type model with an input-output linkage structure, which can represent two countries linked through the trade of intermediate goods or a closed economy with two interdependent sectors. Thirdly, the study proposes a method to link the theoretical and numerical models by adopting structural decomposition analysis and quantitatively evaluates the magnitude of different leakage effects. The policy implication is that policy makers should consider domestic sectoral linkages in the determination of climate regulations and anti-leakage measures.

The remainder of the paper is organized as follows. Section 2 develops a Harberger-type theoretical model with an input-output linkage structure and derives closed-form expressions of four different leakage effects. Section 3 builds China's CGE model for empirical simulation and introduces structural decomposition analysis to link the theoretical and empirical models. Section 4 discusses the simulation results. The conclusions are presented in section 5.

2. The theoretical model

With the development of production fragmentation, firms in different sectors and regions are more closely connected to each other through intermediate input linkage. Sectoral linkage may have an obvious impact on the environmental effect of climate regulations. In order to present the relation between intermediate input linkage and carbon leakage, this study extends the model presented in Baylis *et al.* (2014), which assumes two independent sectors by introducing a sectoral input-output linkage structure. Our model allows us to quantify the impact of intermediate input linkage on carbon leakage under a small change in the carbon tax. The theoretical model of this study is presented in the following subsection.

2.1. Theoretical model

2.1.1. Production

In a closed economy, two competitive sectors $(i, j = X, Y)$ use intermediate input M_i, clean input K_i and carbon emissions E_i, with decreasing marginal products in a constant return to scale production function. For illustration purposes only, this study assumes that the sector X represents the electricity generation sector and the sector Y represents the other sector. The final output of sector $i(O_i = f(M_i, K_i, E_i))$ satisfies both the final demand of consumers (C_i) and the intermediate demand of the other sector $j(M_j)$. The intermediate input share is $\xi_{iM} = M_i P_j / O_i P_i, (i \neq j)$. The clean and dirty factor input shares are $\xi_{iK} = (1 - \xi_{iM})\theta_{iK}$ and $\xi_{iE} = (1 - \xi_{iM})\theta_{iE}$, where θ_{iK} and θ_{iE} $(\theta_{iK} + \theta_{iE} = 1)$ are the share of clean and dirty inputs to the gross factor input. We assume that the electricity generation sector X has a greater carbon intensity $(\xi_{XE} > \xi_{YE})$. Differentiating each sector's production function, we obtain the following:

$$\hat{O}_i = \xi_{iM}\hat{M}_i + \xi_{iK}\hat{K}_i + \xi_{iE}\hat{E}_i. \tag{1}$$

The presence of a *hat* notation above any variable represents each proportional change (e.g., $\hat{O}_i = \Delta O_i / O_i$).

Firms would adjust the input structure with changes in the relative price, and this corresponds to the PSE. For instance, they would reduce carbon emissions per unit of output by incremental capital investment. The

Harberger-type model with three or more inputs usually adopts Allen elasticities of substitution. Karney (2016) proposes a method to switch from Allen to Morishima elasticities and demonstrates a one-to-one numerical equivalence of models using two different elasticities. Therefore, our paper also adopts Allen elasticities of substitution and defines the elasticity of substitution between intermediate and factor inputs as e. We obtain the following:

$$\begin{cases} \hat{M}_i - \hat{E}_i = \xi_{iM}(e^i_{MM} - e^i_{EM})\hat{P}_j + \xi_{iK}(e^i_{MK} - e^i_{EK})\hat{P}_K + \xi_{iE}(e^i_{ME} - e^i_{EE})\hat{P}_{iE} \\ \hat{K}_i - \hat{E}_i = \xi_{iM}(e^i_{KM} - e^i_{EM})\hat{P}_j + \xi_{iK}(e^i_{KK} - e^i_{EK})\hat{P}_K + \xi_{iE}(e^i_{KE} - e^i_{EE})\hat{P}_{iE} \end{cases}. \tag{2}$$

The capital is movable across electricity generation sector X and the other sector Y, with the same return (P_K) and a fixed supply $(\overline{K} = K_X + K_Y)$. Completely differentiating the capital constraint equation $\overline{K} = K_X + K_Y$, we obtain the following:

$$\alpha_X \hat{K}_X + \alpha_Y \hat{K}_Y = 0, \tag{3}$$

where α_X and α_Y are the sectoral share of the capital distribution between two sectors and satisfy $\alpha_X + \alpha_Y = 1$.

2.1.2. Price

Perfect competition and constant returns to scale imply zero profit, so $P_i O_i = P_j M_i + P_K K_i + P_{iE} E_i$. Completely differentiating these equations and using companies' profit-maximizing first-order conditions yields the following:

$$\hat{P}_i + \hat{O}_i = \xi_{iM}(\hat{P}_j + \hat{M}_i) + \xi_{iK}(\hat{P}_K + \hat{K}_i) + \xi_{iE}(\hat{P}_{iE} + \hat{E}_i). \tag{4}$$

According to equation (1), we find the relationship of the proportional change in price levels,

$$\hat{P}_i = \xi_{iM}\hat{P}_j + \xi_{iK}\hat{P}_K + \xi_{iE}\hat{P}_{iE}. \tag{4a}$$

The price level faced by consumers $(\hat{I})$ is determined by the price level of two sectors $(\hat{I} = \frac{C_X \Delta P_X + C_Y \Delta P_Y}{C_X P_X + C_Y P_Y} = \frac{C_X P_X}{C_X P_X + C_Y P_Y} \Delta P_X / P_X + \frac{C_Y P_Y}{C_X P_X + C_Y P_Y} \Delta P_Y / P_Y)$. Supposing ϑ_i is the share of income spent on sector $i (\vartheta_i = P_i C_i / (P_i C_i + P_j C_j), (i \neq j))$, we obtain the following:

$$\hat{I} = \vartheta_X \hat{P}_X + \vartheta_Y \hat{P}_Y. \tag{5}$$

According to the production approach of nominal gross domestic product (GDP) (N), the mathematical expression is $N = (1 - \xi_{YM}) O_X P_X + (1 - \xi_{YM}) O_Y P_Y$. Taking the logs and totally differentiating, we obtain the following:

$$\hat{N} = \frac{\vartheta_X + \xi_{YM}\vartheta_Y}{1 - \xi_{XM}\xi_{YM}}(1 - \xi_{XM})(\hat{O}_X + \hat{P}_X) + \frac{\xi_{XM}\vartheta_X + \vartheta_Y}{1 - \xi_{XM}\xi_{YM}}(1 - \xi_{YM})(\hat{O}_Y + \hat{P}_Y). \tag{6}$$

The real GDP (G) satisfies $G = N/I$. Taking the logs and totally differentiating, we obtain $\hat{G} = \hat{N} - \hat{I}$. Climate regulations would influence the real GDP and the final emissions. The scale effect (SE) of carbon leakage is obtained from the change in real GDP.

