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**Analyzing market-induced carbon leakage problem in Chinese Certified  
Emission Reduction projects**

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## Abstract

The issue of climate warming has aroused widespread concern around the world. And after Paris Agreement which requires all Parties to undertake the emission reduction obligations, the developing countries who were once exempted from emission reduction liability are now becoming more and more important. This study focuses on the mitigation action in China, the largest carbon emitter as well as the largest developing country in the world. Precisely, we study the Chinese Certified Emission Reduction (CCER) projects. The objective is to compare the reduction efficiency of three types projects: simple abatement and completely renewable energy alternative projects at the supply side, and demand side projects, thus to provide a new perspective for the government to evaluate different CCER projects so that help develop the mechanism more efficiently. From the aspect of market-induced carbon leakage issue, a dual market equilibrium model is built, theoretical results show that the key factors affecting the leakage rates are price elasticities of both demand and supply sides and market share parameters. In most cases, renewable energy alternative projects show the least leakage rate while demand side projects show the most. Sensitivity analysis finds that the leakage rate for the three types projects are more sensitive to price elasticity parameters than market share parameters. Moreover, factors  $E_c^{de}$  (electricity price elasticity of coal demand from coal-fired generation) and  $E_e^d$  (electricity price elasticity of electricity demand) affect not only the leakage rate of each project but also the comparative results between them. Although our study is based on China, the theory analysis is applicable in other regional voluntary emission reduction market around the world. So finally a systematic approach to comprehensively analyze the issue is summarized as well as some key suggestions to apply this in other regions, considering their market development stage.

**Key words:** Market-induced carbon leakage, CCER project, Comparison, Influential factors,

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## 1. Introduction

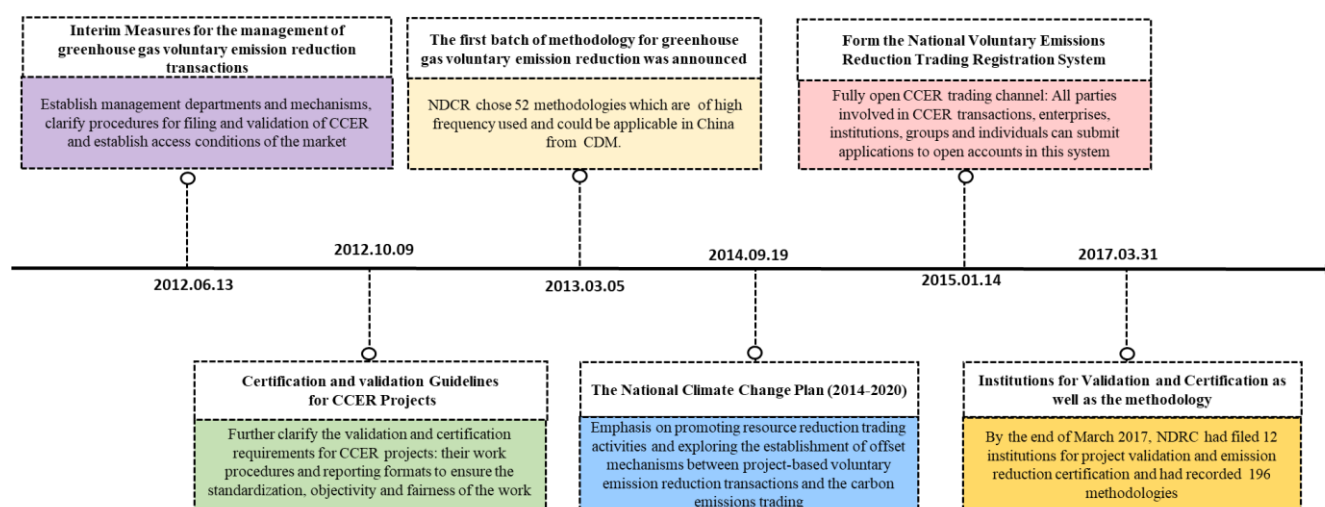
The issue of climate change has a serious impact on both human society and the ecological environment. According to Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, the annual average CO<sub>2</sub> concentration has increased by 1.7 ppm from 1980 to 2011; through 1880 to 2012, the average temperature has increased by 0.85 °C with 0.72 °C increase come from the recent 60 years. (Pachauri et al., 2014). From the early adopted United Nations Framework Convention on Climate Change Kyoto Protocol (UNFCCCCKP) in 1997 with mechanisms Emission Trading (ET), Clean Development Mechanism(CDM), and Joint Implementation (JI) to the Paris Agreement in which regional- and subnational-level policies are emphasized (de Souza and Pacca, 2019) reducing greenhouse gas emissions to address climate change has become a consensus in world countries.

Since reform and opening up, the contradiction between economy and environmental protection has become increasingly prominent in China. As a result, the average land temperature has increased by 0.9~1.5 °C in China, much higher comparing with the world's of 0.8°C (National Panel of Climate Change Assessment, NPCCA 2015). As the largest Greenhouse Gas (GHG) emissions producer on the planet (Duan et al., 2017), Chinese government actively respond to global climate change: In 2009 Copenhagen Conference, the domestic carbon reduction target is firstly declared, i.e, the carbon intensity is reduced by 40-45% from 2005 to 2020. Then at the 21st conference of the Parties of the UNFCCC held in Paris in 2015, China proposed their greenhouse gas reduction goals through implementing Intended Nationally Determined Contribution (INDC) that the carbon emission would reach the peak by 2030, the CO<sub>2</sub> emissions per unit of GDP would be reduced by 60-65% from 2005 to 2030.

With the fulfillment of China's carbon emission reduction obligations and under the constraints of the Paris Agreement, China will play a decisive role on the issue of global climate warming. Therefore, it is necessary to investigate and evaluate the domestic emission regulation tools in China (Duan et al., 2017). Among those tools the Emissions Trading Scheme is regarded as the most cost-effective mechanism and is widely used around the world (Wang et al., 2018). Chinese national carbon trading market is the largest system in the world with an expected market size to be 4 billion tons of carbon dioxide equivalent (Tollefson and Jeff, 2016 ; Li et al., 2016). A large number of research pointing to improve the performance of the trading market could be found, see for example Qiu et al. (2017) and Weng and Xu (2018), however, regarding the important supplementary mechanism to the market, CCER (Chinese Certified Emission Reduction, which is the emission reductions generated from voluntary emission reduction projects filed by National Development and Reform Commission that can be used by

compliance enterprise to offset their emissions), a project-based market originated from Clean Development Mechanism (CDM) are limited studied (Li et al., 2019; Wang and Wang, 2015).

The implementation of Interim Measures for the management of greenhouse gas voluntary emission reduction transactions (NDRC.,2012) in June 2012 is the start point of CCER trading mechanism, from then on, a series of supporting measures and policies have been implemented in order to better develop it, as shown in **Fig.1**. Now, China has formed a large scale CCER trading market (Shen and Wang, 2019). Till the end of 2018, from National Development and Reform Commission (NDRC), the number of CCER validation projects had reached 2871 and 254 projects had been certified for emission reductions.<sup>1</sup> The development of CCER contributes a lot to the trading market, not only helps enterprises to achieve emission reduction targets in a more cost-effective way (Li et al., 2019) but also activates the carbon trading market by attracting more social capital into the market (Weng and Xu, 2018). However, domestic CCER market in China is still at the stage of exploration. Despite the above-mentioned benefits, its problems are gradually exposed (Zhang et al.,2017), and how to better construct the mechanism becomes a burning issue. That is why in March 2017, NDRC suspended the registration of CCER, and claimed that the government would revise the Interim Measures in order to perfect the development of CCER (NDRC.,2017a). Among those exposed problems, the potential of project oversupply and poor quality of some projects are negligible (NDRC., 2017a, Meng ,2018), which are the problems that most trading market faced with. For example, at the end of the second phase of European Union carbon market (2008-2012), there were nearly 1.8 billion tons of surplus quotas due to a massive use (nearly 1.1 billion tons) of voluntary emission reduction, and further led to a sharp fall in quota prices which seriously affect the market operation ( De Perthuis and Trotignon, 2014).Therefore, a way to evaluate different kinds of offset projects and propose the priority ones are of great significance.



<sup>1</sup> The data is sorted out from China's Carbon Emission Trading Website.  
Available at: <http://www.tanpaifang.com/CCER/201804/2461859.html>

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**Fig.1.** Key CCER trading mechanism policies in China

Carbon leakage issue is an important and non-negligible factor that may impact on the effectiveness of the mechanism (Rosendahl and Strand, 2009 ; Aukland et al., 2003). And this provides a perspective from which to evaluate the emission reduction efficiency of different CCER projects. The concept of carbon leakage originated from unilateral emission reduction regulation and has always been a hot topic in terms of carbon trading markets. (see a review done by Zhang, 2012). For voluntary greenhouse emission reduction projects, carbon leakage refers to an increase emission outside the project boundary which is measurable and attributed to the project itself (Watson et al., 2000). There are three types or pathways to it: ecological, technological and economic one (FrankVöhringer et al., 2006). Ecological leakage is often studied from the physical perspective, meaning the structure of the earth's surface changes due to the development of a project. These changes spread beyond the project's boundary and are not included in the emission reduction in later calculation stages. This type of leakage could be further explored in the field of natural science. Technological leakage implies the development of a project is accompanied by advanced technologies which may spread beyond the project boundary to different extents. Manufacturers in other regions could master the technology thus leading to a negative leakage. Measuring technology leakage is difficult and considered beyond the scope of this study. Economic leakage could be further divided into two categories, direct and indirect economic leakage. The former is caused by economic activities, for example, transport activities helping to develop the project will cause extra emission. The latter, indirect economic leakage, also named market-induced leakage, occurs by changing the product's price via supply and demand market. For example, a large number of photovoltaic power generation projects will reduce the demand for coal, thus reducing the price of coal resource, which would cause an increase of generation from other coal-fired plants. According to the actual situation in China, the quantification of direct economic leakage is relatively straightforward. From the methodology of CCER projects introduced in China, this kind leakage has already been included in emission reduction accounting (NDRC, 2013). On the contrary, market leakage effects have so far not been accounted for. As there are more and more projects coming into the market, the great effect of it should not be ignored (Kuosmanen et al., 2004) and is therefore the focus of this paper.

Considering the potential role of CCER in achieving emission reduction target and with the aim to better build the mechanism, this study intends to propose the priority type CCER projects through comparing their reduction efficiency from the aspect of carbon leakage, and to find out the related influencing factors. Although the study is based on Chinese CCER market, the theory analysis part presented in section 3 is applicable in any other regional voluntary emission reduction market, based on which further climate mitigation strategies concerning this issue can be proposed. The remainder of the

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paper is organized as follows. Relevant literature review including national and project perspectives on carbon leakage is introduced in Section 2. Section 3 formulates a dual market equilibrium model to systematically investigate and compare this issue on different types CCER, which displays different performance under given conditions. In Section 4, the result of numerical and sensitivity analysis is provided with its insights for the emission trading markets around the world. Followed by Section 5 in which conclusions and future works are presented.

## **2.Literature review on carbon leakage**

The issue of carbon leakage has long been a research topic in field of climate mitigation strategies (Marcu et al., 2013). A large number of studies have been carried out concerning this problem and they can be roughly divided into two groups: one analyzing from national perspective, which originates from unilateral regulations like UNFCCCCKP, the other is from offset projects perspective.

### **2.1 National perspective**

Most researches explore carbon leakage problem from this perspective, which is considered as an international externality (Hoel, 1996). From IPCC the issue here implies “The increase in CO<sub>2</sub> emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries.” (Metz et al., 2007). It occurs mainly through three widely accepted channels: competitiveness, demand and energy channel (Tan et al., 2018).

Considering analytical work, there is a large body of relevant research presenting different conclusions, for example Burniaux and Martins (2012) considered that unilateral emissions reduction mechanisms reduced demand for high-carbon fossil energy, which drove down the price of global fossil energy, as a result, non-Annex I countries used more low-cost fossil fuels to replace the other production factors, resulting in more carbon emissions, thus causing carbon leakage problems. Baylis et al. (2014) investigated the technology transfer effect, indicating that advanced low carbon production technology would transfer to non-Annex I countries, resulting in a negative carbon leakage. Earlier researches such as that of Antweiler et al. (2001) argued through factor endowment hypothesis that the carbon leakage problem did not exist. As for empirical study, a substantial number of studies have been undertaken, mostly with computable general equilibrium (CGE) and Global Trade Analysis Project (GTAP) models. Most of them proposed a positive global rate of carbon leakage, see for example Kiuiila et al. (2016), Carbone (2013), Böhringer et al. (2012). However, some scholars have had different ideas, like Sartor (2013) who used data from the European carbon emissions trading system from 2005 to the second quarter of 2011 to study the impact of carbon price on carbon leakage in the aluminum industry, indicating that there is no carbon leakage in this industry. Naegele and Zaklan (2019) used GTAP model

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and data from European carbon trading system to assess the impact of environmental policies on trade, producing the same result. Recently, more and more scholars have investigated solutions to solve carbon leakage problems through border carbon adjustments (BCAs) ( [Branger and Quirion \(2014\)](#), [Antimiani et al. \(2016\)](#); [Sakai and Barrett \(2016\)](#)) and carbon border tax (CBT) policy ([Allevi et al., 2017](#); [Antimiani et al., 2013](#)) Other measures like grandfathering of CO2 allowances ([Allevi et al., 2017](#)) and government subsidies ( [Fischer et al., 2014](#) ) have also been studied.

## 2.2 Project perspective

Greenhouse gas emission reduction projects, like CDM and CCER projects, represent an important emission reduction mechanism, In this perspective, carbon leakage means an unanticipated increase or decrease in GHG benefits outside of the project's accounting boundary as a result of the project activities ([Watson et al., 2000](#)).

[Bollen et al. \(1999\)](#) are the scholars in early days that discussing the relationship between CDM and carbon leakage problem. They used a general equilibrium model and proposed that CDM would increase carbon leakage when considered the overall impact. [FrankVöhringer et al. \(2006\)](#) conducted a systematic analysis of the problem, proposed that carbon leakage in projects occurred through the three channels mentioned earlier: economic, ecological and technological one. They further proposed that economic leakage could be divided into direct economic and market-induced types, and emphasized the importance of market-induced carbon leakage which was often neglected in projects' methodology. (also emphasized in [Kallbekken, 2007](#)). This is also the focus of our paper as explained in section 1. Researchers have mainly used models to investigate market-induced carbon leakage and often from large scale aspect, For example [Glomsrød et al. \(2011\)](#) used a CGE model to explore the problem in a CDM tree-planting project in Tanzania, showing a negative leakage rate through markets in the range of 60%-120% .Similarly [Kuik \(2013\)](#) computed leakage rates of 0.5% and 11.3% for projects in Brazil and Malaysia, respectively, through a CGE model. [Kallio et al. \(2018\)](#) used a global forest sector model to analyze forest carbon sinks projects, concluding that some inter-sectoral carbon leakage would take place. There have also been some small-scaled models that have been used to study the issue, with this type model able to more clearly reveal how leakage occur through market paths. [Murray et al. \(2004\)](#) explored the impact of leakage from a reserve to a forested area outside a reserve through a "price-induced supply response" using a forest and agricultural sector optimization model. [FrankVöhringer et al. \(2006\)](#) provided a single market equilibrium model and gave a proposal for the attribution of market leakage to CDM projects. [Kim et al.\(2014\)](#) built a market equilibrium model in two regions, through the derivation of elasticity, they gave out a leakage discounting formula for land-based greenhouse gas emission offset projects. However, from the best of our knowledge, none research has been done to compare the market-induced



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leakage issue in different types reduction projects.

In summary, the issue of carbon leakage has been fully discussed in national perspectives from both theoretical and empirical aspects. For the project perspective, most researchers focus on forestry related projects and none research have provided an analysis to compare the performance of different types reduction projects. Moreover, little research has been done for China's unique fast-growing CCER projects. In order to give more information about the market-induced leakage process and further compare the issue in different types of CCER projects, this study extends the simple fossil fuel market model (detailed explanation of it is presented in Appendix A) by adding the downstream market into analysis and proposes a dual market model. Therefore, the main contributions of the study include (1) enriching existing research about market-induced carbon leakage problems in CCER projects by introducing dual market equilibrium models (2) comparing the market-induced carbon leakage in three types of CCER projects as well as analyzing the main factors that influence the value of the leakages (3) providing a new perspective for the government to evaluate different types CCER projects.(4) summarizing a systematic approach for the other regional markets to comprehensively analyze this issue as well as giving key suggestions to apply.

### 3. Methodology

A dual market equilibrium model is formulated in this section in order to distinguish different types CCER projects thus comparing their market-induced leakage issue. The model, as presented in **Fig.2** takes all the supply & demand sides responses in the system into consideration thus giving out a comprehensive result for the problem.

According to China Certified Emission Reduction Exchange Info-Platform<sup>2</sup>. There are 254 projects that have been certified for emission reduction. Among them, those related to electricity market take up more than 80% with the number of 212. Therefore, we take electricity as the downstream market and fossil fuel as the upstream market to conduct our analysis. Here coal market is used to represent upstream fossil fuel market considering the fact that coal-fired generation takes up more than 90% of the total fossil fired generation in China (Yang et al.,2013). Normally, a CCER project will affect both downstream and upstream market, but in different ways. They can be divided into two types, one acts on the demand side, for example in a building energy-saving project located in Southern District of Chao Yang SOHO Center, the voluntary emission reduction is generated from the reduced electricity consumption during the crediting period.<sup>3</sup>Another example is a Aluminum electrolysis optimization and energy-saving renovation project in Hunan Province, in which the emission reduction comes from the

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<sup>2</sup> Available at: <http://cdm.ccchina.org.cn/yba.aspx?clmId=169&page=0>  
Accessed 2 February 2019

<sup>3</sup> Detailed information about the project is available at: <http://cdm.ccchina.org.cn/zybDetail.aspx?Id=674>

reduced electricity consumption in the smelting process of Aluminum.<sup>4</sup> The other type of project acts on the supply side, which can be further disaggregated: for electricity supply, some projects use renewable energy to completely replace coal-fired power plants while some projects only replace a part. Here, to clarify the bounds of our study, for supply side type projects we discuss two extreme situations: the complete renewable energy alternative (alternative project) and the simple abatement one (no replacement). Such classification has previously been used by Rosendahl and Strand (2009). Therefore, three types of CCER projects will be studied in the remainder of this section.