2.1.3. Consumption

We assume that all tax revenue ($R = P_{XE}E_X + P_{YE}E_Y$) is returned to individuals via a lump-sum rebate. Under the budget constraint ($r\overline{K} + R \geq P_X C_X + P_Y C_Y$), identical individuals maximize homothetic utility ($U(C_X, C_Y; E_{total})$) by choosing products from the two sectors. This paper assumes that the welfare gain from carbon reduction ($\Delta E_{total} = \Delta E_X + \Delta E_Y$) is separable in utility (Baylis *et al.*, 2013) and focuses on the welfare effects from consumption. Under the assumption that pollution is separable in utility, we define σ_u as the elasticity of substitution in utility between different products:

$$\hat{C}_X - \hat{C}_Y = \sigma_u(\hat{P}_Y - \hat{P}_X). \tag{7}$$

Consumers tend to consume more of the products with a relatively lower price level and less of the more expensive products. We obtain the CSE of carbon leakage. According to the product market clearance assumption[2] and the intermediate input share, we obtain $O_i P_i = C_i P_i + \xi_{jM} O_j P_j, (i \neq j)$. Completely differentiating the above two equations yields the following:

$$\hat{O}_i = \hat{C}_i + \frac{(\sigma_u - 1)\xi_{jM}\vartheta_j}{\vartheta_i + \xi_{jM}\vartheta_j}(\hat{P}_i - \hat{P}_j), (i \neq j). \tag{8}$$

Equation (8) shows that the output change is not only determined by the final consumption change but is also influenced by the intermediate input structure through the ME. In addition, equation (8) shows that the ME has a close relation with the consumption substitution elasticity. $\sigma_u = 1$ means that the share of income spent on electricity and other products is fixed ($\hat{C}_X + \hat{P}_X = \hat{C}_Y + \hat{P}_Y$). Then, the final output has a linear relation with the final consumption, and the rates of percentage change in these two variables are the same.

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[2] The product market clearance implies that the value of gross output equals the sum of intermediate input and final demands, $O_i = C_i + M_j, (i \neq j)$.

2.1.4. Climate policy

We assume that climate regulation applies only to the electricity generation sector X, which has a greater carbon intensity.

$$\hat{P}_{XE} = \tau \tag{9}$$

$$\hat{P}_{YE} = 0. \tag{10}$$

In addition, this paper assumes that the capital price level is chosen as the *numeraire* $\hat{P}_K = 0$. There are 18 variables and 18 equations for the theoretical analytical framework, and the model is solvable mathematically. The parameters, variables and equations of the theoretical model are summarized in appendix A.

2.2. Decomposition analysis of theoretical results

The proportional change in carbon emissions of the unregulated sector can be explained by four different effects: the scale effect (SE), the consumption substitution effect (CSE), the multiplier effect (ME), and the production substitution effect (PSE).

$$\hat{E}_Y = SE + CSE + ME + PSE \tag{11}$$

The derivation of equation (11) is presented in appendix B. The environmental effects of climate policies through the expansion or contraction of the overall economic scale, which is represented by the real GDP (G), is named the scale effect (SE). The mathematical expression of the percentage change of G is represented by parameters and the exogenous policy shock. The results show that the SE is related to the intermediate input linkage through two different mechanisms. First, the SE is influenced by the intermediate input linkage structure, which is represented by the intermediate input coefficient (ξ_{XM} and ξ_{YM}). Under the extreme case that two sectors are independent ($\xi_{XM} = \xi_{YM} = 0$), we obtain $\hat{G} = -\alpha_X(e^X_{KE} - e^X_{EE})\theta_{XE}\theta_{XE}\tau - (\vartheta_X\alpha_Y - \vartheta_Y\alpha_X)\sigma_u\theta_{XE}\tau$. We can prove that climate regulations under the carbon-intensive sectors will reduce the gross economic scale[3] if we ignore the intermediate input linkage. Secondly, the SE has a close relation with the intermediate substitution elasticity of both the electricity generation sector X and the other sector Y (e^X_{ME}, e^Y_{KM} and e^Y_{EM}). This reflects the impact of intermediate input linkage change on the environmental effect of climate regulations indirectly through the SE.

The climate policies shock the final price level faced by consumers, and the changes in final prices are $\hat{P}_X = \frac{1-\xi_{XM}}{1-\xi_{XM}\xi_{YM}}\theta_{XE}\tau$ and $\hat{P}_Y = \frac{(1-\xi_{YM})\xi_{YM}}{1-\xi_{XM}\xi_{YM}}\theta_{XE}\tau$. When $\xi_{YM} < 1$, we obtain $\hat{P}_X > \hat{P}_Y$. This means that the consumer will face a relatively higher electricity price level (sector X). Then, consumers will adjust their consumption structure and improve the

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[3] When $\xi_{XM} = 0$ and $\xi_{YM} = 0$, sector X has greater carbon intensity means $\alpha_Y/\vartheta_Y > \alpha_X/\vartheta_X$. According to $e^X_{EE} < 0$, we obtain $\hat{G} < 0$.

share of consumption on products of the other sector Y. The environmental impact of a consumption structure adjustment due to a relative final price change is named the consumption substitution effect (CSE). When $\xi_{XM} = 1$ or $\xi_{YM} = 1$, all products of sector Y or X are used to satisfy the intermediate demand, and the products of the two sectors are not substitutes. Therefore, the consumption substitution will be zero. $\frac{dCSE}{d\xi_{XM}} < 0$ and $\frac{dCSE}{d\xi_{YM}} < 0$, which means that the closer the sectoral linkage is, the smaller the change in relative final price levels will be and the scale of the CSE will be much smaller.