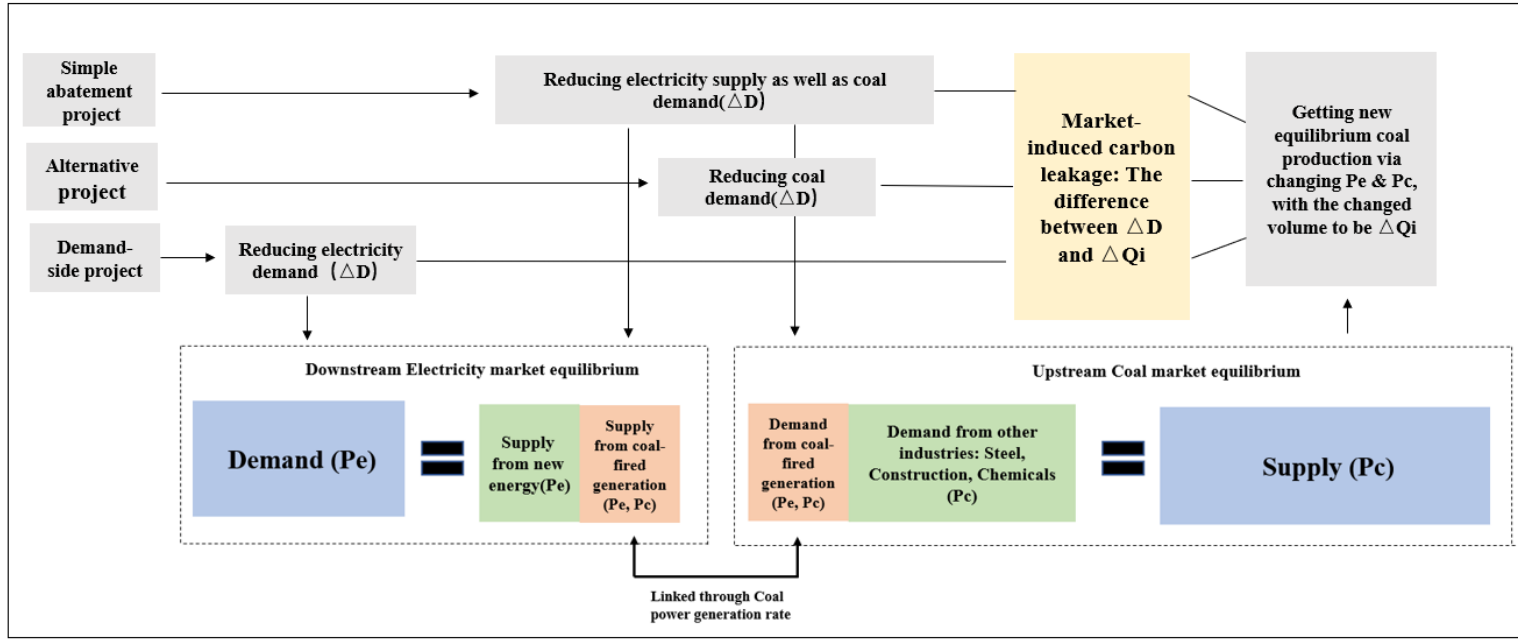


Fig.2 Mechanism of market-induced carbon leakage for three types projects

### 3.1 Market equilibrium before implementing CCER

In the upstream market, coal demand sectors are divided into two parts points to link it with downstream market: the coal-fired electricity industry ( $D_{cf}$ ) and the other sectors ( $D_{otr}$ ) such as steel, building materials and chemicals Feng et al., 2016. In the downstream market, supposing that the electricity supply side is composed of coal-fired generation and renewable energy generation ( $S_{rew}$ ), and that the former can be connected with the upstream market by a parameter  $\xi$  indicating one unit of coal produces  $\xi$  units of electricity. Note that we assume market equilibrium in both upstream and downstream market, so the system could be described as follows,

$$\text{Upstream coal market: } S_c(P_c, z_1) = D_{cf}(P_c, P_e, z_2) + D_{otr}(P_c, z_3)$$

<sup>4</sup> Detailed information about the projects is available at: <http://cdm.ccchina.org.cn/zybDetail.aspx?Id=339>

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$$\text{Downstream electricity market: } \xi \cdot D_{cf}(P_c, P_e, \mathbf{z}_2) + S_{rew}(P_e, \mathbf{z}_4) = D_{elc}(P_e, \mathbf{z}_5)$$

in which:  $P_c$ ,  $P_e$  are the coal price and electricity price respectively,  $D_{elc}$  is the overall electricity demand,  $S_c$  is coal supply and  $\mathbf{z}_i$  are vectors of other factors that influence related variables.

### 3.2 Market equilibrium after implementing CCER

$\Delta D$  is assumed to be the amount of nominal emissions reduction of a project. In supply side type projects: for simple abatement projects, they act on both coal and electricity markets by reducing coal demand as well as reducing electricity supply. While for the alternative projects, since coal resources are fully replaced by renewable, indicating electricity supply in the downstream market remains unchanged, thus they act only on the coal market (Rosendahl and Strand, 2009). As for demand side type projects, they act only on the electricity market since the reduction comes from the demand side instead of the power generation side. So the dual market system becomes:

For simple abatement projects,

$$S_c(P_{c1}, \mathbf{z}_1) = D_{cf}(P_{c1}, P_{e1}, \mathbf{z}_2) + D_{otr}(P_{c1}, \mathbf{z}_3) - \Delta D$$

$$\xi \cdot D_{cf}(P_{c1}, P_{e1}, \mathbf{z}_2) + S_{rew}(P_{e1}, \mathbf{z}_4) - \xi \Delta D = D_{elc}(P_{e1}, \mathbf{z}_5)$$

For alternative projects,

$$S_c(P_{c2}, \mathbf{z}_1) = D_{cf}(P_{c2}, P_{e2}, \mathbf{z}_2) + D_{otr}(P_{c2}, \mathbf{z}_3) - \Delta D$$

$$\xi \cdot D_{cf}(P_{c2}, P_{e2}, \mathbf{z}_2) + S_{rew}(P_{e2}, \mathbf{z}_4) = D_{elc}(P_{e2}, \mathbf{z}_5)$$

For demand side projects,

$$S_c(P_{c3}, \mathbf{z}_1) = D_{cf}(P_{c3}, P_{e3}, \mathbf{z}_2) + D_{otr}(P_{c3}, \mathbf{z}_3)$$

$$\xi \cdot D_{cf}(P_{c3}, P_{e3}, \mathbf{z}_2) + S_{rew}(P_{e3}, \mathbf{z}_4) = D_{elc}(P_{e3}, \mathbf{z}_5) - \Delta D$$

### 3.3 Derivation of market-induced carbon leakage

In this part, we introduce the conception of price elasticity into the derivation and assume that electricity and coal price are the only influenced variables. In this way, we can cover all the supply & demand side responses, besides, elasticity parameters are applicable for a numerical empirical analysis.

Supposing the price elasticity of coal supply,  $E_c^s$ , is defined as,

$$E_c^s = \frac{\Delta Q_c}{Q_{c0}} \times \frac{P_{c0}}{\Delta P_c}$$

then, the market-induced carbon leakage rate can be defined as Eq.(1), in the first component of which the numerator is the leakage quantity, which is equal to the difference between nominal emissions reduction and the real emissions reduction.

$$L_{rate} = \frac{\Delta D - (Q_{c0} - Q_{c1})}{\Delta D} = 1 + \frac{\Delta Q_c}{\Delta D} = 1 + \frac{E_c^s Q_{c0}}{\Delta D} \cdot \frac{\Delta P_c}{P_{c0}} \quad (1)$$

**Table.1** Nomenclature

Variable	Description
$Q_{c0}$	the equilibrium output of coal in baseline market (t)
$Q_{e0}$	the equilibrium output of electricity in baseline market (kw·h)
$P_{c0}$	the equilibrium price of coal in baseline market (yuan/t)
$P_{e0}$	the equilibrium price of electricity in baseline market (yuan/kw·h)
$\varphi$	the share of coal-fired generation in coal demand market
$\omega$	the share of coal-fired generation in electricity supply market.
$\xi$	the conversion coefficient, meaning one unit of coal produces $\xi$ unit of coal-fired generation(kw·h/t)
$\Delta D$	the amount of nominal emission reduction of a project (t)
$E_c^s$	the coal price elasticity of coal supply
$E_c^{dc}$	the coal price elasticity of coal demand from coal-fired generation
$E_c^{de}$	the electricity price elasticity of coal demand from coal-fired generation
$E_c^{dotr}$	the coal price elasticity of coal demand from the other downstream industry
$E_e^{srew}$	the electricity price elasticity of electricity supply from renewable energy
$E_e^d$	the electricity price elasticity of electricity demand

In order to calculate Eq.(1), we further develop a dynamic equilibrium system as described below with nomenclature presented in **Table.1**.

### 3.3.1 Simple abatement project

The following equations describe the dynamic equilibrium system for the simple abatement project. The upstream coal market:

$$\Delta Q_c = E_c^s Q_{c0} \frac{\Delta P_c}{P_{c0}} \quad (2)$$

$$\Delta D_c = (1-\varphi) Q_{c0} E_c^{dotr} \frac{\Delta P_c}{P_{c0}} + \varphi Q_{c0} (E_c^{de} \frac{\Delta P_e}{P_{e0}} + E_c^{dc} \frac{\Delta P_c}{P_{c0}}) - \Delta D \quad (3)$$

where Eq. (2) is the change in coal supply due to coal price change, and Eq.(3) is the change in coal demand via price change. Supply is equal to the demand change from the other downstream industry plus that from coal-fired electricity industry minus the reduction from CCER projects.  $\varphi$  is the share of coal-fired generation in the coal demand market

The downstream electricity market,

$$\Delta Q_e = \xi \varphi Q_{c0} (E_c^{de} \frac{\Delta P_e}{P_{e0}} + E_c^{dc} \frac{\Delta P_c}{P_{c0}}) + (1-\omega) Q_{e0} E_e^{srew} \frac{\Delta P_e}{P_{e0}} - \xi \Delta D \quad (4)$$

$$\Delta D_e = Q_{e0} E_e^d \frac{\Delta P_e}{P_{e0}} \quad (5)$$

where Eq.(4) is the electricity supply change composed of three parts. The first part is supply change from coal-fired generation which is equal to the change in coal demand in Eq. (3) multiplied by  $\xi$ . The second part is the supply change from renewable energy generation and the last part is the reduction from CCER projects. Eq.(5) is the electricity demand change and  $\omega$  is the share of coal-fired generation in electricity supply market.

Besides, in the baseline dual market we have,

$$\xi \varphi Q_{c0} = \omega Q_{e0} \quad (6)$$

indicating that coal demand from coal-fired generation in the upstream coal market multiplied by coefficient  $\xi$  is equal to the coal-fired generation in the downstream electricity market.

Now Eqs.(2) and (3) are set as equal to each other in the coal market equilibrium, and Eqs.(4) and (5) as equal to each other in the electricity market equilibrium. With the substitution of Eq.(6) into these equalities, after derivation, the change of coal output caused by simple abatement CCER projects is given below (detailed proof is presented in Appendix B.1):

$$\Delta Q_c = E_c^s Q_{c0} \frac{\Delta P_c}{P_{c0}} = \frac{\Delta D E_c^s [E_e^d - (1-\omega)E_e^{Srew}]}{\left[ \omega E_c^{de} + (1-\omega)E_e^{Srew} - E_e^d \right] \left[ E_c^s - (1-\varphi)E_c^{dotr} \right] + \varphi E_c^{dc} [E_e^d - (1-\omega)E_e^{Srew}]} \quad (7)$$

inserting Eq.(7) into Eq.(1) we get the market-induced carbon leakage rate for the simple abatement type CCER projects:

$$L_{rate1} = 1 + \frac{\Delta Q_c}{\Delta D} = 1 + \frac{E_c^s [E_e^d - (1-\omega)E_e^{Srew}]}{\left[ \omega E_c^{de} + (1-\omega)E_e^{Srew} - E_e^d \right] \left[ E_c^s - (1-\varphi)E_c^{dotr} \right] + \varphi E_c^{dc} [E_e^d - (1-\omega)E_e^{Srew}]} \quad (8)$$

### 3.3.2 Alternative project

The dynamic equilibrium in the upstream coal market for this type of projects is the same as for the simple abatement project as shown in Eq.(2) & (3). However, the downstream electricity market is different, with the following equations:

$$\Delta Q_{e1} = \xi \varphi Q_{c0} \left( E_c^{de} \frac{\Delta P_{e1}}{P_{e0}} + E_c^{dc} \frac{\Delta P_{c1}}{P_{c0}} \right) + (1-\omega) Q_{e0} E_e^{Srew} \frac{\Delta P_{e1}}{P_{e0}} \quad (9)$$

$$\Delta D_{e1} = Q_{e0} E_e^d \frac{\Delta P_{e1}}{P_{e0}} \quad (10)$$

where, Eq.(9) is the electricity supply change composed of only two parts. The first part is change in

supply from coal-fired generation which equals to the change in coal demand in Eq.(3) multiplied by  $\xi$ . The second part is the change in supply from renewable energy generation. Eq.(10) is the electricity demand change. As in the first example, Eq.(6) is the case for the baseline market, thus the leakage rate for this type of CCER is shown in Eq(11) (detailed proof is presented in Appendix B.2),

$$L_{rate2} = 1 + \frac{\Delta Q_{c1}}{\Delta D} = 1 + \frac{E_c^s [E_e^d - (1-\omega)E_e^{Srew} - \omega E_c^{de}]}{[\omega E_c^{de} + (1-\omega)E_e^{Srew} - E_e^d][E_c^s - (1-\phi)E_c^{dotr}] + \phi E_c^{dc}[E_e^d - (1-\omega)E_e^{Srew}]} \quad (11)$$

### 3.3.3 Demand side project

The following equations define the equilibrium in the demand side project. The upstream coal market balance is defined by:

$$\Delta Q_{c2} = E_c^s Q_{c0} \frac{\Delta P_{c2}}{p_{c0}} \quad (12)$$

$$\Delta D_{c2} = (1-\phi) Q_{c0} E_c^{dotr} \frac{\Delta P_{c2}}{p_{c0}} + \phi Q_{c0} (E_c^{de} \frac{\Delta P_{e2}}{p_{e0}} + E_c^{dc} \frac{\Delta P_{c2}}{p_{c0}}) \quad (13)$$

where, Eq.(12) is the supply change in the coal market via coal price. Eq.(13) is the coal demand change composed of change from the other downstream industries plus that of the coal-fired electricity industry.

The downstream electricity market is defined by:

$$\Delta Q_{e2} = \xi \phi Q_{c0} (E_c^{de} \frac{\Delta P_{e2}}{p_{e0}} + E_c^{dc} \frac{\Delta P_{c2}}{p_{c0}}) + (1-\omega) Q_{e0} E_e^{Srew} \frac{\Delta P_{e2}}{p_{e0}} \quad (14)$$

$$\Delta D_{e2} = Q_{e0} E_e^d \frac{\Delta P_{e2}}{p_{e0}} - \Delta D \quad (15)$$

where, Eq (14) is the electricity supply change composed of only two parts. Eq (15) is the electricity demand change including change via price and the reduction from the project. Through Eq.(6) and Eq.(12)-(15), we get:

$$\Delta Q_{c2} = E_c^s Q_{c0} \frac{\Delta P_{c2}}{p_{c0}} = \frac{-\Delta D E_c^s E_c^{de} \omega}{\xi [\omega E_c^{de} + (1-\omega)E_e^{Srew} - E_e^d][E_c^s - (1-\phi)E_c^{dotr}] + \xi \phi E_c^{dc}[E_e^d - (1-\omega)E_e^{Srew}]} \quad (16)$$

then, if measured by coal, the nominal emissions reduction of projects here is  $\frac{\omega \Delta D}{\xi}$ <sup>5</sup>, thus, market-

induced carbon leakage for this type project is given by the following (detailed proof is presented in

Appendix B.3),

<sup>5</sup> Nominal emissions reduction from coal-fired generation would be  $\omega \Delta D$  since we have assumed the market share, thus if measured by coal, those nominal emissions would be  $\frac{\omega \Delta D}{\xi}$

$$L_{rate3} = 1 + \frac{\Delta Qc2}{\omega \Delta D / \xi} = 1 + \frac{-E_c^s E_c^{de}}{[\omega E_c^{de} + (1-\omega)E_e^{srew} - E_e^d][E_c^s - (1-\varphi)E_c^{dotr}] + \varphi E_c^{dc}[E_e^d - (1-\omega)E_e^{srew}]} \quad (17)$$

The above results show that, for the three types of projects, factors affecting the leakage rates are price elasticities of both demand and supply sides and the market share parameters, see Eq.(8)(11)(17). For supply side projects,  $L_{rate1}$  is larger than  $L_{rate2}$  since we have  $E_c^{de}, E_c^s, E_e^{srew} > 0$  and  $E_c^{dc}, E_e^d, E_c^{dotr} < 0$ , indicating that simple abatement projects demonstrate more serious market-induced carbon leakage problems than the alternative projects. The reason behind this, is that in the downstream electricity market, there is a decline in supply directly comes from the simple abatement projects which leads to a higher electricity price while there is no such impact for the alternative projects. So then, in the coal market, an increased electricity price gives rise to a higher demand for coal, thus entailing more positive carbon leakage. However, we can't define the comparative size between demand side projects and supply side projects, which needs further assumptions on the influential parameters.

## 4. Results and discussions

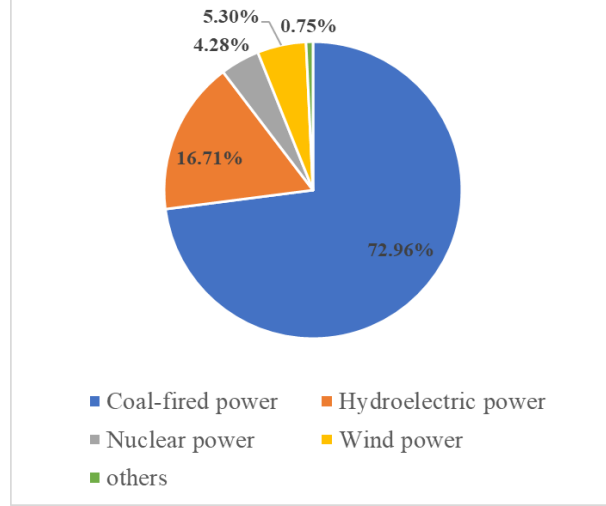
In this section, we conduct numerical studies to compare the carbon leakage rates of the three types CCER projects and analyze the potential impact of each parameter. By doing so, we hope to provide some insights for policymaking on CCER mechanisms. Moreover, we extend our analysis to a global perspective, and discuss the possible suggestions for each regional offset project market.

### 4.1 Estimation of parameters

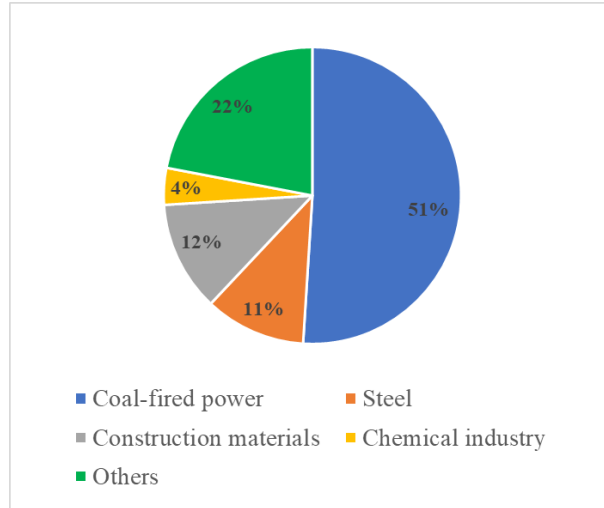
Considering the reality of China as well as reviewing the literature, this study obtained the relevant parameters as shown in **Table.2**, providing a basis for numerical analysis.