The ME influences the environmental effects of climate policies by impacting the volume change of final products due to changes in final demand. The sign of ME is determined by the consumption substitution elasticity. The final output and final consumption of the unregulated sector satisfy $(1 - \xi_{XM}\xi_{YM})O_Y P_Y = \xi_{XM} C_X P_X + C_Y P_Y$.[4] When $\sigma_u = 1$, the expenditure structure remains consistent. We can obtain that the final output and consumption will share the same percentage change ($\hat{O}_Y = \hat{C}_Y$), and the ME has no influence on the rate of change of these two variables. $\sigma_u > 1$ means that the expenditure share has a negative relation with the relative price level, and consumers would decrease the share of gross income spent on unregulated products; therefore, the sign of ME is negative. $\sigma_u < 1$ means that consumers will increase the expenditure share of unregulated products, and the sign of ME is positive. In addition, the ME is closely related to the intermediate input coefficient. When $\xi_{XM} = 0$, climate regulations on the upstream firms will face a zero ME of the regional carbon leakage because the products of the downstream industry are used to satisfy the final consumption.

Climate policies would shock the production structure, and the environmental effect of the production structure change caused by climate regulations is called the production substitution effect (PSE). The PSE is made up of two parts. The first part is related to the intermediate input structure change, and the second part is related to the factor input structure change. Climate regulations would increase the electricity price level, and the unregulated sector would reduce the intermediate demand for electricity and increase the factor demand. In addition, producers would adjust the factor input structure with the relative price change. The sign of the PSE is determined by the substitution elasticity. We can see that the sign of the PSE is ambiguous. The mathematical expression of carbon leakage appears to be complex, but we can obtain several simplified forms for special cases. For instance, when substituting the sectoral interdependence ($\xi_{XM} = 0$ and $\xi_{YM} = 0$), the theoretical results are consistent with the model of Baylis *et al.* (2014).[5]

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[4] This is obtained from the equations $O_X P_X = C_X P_X + \xi_{YM} O_Y P_Y$ and $O_Y P_Y = C_Y P_Y + \xi_{XM} O_X P_X$.

[5] When $\xi_{XM} = 0$ and $\xi_{YM} = 0$, we obtain $\hat{E}_Y = \sigma_u \alpha_X \theta_{XE} \tau - (\theta_{XE} e^X_{KE} - \theta_{XE} e^X_{EE}) \alpha_X \theta_{XE} \tau$. According to the characteristics of Allen substitution elasticity, we obtain $\theta_{iK} e^i_{KK} + \theta_{iE} e^i_{KE} = 0$ and $\theta_{iK} e^i_{EK} + \theta_{iE} e^i_{EE} = 0$. Defining $\sigma_i =$

3. The numerical model

The theoretical model shows the potential impact of the intermediate input linkage on the problem of carbon leakage and demonstrates the importance of considering sectoral linkage when discussing carbon leakage. Given that electricity is widely used in industrial production as intermediate inputs and the electricity generation sector is a key target of climate regulations, we take the electricity generation sector as a case to quantitatively evaluate the magnitude of four different leakage effects identified in the theoretical model. To that end, this study builds a CGE model of China's economy and introduces structural decomposition analysis to link both the theoretical and empirical models.

3.1. *Computable general equilibrium model*

The CGE model describes the behaviors of different economic agents (the government, households and enterprises) using a system of equations. To minimize costs, enterprises use intermediate inputs and factor inputs to produce products, subject to certain technological constraints. Households choose domestic and imported products to maximize their utility under budget constraints. As a tax collector, the government determines its expenditures, transfers and savings, according to tax revenues. The static CGE model constructed by this paper is made up of four blocks: production, consumption and trade, emissions and policy, equilibrium and closure.[6] The database is the social accounting matrix (SAM) of China in 2007, which is obtained from the Development Research Center of the State Council. To reflect the substitution among different types of electricity, this paper decomposes the electricity generation sector into the thermal power sector, the hydropower sector and the nuclear power sector. Refer to appendix C for the 44 sectors discussed in this study. The sectoral carbon emissions are calculated based on the fossil fuel demand (NBS, 2008) and carbon emission factors (IPCC, 2006).

3.1.1. Production

The production technology is represented by a five-stage nested constant elasticity of substitution (CES) production function. The nesting structure of production is shown in figure 1. Being taken out of the intermediate input nest, the energy is incorporated into the value-added nest. The final output is the compositions of value-added energy composite and intermediate inputs through a Leontief function. The value-added energy composite is the composition of the capital-energy composite and labor. Labor is divided into agricultural labor, production labor and professional labor. Energy is divided into electricity and non-electricity. The electricity

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$\theta_{iK} e^i_{EK} - \theta_{iK} e^i_{KK} = \theta_{iE} e^i_{KE} - \theta_{iE} e^i_{EE}$, we obtain $\hat{K}_i - \hat{E}_i = \sigma_i(\hat{P}_{iE} - \hat{P}_K)$ and $\hat{E}_Y = \sigma_u \alpha_X \theta_{XE} \tau - \sigma_X \alpha_X \theta_{XE} \tau$, which is just the result of the FKB model (Baylis *et al.*, 2014).

[6] It should be noted that this study briefly presents a numerical simulation model due to space limitations. Refer to Li and He's (2010) study and our previous study (Zhang *et al.*, 2013) for the mathematical description of the model.