#### (1) Market share parameters:

According to the Statistical Data of the National Electric Power Industry in 2018 ([China Electricity Council., 2018](#)), the power supply structure is shown in **Fig.3-1**, so it is assumed here that the share of coal-fired electricity generation,  $\omega=73\%$ . Besides, in China, the main downstream demand industries utilizing coal are coal-fired power, steel, construction materials and chemical industry and their proportions are shown in **Fig.3-2** ([Chen X.,2017](#)) thus we assume  $\varphi=51\%$



**Fig.3-1** Structure of Power supply in China



**Fig.3-2** Downstream industry structure of coal demand

## (2) Price elasticity parameters

There have been a number of studies investigating the electricity demand in China which provide the value of elasticity,  $E_e^d$ , see for example [Du et al. \(2017\)](#). Here we take an average value from these studies, assuming  $E_e^d = -0.78$ . Following [Zhang et al., \(2016\)](#) who studied the coal supply capacity of China, we have  $E_c^s = 1.16$ . As for the coal price elasticity and the electricity price elasticity of coal demand from coal-fired generation, the results of [Qiao et al., \(2016\)](#) have been utilized, in which an empirical study was undertaken on the relationship among electric coal demand, coal price and electricity price, thus we set  $E_c^{de} = 0.1$ ,  $E_c^{dc} = -0.28$ . The steel industry is used here to represent the other downstream industries of coal demand, because the industrial structures of the other two are much more complex and



harder to define. So, following Shi., (2011), we set  $E_c^{dotr}=-0.27$ . Finally, for  $E_e^{Srew}$ , the electricity price elasticity of electricity supply from renewable energy, to the best of our knowledge, no related research has been undertaken on this, for the primary reason that there are many incentive policies for the renewable energy industry in China, so it is difficult to investigate the price elasticity of renewable energy supply. Huang J.,(2017) conducted an empirical study on the relationship between renewable energy generation and its subsidized electricity price, we use this result of it as a proxy,  $E_e^{Srew}=0.02$ , which is considered reasonable since the subsidized price is highly related to the market.

**Table.2**  
Summary of parameters' value

$\omega$	0.73
$\varphi$	0.51
$E_c^{de}$	0.1
$E_e^{Srew}$	0.02
$E_c^s$	1.16
$E_c^{dc}$	-0.28
$E_e^d$	-0.78
$E_c^{dotr}$	-0.27

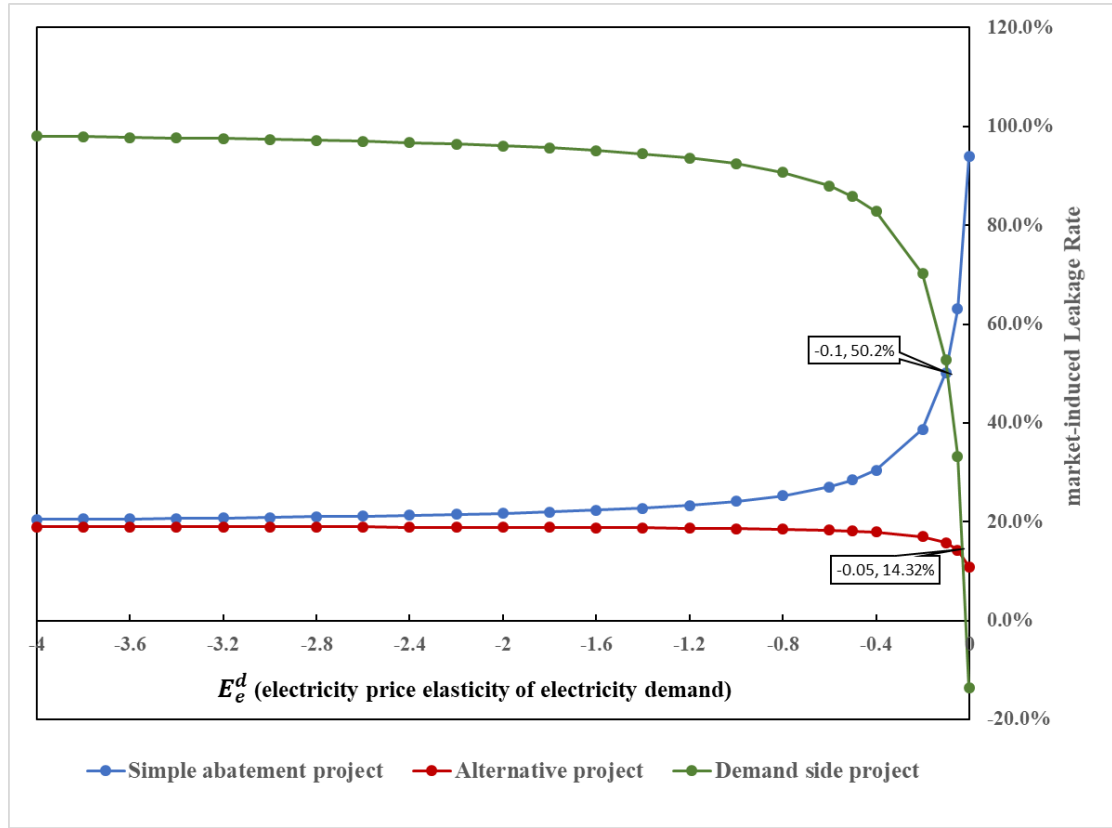
## 4.2 Numerical analysis

With the above parameters, following Eq. (8) (11) (17) we calculate the market-induced carbon leakage for those three types CCER projects to be,  $L_{rate1}=25.4\%$ ,  $L_{rate2}=18.5\%$ ,  $L_{rate3}=90.5\%$ . This implies that based on the current situation in China, generally, demand side CCER projects demonstrate much more market-induced carbon leakage problem than supply side projects. The leakage percentage of demand-side projects is close to 100 percent, indicating that there is nearly no net emissions reduction by this type of project if take the leakage problem via market path into consideration. So, here demand side type projects are of low efficiency in terms of leakage problem.

In order to understand the bounds and variation of this behavior, a sensitivity analysis was undertaken, comparing the impact of each parameter on different types of CCER projects. Firstly, an analysis for price elasticity parameters was undertaken. The results are divided into three parts:

(1) For different values of electricity price elasticity of electricity demand  $E_e^d$ , results are shown in Fig.4. The increase of  $E_e^d$  helps alleviate leakage problems in the alternative projects and demand side projects while aggravating leakage in simple abatement projects.  $E_e^d$  is also influential on ranking these three types projects with regards to the leakage issue, as shown in the figure, the demand side projects perform best when  $E_e^d$  is close to zero while the worst if  $E_e^d$  is lower than -0.1. This implies that factors affecting  $E_e^d$  need to be paid attention to. Among them, government policy is the most influential one.

Today, in China the electricity prices are still partially regulated, meaning that there is a lack of elasticity in electricity demand, thus the current value of  $E_e^d$  could be close to zero. However, in the future, with the promotion of Market-oriented Reform of Electricity Price (NDRC.,2017b) in China, the commodity will have a higher price elasticity. This suggests that in the future, the demand side project may demonstrate much more leakage problem when compared with the other two. In addition to government policy, different fields that the projects involve also matter. For example, the values of  $E_e^d$  are different between business users and residential users. Moreover, the duration of projects is also an important factor because most products show high elasticity in the long-term while having relatively low elasticity in the short term.



**Fig.4** Effects of  $E_e^d$  on carbon leakage rate for three types CCER projects

(2) The leakage rates under different electricity price elasticity of coal demand in coal-fired generation  $E_c^{de}$  are shown in **Fig.4**. Similarly, the increase of  $E_c^{de}$  help alleviate leakage problems in the second and the third type projects, but aggravate that in the first one. Besides, the third type projects perform worst when  $E_c^{de}$  is close to zero, while the best if  $E_c^{de}$  is larger than 2.8. As for the factors affecting  $E_c^{de}$ , still, government policy should be paid more attention to. Here,  $E_c^{de}$  can be directly reflected on the electricity price elasticity of coal-fired generation. So those affecting

coal-fired industry policies need to be considered. Now, in China, in order to promote the development of renewable energy, a structure reform of generation industry (NDRC.,2016) is being implemented. In which, the proportion of coal-fired generation is required to drop to 55%. So in the long term, since this generation is restricted by the government to a certain size, the supply of it will be insensitive to electricity price, thus  $E_c^{de}$  will become close to zero in long term. However, in near-term future when it is still in the process of such transformation, the reform promotes the market competition, meaning those who are not able to make profit will be eliminated and closed more fast. Therefore, in the short term, the supply of it will be more sensitive to the electricity price, in other words  $E_c^{de}$  will be higher comparing with currently estimated 0.1. So, from changing value of  $E_c^{de}$  as shown in Fig.5, the first type projects will demonstrate the most leakage problem in near-term future while the third type projects become the worst in long term. Also, as analyzed before, factors like projects duration and their involved fields are impactful that can act as references when evaluating and comparing different types projects.

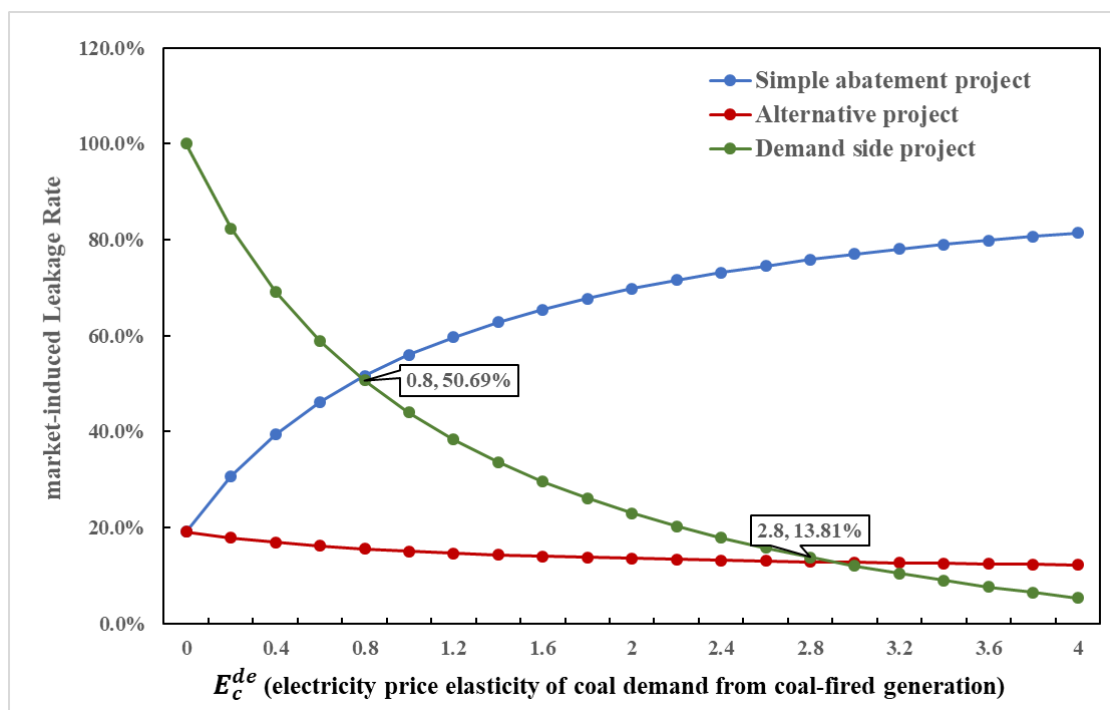
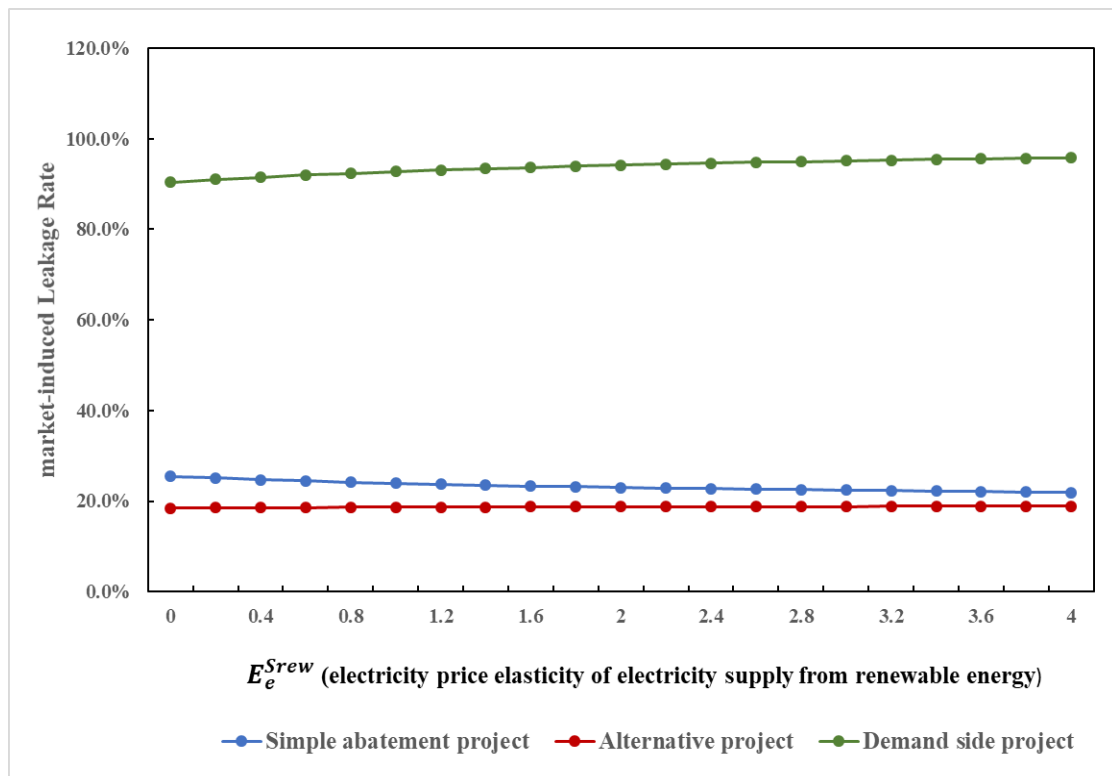


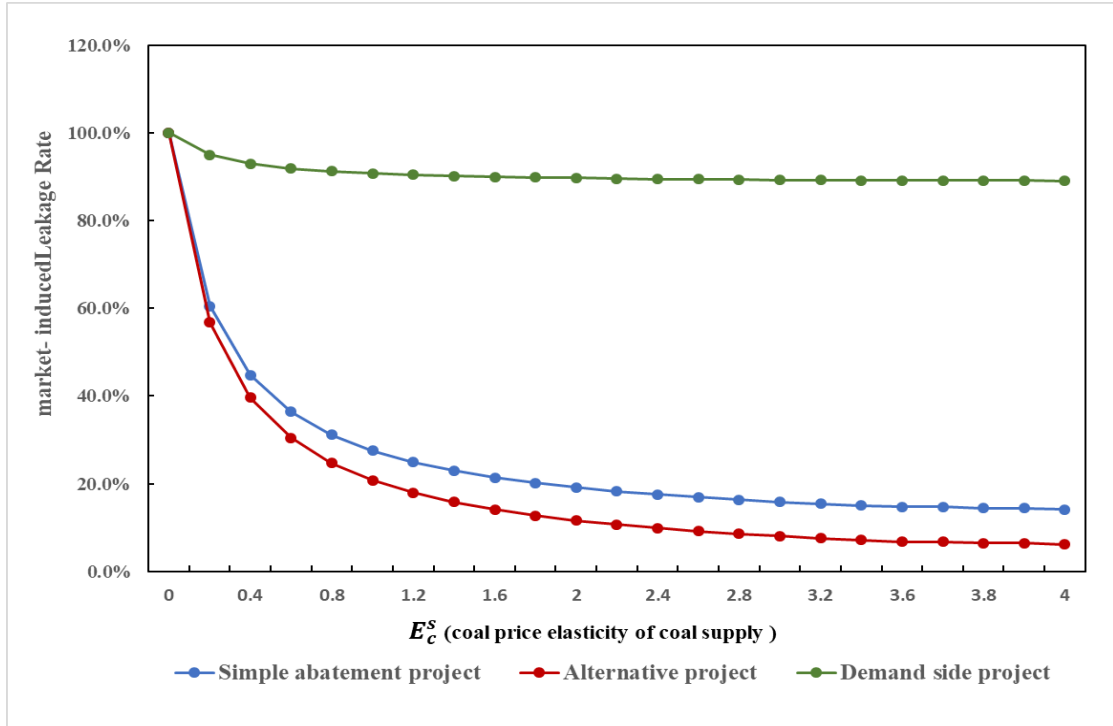
Fig.5. Effects of  $E_c^{de}$  on carbon leakage rate for three types CCER projects

(3)As for the remaining price elasticity parameters:  $E_e^{Srew}$ (electricity price elasticity of electricity supply from renewable energy),  $E_c^s$  (coal price elasticity of coal supply),  $E_c^{dc}$  (coal price elasticity of

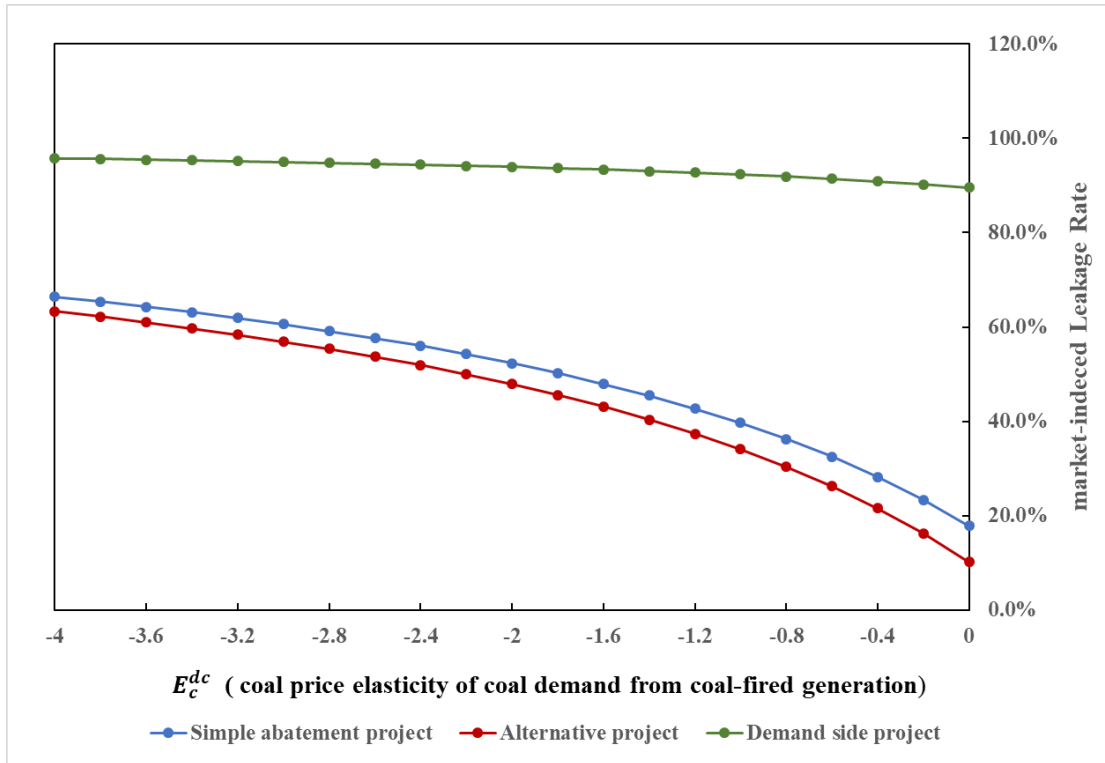
coal demand from coal-fired generation) and  $E_c^{dotr}$  (coal price elasticity of coal demand from the other downstream industries), results are shown in **Fig.6-1** to **Fig.6-4**. Different from the above two parameters, those four price elasticity parameters have no impact on the rankings of these three types of projects with regards to leakage. In all cases, the alternative projects perform best while the demand side projects are the worst. In addition, parameters  $E_c^s$ ,  $E_c^{dc}$  and  $E_c^{dotr}$  produce similar impact, the increase of these parameters helps ease the problems in all three types of projects with relatively less impact on the demand side projects. However, for  $E_e^{Srew}$ , the impact is much smaller with different results, the increase in this parameter only eases the problem for the simple abatement type projects, while aggravating it for the other types.