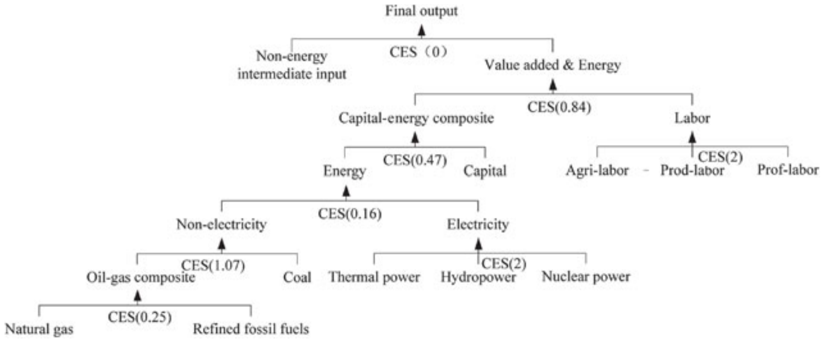

Figure 1. *Production structure of the computable general equilibrium model*

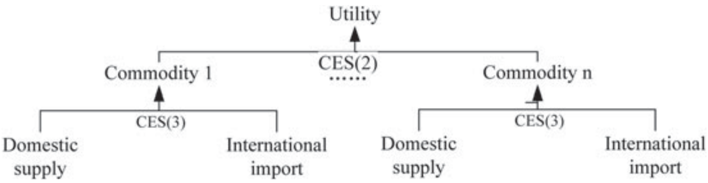

Figure 2. *Consumption structure of the computable general equilibrium model*

is provided by thermal, hydroelectric and nuclear power plants. Non-electricity is the composition of coal and non-coal, which is made up of natural gas and refined fossil fuels. The energy substitution elasticities used in this paper are derived from the existing literature (Beckman *et al.*, 2011; Stern, 2012). The capital/energy/labor substitution elasticities are obtained from Lv *et al.* (2009).

3.1.2. Consumption and trade

Households earn income from the factor return and government transfer. All the income is spent on commodities, direct taxes and household savings. To maximize the utility, households' behaviors are described by the CES function. The consumption demand for certain products is positively related to the real income level and is negatively related to the price level. Under climate regulations, consumers will adjust their consumption structure with the change of income and price levels. The enterprise earns revenue by sold products. The revenue is spent on intermediate goods, transferred to a household through factor return, and paid in taxes to the government. The total domestic demand for manufactured goods is determined by the intermediate input demand of enterprises, the final consumption demand of households and the government, and products exported to foreign countries. This demand pool is satisfied by a combination of goods produced by different companies in the domestic market and other regions. We assume that the products of different regions compete as imperfect substitutes (the Armington assumption). The elasticity parameters are obtained from the previous literature (Tarr, 2012).

3.1.3. Emissions and policy

The sectoral emissions are calculated by multiplying the demand for different fossils by the carbon emissions factors. Under the complete information and perfect competition assumption, the CGE model assumes that the carbon price is equal to the trading price of carbon permits. Qi and Cheng (2015) note that the difference in the carbon price of the seven carbon trading pilots decreases gradually, ranging from Yuan 24 to 55 per ton. China's seven carbon emissions trading pilots all cover both direct and indirect emissions from electricity. This study simulates the effect of pricing carbon at Yuan 30 per ton in the electricity sector. All tax revenues will be returned to the households through transfer payments. For simplicity, the study assumes that the carbon abatement cost of the electricity generation sector can be passed through to the downstream industries directly.[7]

3.1.4. Equilibrium and closure

The CGE model incorporates the commodity market, factor market and exchange market of domestic and foreign products. The equilibrium module presents the clearance of each market. For instance, commodity market clearance implies that the value of gross output equals the sum of intermediate input and final demands. The closure module describes

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[7] Electricity tariffs have remained controlled by the central government since China split the State Power Corporation and separated electricity generation from its transmission and distribution in 2002. Although electricity tariffs were raised a few times under the coal-electricity price 'co-movement' mechanism, they remain flat and regulated (Zhang, 2014). This not only reduces the effectiveness of addressing the daunting challenges of cutting emissions and strengthening industrial upgrading, but also complicates the implementation of pilot carbon trading schemes in the power sectors in China. The latter creates a new impetus for power pricing reforms to allow the pass-through of carbon costs in the electricity sector as a result of implementing carbon trading (Zhang, 2015a, 2015b). An encouraging sign is that the central government recently released several documents to further deepen and speed up the reform of the power pricing reform (Central Committee of Communist Party of China and The State Council, 2015; State Council, 2016).

$$
\begin{aligned}
E' - E^0 &= F'B'S'G' - F^0B^0S^0G^0 \\
&= F'B'S'G' - F^0B^0S'G' + F^0B^0S'G' - F^0B^0S^0G^0 \\
&= (F'B' - F^0B^0)S'G' + F^0B^0(S'G' - S^0G^0) \\
&= (F'B' - F^0B^0)S'G' + F^0B^0(S'G' - S^0G^0) \\
&\quad + F^0(S'G' - S^0G^0) - F^0(S'G' - S^0G^0) \\
&= (F'B' - F^0B^0)S'G' + F^0(B^0 - I)(S'G' - S^0G^0) + F^0(S'G' - S^0G^0) \\
&= (F'B' - F^0B^0)S'G' + F^0(B^0 - I)(S'G' - S^0G^0) \\
&\quad + F^0S^0(G' - G^0) + F^0(S' - S^0)'G'
\end{aligned}
$$

the balance of saving and investment, government budget and international payments. This paper adopts the neoclassical closure principle. First, total investment in the economy is adjusted to the gross savings (household savings, corporate savings, government savings, public sector surplus earnings and foreign savings) to balance the savings-investment closure. Secondly, the tax rate, transfer payments and government consumption are fixed, whereas government savings are endogenous to balance the government budget closure. Thirdly, the exchange rate is endogenously determined to balance the international payments.