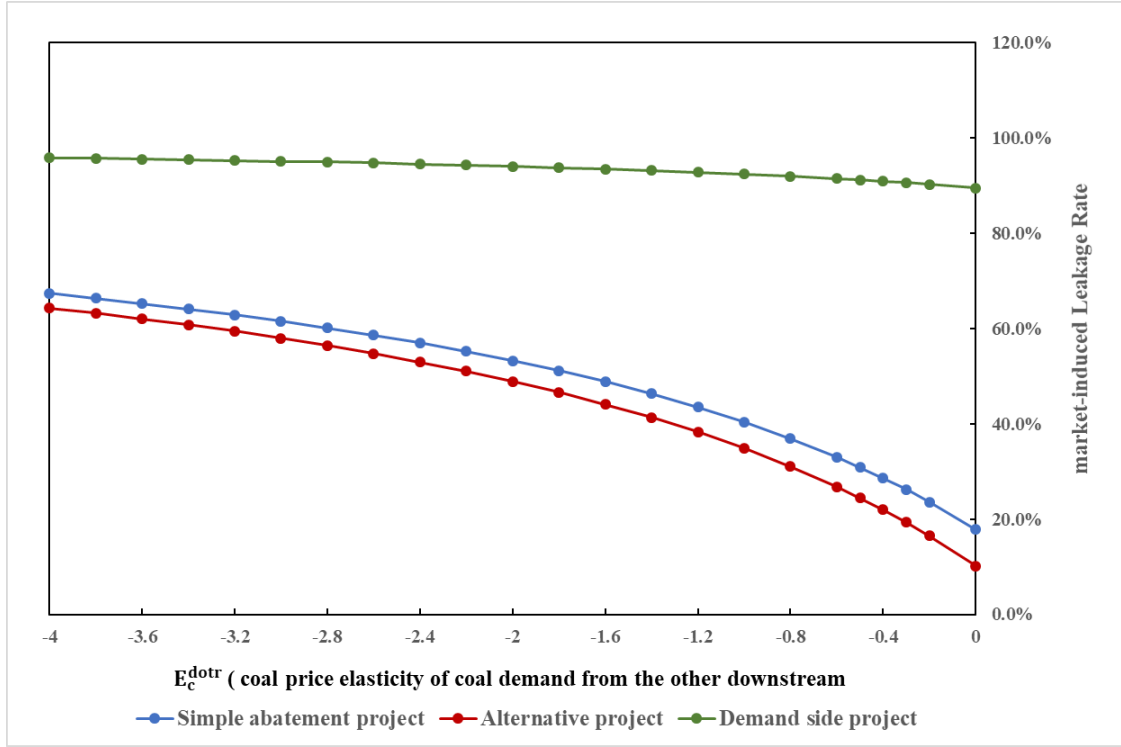
**Fig.6-1** Effects of  $E_e^{Srew}$  on the carbon leakage rates



**Fig.6-2** Effects of  $E_c^S$  on the carbon leakage rates

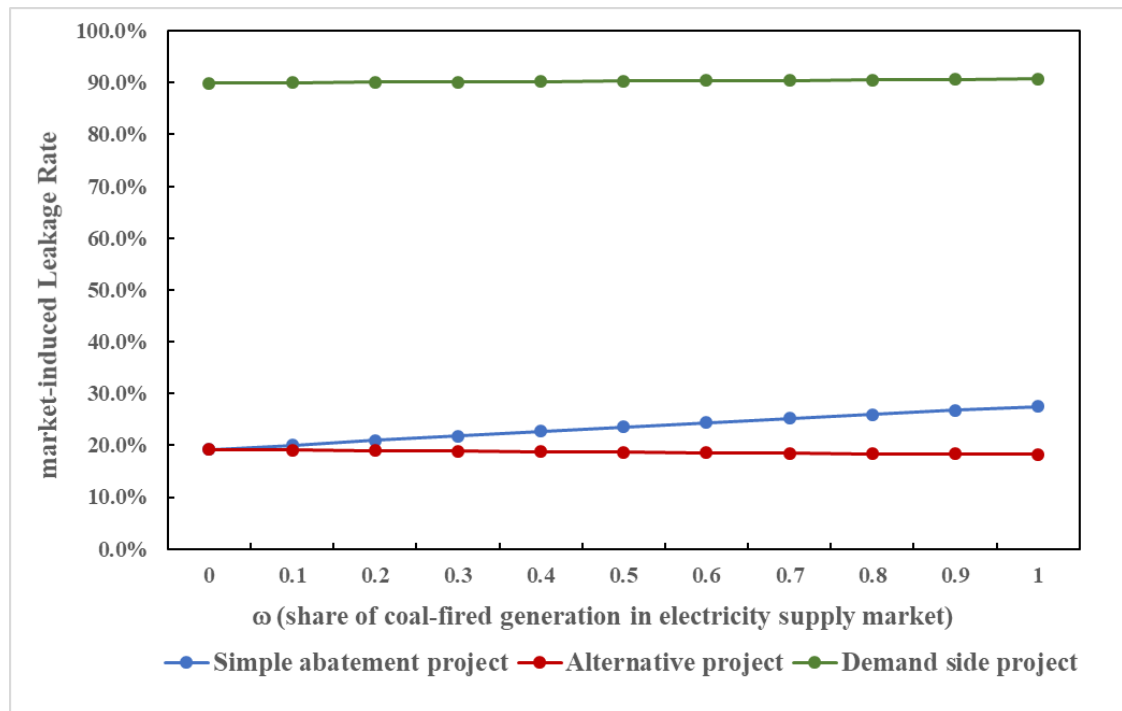


**Fig.6-3** Effects of  $E_c^{dc}$  on the carbon leakage rates

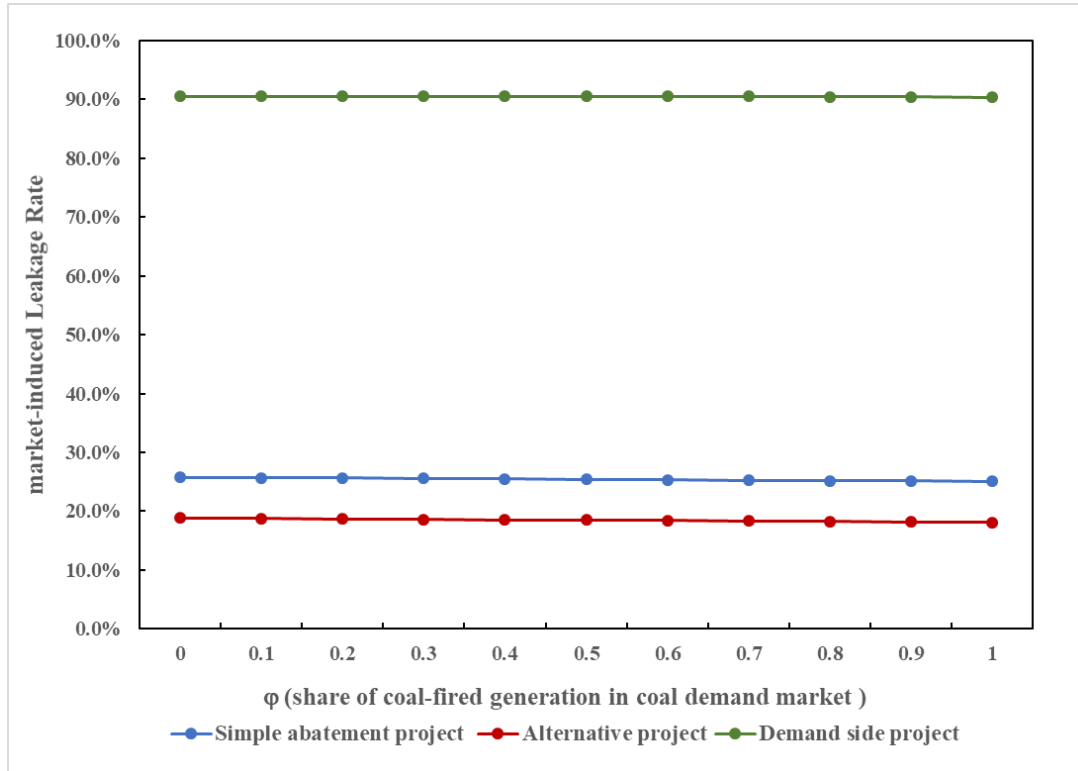


**Fig.6-4** Effects of  $E_c^{dotr}$  on the carbon leakage rates

Secondly, we investigate carbon leakage performance of the three types of projects under different market share conditions, as shown in **Fig.7-1** & **Fig.7-2**. Both  $\varphi$  (the share of coal-fired generation in coal demand market) and  $\omega$  (the share of coal-fired generation in the electricity supply market) have much slighter impact on the leakage rate when compared with the price elasticity parameters. The implication of this is that the market share parameter works as a weight of related price elasticity parameters, so their influences depends on the comparative values of those price elasticities. For  $\varphi$ , since absolute values of  $E_c^{de}$ ,  $E_c^{dc}$  and  $E_c^{dotr}$  are close to each other, changes in their weights don't affect the overall leakage rate, thus  $\varphi$  has almost no impact on leakage issue. As for  $\omega$ , according to Eq.(4) (9) (14), only the simple abatement projects act on the supply side of the electricity market, so  $\omega$  generates little or no effect on leakage rate for the other two types of projects. Besides, since the absolute values of  $E_c^{de}$  and  $E_c^{dc}$  are relatively higher than  $E_e^{Srew}$ , the increase of  $\omega$  aggravates the problem in the abatement projects