3.2. *Structural decomposition analysis*

Using the numerical model presented above, we can simulate the economic and environmental effects of climate regulations on the electricity generation sector. However, the CGE model reports only the single net aggregated simulation result without showing the fact that different effects may offset each other (Baylis *et al.*, 2014). This study introduces a structural decomposition analysis to numerically evaluate the four different leakage effects presented in the theoretical model. We suppose that G represents the real GDP, S represents the sectoral share of final demand, B represents the Leontif matrix $(1-A)^{-1}$, and F represents the sectoral carbon matrix, which is related to the energy consumption structure and carbon emission coefficient of the fossil energy. The sectoral direct emissions satisfy

$$E = FBSG. \tag{12}$$

According to the structural decomposition analysis, the change in sector emissions is presented below:

$$\begin{aligned} E' - E^0 &= F'B'S'G' - F^0B^0S^0G^0 \\ &= \underbrace{F^0S^0(G'-G^0)}_{\text{SE}} \underbrace{+F^0(S'-S^0)'G'}_{\text{CSE}} \underbrace{+F^0(B^0-I)(S'G'-S^0G^0)}_{\text{ME}} \\ &\quad \underbrace{+(F'B'-F^0B^0)S'G'}_{\text{PSE}}. \end{aligned} \tag{13}$$

The first part reflects the environmental effect of climate regulations due to the change in the gross economic scale, which reflects the SE. The second part reflects the change of carbon emissions due to the change in the consumption structure, which is related to the CSE. The intermediate input linkage $(B^0 - I)$ has an amplification effect on the scale and CSEs of carbon leakage, which represents the ME. Consistent with the theoretical model, the fourth part reflects the PSE, which is related to both the change in the intermediate input structure and energy consumption structure.

4. Numerical results

This section presents numerical simulations of the economic and environmental effects of carbon regulation. Climate regulations on the electricity generation sector have a negative impact on the economy scale, represented by real GDP. The results show that the rate of change of real GDP is −0.35 per cent, which means that the carbon pricing would put downward pressure on China's economic growth in the short term. In addition, climate regulations would drive up the electricity price level, which would increase by 3.40 per cent. The higher electricity price level would further raise the production cost of other sectors. For instance, the price level of chemical products would increase by 1.0 per cent. The consumer price index (CPI) would increase by 0.49 per cent.

Climate regulations have a negative impact on employment. The simulation results show that the employment for production labor decreases by 0.13 per cent, followed by agricultural (−0.10 per cent) and professional labor (−0.09 per cent). Climate regulations on electricity have a more significant impact on the production labor. From an environmental perspective, the gross emissions and carbon intensity decrease by 3.69 and 3.35 per cent, respectively. The carbon pricing will help to achieve China's target of a 40–45 per cent carbon intensity reduction by 2020, compared to 2005 levels. In addition, climate regulations on the electricity generation sector would promote the development of renewable energy, which is represented by hydropower and nuclear power in this present study. We found that the output of renewable energy would increase by 1.80 per cent.

We further present the environmental effects of climate regulation and decompose the change in sectoral emissions into different terms. The aggregated results are presented in table 1 and the decomposition of changes in sectoral emissions is presented in appendix B.

As shown in table 1, we decompose the change in sectoral emissions into four components: the SE, the CSE, the ME and the PSE. The first four columns present the volume and percentage changes in sectoral emissions due to four different effects, and the last column shows the overall change. The results show that the carbon emissions of the thermal power sector decrease by 5.36 per cent, and the carbon emissions of other unregulated sectors decrease by 1.36 per cent. Notably, the other unregulated industries face the greatest scale of carbon reduction (−21.09 million tons of CO_2 emissions) because industrial firms are more sensitive to the electricity price level. Defined as the share of the change in unregulated-sector emissions to the reduction in regulated-sector emissions, the sectoral carbon leakage rate is −17.62 per cent.

Wu *et al.* (2016) analyzed the carbon leakage problem faced by carbon emissions trading in China and found that more than 90 per cent of non-trading sectors experience carbon reduction under all scenarios, which is mainly explained by the perspective of input-output linkages. It should be noted that the sectoral carbon leakage rate of the present study is lower than that of Wu *et al.*'s (2016) study because these two studies choose different sectors as regulated ones. Wu *et al.* (2016) assume that the carbon trading system covers eight energy and energy-intensive industries, whereas this paper focuses only on carbon pricing on the electricity generation sector. The energy-intensive sectors tend to face a greater scale of carbon reduction; therefore, the carbon leakage rate of this paper is lower than that of Wu *et al.*'s (2016) study.

Table 1. *Decomposition analysis of environmental effects of climate regulations (million tons of CO_2 emissions)*

	SE	*CSE*	*ME*	*PSE*	*Sum*
Agriculture	−0.14 (−0.10%)	0.19 (0.14%)	−0.19 (−0.14%)	−2.79 (−2.07%)	−2.94 (−2.18%)
Industry	−0.79 (−0.02%)	−33.28 (−0.75%)	−41.07 (−0.92%)	−105.06 (−2.37%)	−180.21 (−4.06%)
Thermal power	−0.39 (−0.01%)	−31.96 (−1.08%)	−34.27 (−1.16%)	−92.49 (−3.12%)	−159.11 (−5.36%)
Other industries	−0.40 (−0.03%)	−1.32 (−0.09%)	−6.80 (−0.46%)	−12.57 (−0.85%)	−21.09 (−1.43%)
Construction	−0.23 (−0.34%)	0.20 (0.30%)	0.00 (0.00%)	−0.76 (−1.14%)	−0.80 (−1.19%)
Transportation	−0.21 (−0.08%)	0.23 (0.09%)	−0.76 (−0.29%)	−0.50 (−0.19%)	−1.25 (−0.47%)
Services	−0.23 (−0.20%)	0.19 (0.17%)	−0.20 (−0.17%)	−1.72 (−1.50%)	−1.95 (−1.70%)

Notes: The number in parentheses represents the change rate of sectoral emissions (%). SE: scale effect; CSE: consumption substitution effect; ME: multiplier effect; PSE: production substitution effect.

The numerical simulations show that imposing a carbon price of Yuan 30 per ton on China's electricity generation sector would decrease the GDP by 0.35 per cent. This explains the negative sign of the SE on the emissions of unregulated sectors. For example, the final demand for products of the construction sector would decrease as the GDP decreases. The SE contributes to a decrease in carbon emissions of the construction sector (0.34 per cent). Carbon pricing regulation would increase the electricity price level and the price of other sectors that use electricity as an intermediate input. The industrial sector is more sensitive to electricity prices and would have a relatively higher price level than the other unregulated sectors. Consumers adjust the consumption structure, and the CSE leads to increases in carbon emissions of the products from the agricultural, construction, transportation and service sectors. This is consistent with the theoretical model that the CSE contributes to positive carbon leakage. The change in final demand will influence the sectoral outputs through sectoral linkage, which has an amplification effect on environmental effects. Table 1 shows that the ME contributes to negative carbon leakage. For example, the negative carbon leakage for the transportation sector is mainly induced by the ME. In addition, climate regulations shock the intermediate input structure. The climate regulation encourages firms to use cleaner intermediate and factor inputs, so the PSE corresponds to negative carbon leakage for all sectors. Both the ME and the PSE are closely related to sectoral linkage.

5. Conclusions

Climate regulations tend to cover a limited number of energy-intensive sectors, leading to carbon leakage across sectors. Considering that the regulated products, such as electricity, are widely used in industrial production as intermediate inputs, we attempt to disentangle the influencing mechanism of intermediate input linkage on the problem of carbon leakage.

This present study develops a Harberger-type model considering the sectoral intermediate input linkage structure and provides closed-form solutions for four leakage effects. We find that intermediate input linkage has important implications for assessing carbon leakage. The sectoral linkage directly impacts carbon leakage through the ME, and producers could adjust the intermediate input structure due to climate policies, which is related to the PSE. In addition, the sectoral linkage has an impact on the magnitude of the SE and the CSEs. The present study builds a CGE model of China's economy, proposes a method to link the theoretical and numerical models by adopting structural decomposition analysis and examines the effects of China's climate regulations on the electricity generation sector. The numerical results show that climate regulations on the electricity generation sector would result in significant leakage, which is mainly determined by the PSE, followed by the ME. Both effects are closely related to sectoral linkage. This highlights the importance of considering intermediate input linkage when discussing the problem of carbon leakage.

There are several potential extensions. First, the theoretical model constructed by this study can also represent two countries linked through the intermediate product trade, which could be adopted to analyze the regional carbon leakage of unilateral climate policies. Secondly, this study discusses only four different carbon leakage effects. Future studies could discuss other leakage channels omitted by this study. Thirdly, the empirical study adopts parameters from the literature rather than estimating them econometrically. The theoretical model shows that carbon leakage is sensitive to substitution elasticities; therefore, future studies should address this issue. Finally, this study discusses the environmental effect of China's climate regulations on the electricity generation sector, and the analytical framework of this study can be adopted to discuss the climate policies of other regions.

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Appendix A: Parameters, variables and equations of the theoretical model

Table A1. *Parameters, variables and equations of the theoretical model*

(a) Parameters of the theoretical model

Parameters	*Explanations*
i, j	Sector
k	Capital
e	Allen elasticity
ξ	Intermediate and factor input share
θ	Clean and dirty factor input share
σ	Substitution elasticity
α	Capital distribution
β	Carbon distribution
ϑ	Total income distribution
τ	Climate policy shock

(b) Variables of the theoretical model

Variables	*Explanations*
$\hat{O}_X$	Proportional change of the output of sector X
$\hat{O}_Y$	Proportional change of the output of sector Y
$\hat{C}_X$	Proportional change of the consumption demand of sector X
$\hat{C}_Y$	Proportional change of the consumption demand of sector Y
$\hat{M}_X$	Proportional change of the intermediate input of sector X
$\hat{M}_Y$	Proportional change of the intermediate input of sector Y
$\hat{E}_X$	Proportional change of the carbon emissions of sector X
$\hat{E}_Y$	Proportional change of the carbon emissions of sector Y
$\hat{K}_X$	Proportional change of the capital input of sector X
$\hat{K}_Y$	Proportional change of the capital input of sector Y

(*continued.*)

Table A1. *Continued*

$\hat{P}_{XE}$	Proportional change of the carbon price of sector X
$\hat{P}_{YE}$	Proportional change of the carbon price of sector Y
$\hat{P}_X$	Proportional change of the final output price of sector X
$\hat{P}_Y$	Proportional change of the final output price of sector Y
$\hat{P}_K$	Proportional change of the capital return
$\hat{I}$	Proportional change of the total price level
$\hat{N}$	Proportional change of the nominal GDP
$\hat{G}$	Proportional change of the real GDP

(c) Equations of the theoretical model

Modules	*Equations*
Production module	$\hat{O}_X = \xi_{XM}\hat{M}_X + (1-\xi_{XM})\theta_{XK}\hat{K}_X + (1-\xi_{XM})\theta_{XE}\hat{E}_X$
	$\hat{O}_Y = \xi_{YM}\hat{M}_Y + (1-\xi_{YM})\theta_{YK}\hat{K}_Y + (1-\xi_{YM})\theta_{YE}\hat{E}_Y$
	$\hat{M}_X - \hat{E}_X = \xi_{XM}(e^X_{MM} - e^X_{EM})\hat{P}_Y + (1-\xi_{XM})\theta_{XK}(e^X_{MK} - e^X_{EK})\hat{P}_K + (1-\xi_{XM})\theta_{XE}(e^X_{ME} - e^X_{EE})\hat{P}_{XE}$
	$\hat{K}_X - \hat{E}_X = \xi_{XM}(e^X_{KM} - e^X_{EM})\hat{P}_Y + (1-\xi_{XM})\theta_{XK}(e^X_{KK} - e^X_{EK})\hat{P}_K + (1-\xi_{XM})\theta_{XE}(e^X_{KE} - e^X_{EE})\hat{P}_{XE}$
	$\hat{M}_Y - \hat{E}_Y = \xi_{YM}(e^Y_{MM} - e^Y_{EM})\hat{P}_X + (1-\xi_{YM})\theta_{YK}(e^Y_{MK} - e^Y_{EK})\hat{P}_K + (1-\xi_{YM})\theta_{YE}(e^Y_{ME} - e^Y_{EE})\hat{P}_{YE}$
	$\hat{K}_Y - \hat{E}_Y = \xi_{YM}(e^Y_{KM} - e^Y_{EM})\hat{P}_X + (1-\xi_{YM})\theta_{YK}(e^Y_{KK} - e^Y_{EK}) \times \hat{P}_K + (1-\xi_{YM})\theta_{YE}(e^Y_{KE} - e^Y_{EE})\hat{P}_{YE}$
	$\alpha_X\hat{K}_X + \alpha_Y\hat{K}_Y = 0$
Price module	$\hat{P}_X = \xi_{XM}\hat{P}_Y + (1-\xi_{XM})(\theta_{XK}\hat{P}_K + \theta_{XE}\hat{P}_{XE})$
	$\hat{P}_Y = \xi_{YM}\hat{P}_X + (1-\xi_{YM})(\theta_{YK}\hat{P}_K + \theta_{YE}\hat{P}_{YE})$
	$\hat{I} = \vartheta_X\hat{P}_X + \vartheta_Y\hat{P}_Y$

(*continued.*)

Table A1. *Continued*

	$\hat{N} = \frac{\vartheta_X + \xi_{YM}\vartheta_Y}{1 - \xi_{XM}\xi_{YM}}(1 - \xi_{XM})(\hat{O}_X + \hat{P}_X)$ $+ \frac{\xi_{XM}\vartheta_X + \vartheta_Y}{1 - \xi_{XM}\xi_{YM}}(1 - \xi_{YM})(\hat{O}_Y + \hat{P}_Y)$ $\hat{G} = \hat{N} - \hat{I}$ $\hat{P}_K = 0$
Consumption module	$\hat{C}_X - \hat{C}_Y = \sigma_u(\hat{P}_Y - \hat{P}_X)$ $\hat{O}_X = \hat{C}_X + \frac{(\sigma_u - 1)\xi_{YM}\vartheta_Y}{\vartheta_X + \xi_{YM}\vartheta_Y}(\hat{P}_X - \hat{P}_Y)$ $\hat{O}_Y = \hat{C}_Y + \frac{(\sigma_u - 1)\xi_{XM}\vartheta_X}{\xi_{XM}\vartheta_X + \vartheta_Y}(\hat{P}_Y - \hat{P}_X)$
Policy module	$\hat{P}_{XE} = \tau$ $\hat{P}_{YE} = 0$

Appendix B: The derivation of equation (11)

The SE is represented by real GDP (G). The mathematical expression of the percentage change of G is shown below.

$$
\begin{aligned}
SE &= \hat{G} \\
&= \Bigg\{ \frac{(\vartheta_X + \xi_{XM}\vartheta_Y)(1 - \xi_{XM})\alpha_Y - (\xi_{XM}\vartheta_X + \vartheta_Y)(1 - \xi_{YM})\alpha_X}{1 - \xi_{XM}\xi_{YM}} \\
&\quad \times \left(\sigma_u + \frac{(1 - \sigma_u)\xi_{YM}\vartheta_Y}{\vartheta_X + \xi_{YM}\vartheta_Y} + \frac{(1 - \sigma_u)\xi_{XM}\vartheta_X}{\xi_{XM}\vartheta_X + \vartheta_Y}\right) \frac{(1 - \xi_{XM})(\xi_{YM} - 1)}{1 - \xi_{XM}\xi_{YM}}\theta_{XE} \\
&\quad + \frac{(\vartheta_X + \xi_{YM}\vartheta_Y)(1 - \xi_{XM}) + (\xi_{XM}\vartheta_X + \vartheta_Y)(1 - \xi_{YM})}{1 - \xi_{XM}\xi_{YM}} \\
&\quad \times (1 - \xi_{XM}) \Bigg[\xi_{XM}\alpha_X(e^X_{ME} - e^X_{KE}) - (1 - \xi_{XM})\alpha_X(e^X_{KE} - e^X_{EE})\theta_{XE} \\
&\quad + \frac{\xi^2_{YM}}{1 - \xi_{XM}\xi_{YM}}\alpha_Y(e^Y_{MM} - e^Y_{KM}) + \frac{\xi_{YM}(1 - \xi_{YM})}{1 - \xi_{XM}\xi_{YM}}\alpha_Y(e^Y_{KM} - e^Y_{EM}) \Bigg] \theta_{XE} \\
&\quad + \frac{(1 - \xi_{XM})\xi_{YM}\vartheta_Y + \xi_{XM}(\xi_{YM} - 1)\vartheta_X}{1 - \xi_{XM}\xi_{YM}} \frac{(1 - \xi_{XM})(1 - \xi_{YM})}{1 - \xi_{XM}\xi_{YM}}\theta_{XE} \Bigg\} \tau
\end{aligned}
$$

The closed-form solution for the percentage change of the real GDP is represented by parameters and the exogenous policy shock. The final output and final consumption satisfy $O_i P_i = C_i P_i + \xi_{jM} O_j P_j$, and we obtain $(\hat{O}_i + \hat{P}_i) = \frac{\vartheta_i(\hat{C}_i + \hat{P}_i)}{\vartheta_i + \xi_{jM}\vartheta_j} + \frac{\xi_{jM}\vartheta_j(\hat{C}_j + \hat{P}_j)}{\vartheta_i + \xi_{jM}\vartheta_j}$.

Inserting them into equation (6), we obtain $\hat{N} = \vartheta_X(\hat{C}_X + \hat{P}_X) + \vartheta_Y(\hat{C}_Y + \hat{P}_Y)$. This can be observed as the mathematical expression of real GDP under the expenditure approach. According to the relation between real and nominal GDP $\hat{G} = \hat{N} - \hat{I}$, we obtain

$$\hat{G} = \vartheta_X \hat{C}_X + \vartheta_Y \hat{C}_Y.$$

According to the relation that GDP under the production and expenditure approaches share the same results, we obtain $\vartheta_X \hat{C}_X + \vartheta_Y \hat{C}_Y = SE$. The CSE is obtained according to the consumption substitution relationship between two products, which is represented by equation (7). The mathematical expression of consumption demand for products of sector Y is shown below:

$$\hat{C}_Y = SE + \underbrace{\frac{\sigma_u \vartheta_X (1-\xi_{XM})(1-\xi_{YM})\theta_{XE}}{1-\xi_{XM}\xi_{YM}}\tau}_{CSE}.$$

The final output change due to consumption change is influenced by the intermediate input linkage through the multiplier effect (ME), which is obtained based on the relationship between final consumption and total outputs, represented by equation (8). The mathematical expression is shown below:

$$\hat{O}_Y = SE + CSE + \underbrace{\frac{(1-\sigma_u)\vartheta_X \xi_{XM}(1-\xi_{XM})(1-\xi_{YM})\theta_{XE}}{1-\xi_{XM}\xi_{YM}}\tau}_{ME}.$$

The PSE is obtained according to the production substitution relationship between factor and intermediate inputs, represented by equation (2).

$$\begin{aligned}\hat{E}_Y &= SE + CSE + ME \\ &\quad + \underbrace{\left[\frac{\xi_{YM}\xi_{YM}(1-\xi_{XM})\theta_{XE}(e^{Y}_{EM}-e^{Y}_{MM})}{1-\xi_{XM}\xi_{YM}} + \frac{\xi_{YK}\xi_{YM}(1-\xi_{XM})\theta_{XE}(e^{Y}_{EM}-e^{Y}_{KM})}{1-\xi_{XM}\xi_{YM}}\right]\tau}_{PSE}\end{aligned}$$

Appendix C: Decomposition analysis of sectoral emissions change

Table A2. *Decomposition analysis of sectoral emissions change*

Sectors		*SE*	*CSE*	*ME*	*PSE*	*Sum*
1	Agricultural	−0.10%	0.14%	−0.14%	−2.07%	−2.18%
2	Coal mining	0.00%	0.06%	−1.18%	−1.59%	−2.71%
3	Crude oil mining	0.21%	0.52%	−1.04%	−1.95%	−2.26%
4	Metal ore mining	0.22%	−1.25%	−1.27%	−0.33%	−2.63%
5	Nonmetal ore mining	0.02%	−0.16%	−0.44%	−0.94%	−1.52%
6	Food	−0.17%	0.14%	−0.12%	−1.81%	−1.95%
7	Textile	−0.10%	0.04%	−0.20%	−1.88%	−2.14%
8	Apparel	−0.23%	0.10%	−0.12%	−1.27%	−1.51%
9	Wood processing	−0.12%	0.05%	−0.18%	−1.74%	−1.98%
10	Paper	−0.04%	−0.04%	−0.30%	−1.69%	−2.07%

(*continued*.)

Table A2. *Continued*

Sectors		*SE*	*CSE*	*ME*	*PSE*	*Sum*
11	Oil processing	0.01%	0.01%	−0.62%	−0.52%	−1.11%
12	Chemical	0.00%	−0.29%	−0.56%	−0.45%	−1.30%
13	Nonmetallic mineral products	−0.01%	−0.05%	−0.19%	−0.68%	−0.93%
14	Metal smelting	0.00%	−0.17%	−0.52%	−0.36%	−1.04%
15	Metal products	−0.08%	−0.04%	−0.37%	−1.44%	−1.93%
16	Machinery	−0.13%	−0.13%	−0.35%	−1.41%	−2.02%
17	Transport equipment	−0.15%	−0.03%	−0.24%	−1.74%	−2.16%
18	Electronic machine	−0.13%	−0.04%	−0.38%	−1.67%	−2.22%
19	Telecommunications equipment	−0.10%	−0.19%	−0.46%	−1.94%	−2.70%
20	Instrument	−0.04%	0.38%	−0.58%	−1.92%	−2.15%
21	Other manufacturing	−0.21%	0.00%	−0.19%	−1.58%	−1.97%
22	Waste	0.10%	0.37%	−0.70%	−1.47%	−1.70%
23	Thermal power	−0.01%	−1.08%	−1.16%	−3.12%	−5.36%
24	Hydropower	–	–	–	–	–
25	Nuclear power	–	–	–	–	–
26	Gas	−0.12%	−0.02%	−0.45%	−0.77%	−1.37%
27	Water	−0.09%	−0.81%	−0.44%	−1.84%	−3.17%
28	Construction	−0.34%	0.30%	0.00%	−1.14%	−1.19%
29	Transport	−0.08%	0.09%	−0.29%	−0.19%	−0.47%
30	Post	−0.04%	0.03%	−0.24%	−1.06%	−1.31%
31	Information transmission	−0.16%	0.19%	−0.20%	−2.32%	−2.49%
32	Commerce	−0.17%	0.23%	−0.22%	−2.00%	−2.17%
33	Restaurant	−0.15%	0.11%	−0.17%	−1.69%	−1.91%
34	Finance	−0.09%	0.21%	−0.38%	−1.57%	−1.83%
35	Real estate	−0.26%	0.64%	−0.07%	−1.03%	−0.72%
36	Lease business	−0.08%	0.01%	−0.26%	−0.70%	−1.02%
37	Travel	−0.01%	−0.01%	−0.51%	−1.75%	−2.28%
38	Science	−0.09%	0.09%	−0.37%	−0.78%	−1.16%
39	Technical services	−0.24%	0.23%	−0.17%	−1.21%	−1.39%
40	Other social services	−0.18%	0.17%	−0.20%	−1.02%	−1.23%
41	Education	−0.32%	0.25%	−0.02%	−2.19%	−2.28%
42	Health, security, welfare	−0.37%	0.07%	−0.06%	−2.28%	−2.64%
43	Culture, sports, entertainment	0.00%	0.00%	0.00%	0.00%	0.00%
44	Public administration	−0.35%	0.35%	0.00%	−1.58%	−1.58%

Notes: The scale effect may contribute to an increase in sectoral emissions because the sectoral share of GDP can be negative. For instance, the mining sector has a big trade deficit, which results in negative sectoral share of GDP for the mining sector. The consumption effect may contribute to negative carbon leakage because these sectors are closely related to the electricity sector either directly or indirectly. SE: scale effect; CSE: consumption substitution effect; ME: multiplier effect; PSE: production substitution effect.