**Fig.7-1** Effects of  $\omega$  on the carbon leakage rates



**Fig.7-2** Effects of  $\phi$  on the carbon leakage rates

### 4.3 Discussions

According to “2019 Global Carbon Market Progress Report” published by International Carbon Action Partnership (ICAP, 2019). There are 20 regional carbon trading systems in the world, which will cover nearly 15% of the total global carbon emissions. As an important supplement mechanism to the emission trading market, project-based carbon offset market has also become an important climate policy tool employed by every regional market. Though the result above comes from the reality of China, the methodology is applicable for each offset market, which provides some insights for regional policy makers to establish the market more effectively.

To begin with, market-induced carbon leakage in voluntary emission reduction projects should not be ignored, it may even offset the whole benefit of reduction emission such as the demand-side project in China analyzed before. Then, a systematic approach to comprehensively analyze the issue could be summarized: the main markets (for example fossil fuel markets, electricity markets or wood markets) that will be influenced when implementing offset projects should be identified as the first step, usually the affected markets are able to linked into one system for the analyzing work, for example in our analysis, the coal and electricity market is linked by a conversion coefficient between coal and coal-fired generation; the second step is choosing the level of aggregation for each



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relevant market. In our study, we choose the domestic markets as equilibrium to do the work, because domestic projects are the only offsets allowed in China, and a unified classification and analysis of CCER projects at the national level is considered to be cost-effective, other emission trading market like Korea Emission Trading System faced the same situation where eligibility of offsets is restricted to Korean offsets; at last, an effective evaluation of those market parameters are needed. In this way, the whole offset projects in a regional trading system can be divided into various groups according to their affecting markets, and market-induced carbon leakage rates for each group projects are able to be figured out.

As for how to handle the issue based on the above analysis results thus to build the regional offset market more efficiently. We divide the problem into two situations:

On the one hand, for the relatively small-scaled offset markets like those just established or are planned to be established. The figured-out leakage rates could to be used as one perspective to qualitative evaluate different project. Because a small number of projects may not enough to have great effect on a market equilibrium. Besides, at the starting stage, offset projects need to be encouraged to active the market. Here, when setting the maximum offset ratio for different types projects as most regional emission trading market do (Marcu et al., 2013) or considering project types for priority validated, the leakage rate could be one important factor that need paid attention to.

On the other hand, for those large-scaled mature market. A market-induced carbon leakage discount coefficient is useful (Erickson et al., 2014). The analysis results are helpful to establish different levels of coefficients for different types projects. Here, a sensitivity analysis for each parameter should be undertaken to help find the most influential factors. For example, in our analysis of CCER, price elasticity parameters are much more impactful than market share parameter thus factors related to price elasticity are important. Therefore, the discount coefficient needed to be adjusted when there is a change in those factors.

## **5.Conclusions**

The issue of climate change and global warming is a severe challenge of human being, how to reduce emissions and control climate change has become a global topic. Paris Agreement initiated a new process of global greenhouse gas emission reduction in the post-Kyoto era (after 2020). It advocates the bottom-up Intended Nationally Determined Contributions (INDC), so leads a potential to cope the issue from international- level to regional- level. (de Souza and Pacca, 2019) Besides, it requires all Parties to undertake the emission reduction obligations, which means the developing countries who were once exempted from emission reduction liability are now becoming more and more important (Duan et al.,

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2017). China, as one of the most important developing country, and also the largest carbon emitter in the world, its mitigation action is bound to be of special importance. (Duan et al., 2017).

This study focuses on the CCER market in China, which is an important supplementary mechanism of carbon trading market. From the aspect of market-induced carbon leakage, we built a dual market equilibrium model to systematically and comprehensively analyze the issue for three representative kinds of projects. The obtained results are summarized as follows:

(i) Based on the reality of China, the market-induced carbon leakage rates for the three types CCER projects are 25.4%, 18.5% and 90.5% for simple abatement projects, alternative projects, and demand side projects, respectively.

(ii) From the results of sensitivity analysis, in most cases, demand side projects demonstrate the most market-induced leakage, in other words, in this aspect, this type of projects have the lowest emissions reduction efficiency. Alternative projects show the least leakage, with the simple abatement projects in the middle.

(iii) Price elasticities and market share parameters are the main factors determining the leakage rate for all three types of projects, and the former ones are much more impactful, especially parameters  $E_c^{de}$  (electricity price elasticity of coal demand from coal-fired generation) and  $E_e^d$  (electricity price elasticity of electricity demand) which not only affect the leakage rate for projects but also the comparative performance between them.

The above results offer some insights into the evaluation of different projects. Firstly, the market-induced carbon leakage problem in CCER projects should not be ignored. Secondly, in most cases the alternative projects have the least leakage rate, meaning this type of projects could be given priority to. Thirdly, factors that affecting the value of alternative parameters  $E_c^{de}$  and  $E_e^d$  should be carefully considered. For example, government policies like the structural reform of the supply side in the coal-fired industry and market-oriented reform of the electricity price have significant impacts on  $E_c^{de}$  and  $E_e^d$ , respectively. In this way, our study gives a new perspective to evaluate CCER projects more comprehensively to help the mechanism better realize its economic and environmental benefits, thus promoting the development of carbon trading market.

Moreover, this analysis approach can be replicated for any other regional emission trading market in the world, and we recommend two ways to applied the leakage rate result for different types offset projects based on the reality of the region. Firstly, it could be one perspective to qualitative evaluate different project when setting the maximum offset ratio for different types projects as most regional emission trading systems do or when considering project types for priority validated. Secondly, it is able to act as a basis for developing a market-induced carbon leakage discount coefficient for offset projects type by type, and the sensitivity analysis help find out the most influential factors which gives insights

to the management when an adjust for the discount coefficient is needed.

The present study mainly focuses on the emission reduction efficiency aspect of offset projects. Future extensions may add other aspect like mitigation cost into consideration, investigate the synergetic effect for different types projects. Moreover, the underlying assumptions in the study like perfect competition in the market could be relaxed with some modifications.

## Appendix A. Simple market model

Assuming the supply and demand functions of the market are:

$$S(p) = \beta \cdot (p - p_s) \quad D(p) = \alpha \cdot (p_d - p)$$

The parameter  $p_s > 0$  is the threshold price for any firm to enter the market. The parameter  $p_d > 0$  is the “choke price” at which demand equals zero,  $\alpha > 0$  and  $\beta > 0$  are the slope coefficients. So we get the equilibrium price and output:

$$P_0 = \frac{\alpha \cdot P_d + \beta \cdot P_s}{\alpha + \beta}$$

$$Q_0 = \frac{\alpha \cdot \beta}{\alpha + \beta} \cdot (p_d - p_s)$$

Then, when a CCER project is carried out, we assume it reduces coal demand  $\Delta D$  and has no impact on supply. So after implementing the project, the demand function becomes:

$$D_1(p) = \alpha \cdot (p_d - p) - \Delta D$$

New equilibrium price and output become:

$$P_1 = \frac{\alpha \cdot P_d + \beta \cdot P_s - \Delta D}{\alpha + \beta} = P_0 - \frac{\Delta D}{\alpha + \beta}$$

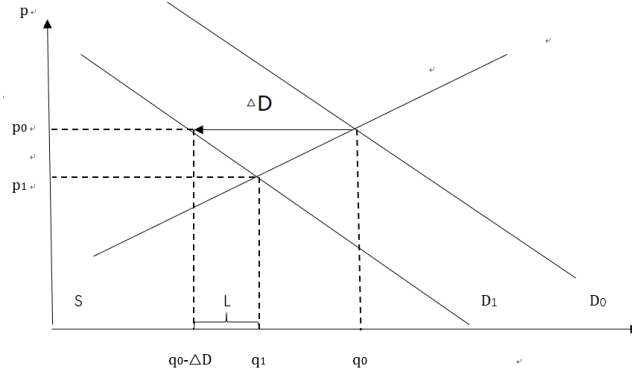
$$Q_1 = \frac{\alpha \cdot \beta}{\alpha + \beta} (p_d - p_s) - \frac{\beta}{\alpha + \beta} \cdot \Delta D = Q_0 - \frac{\beta}{\alpha + \beta} \cdot \Delta D$$

$$Q_0 - Q_1 = \frac{\beta}{\alpha + \beta} \cdot \Delta D$$

A project nominally reduce coal demand  $\Delta D$  thus reduces carbon emissions. However, due to the price decline caused by the market effect, there will be an increase in coal demand outside the project boundary, resulting in leakage and making the overall reduction become less than  $\Delta D$ . So, if  $\tau$  represents the carbon emission coefficient of coal. The amount and rate of carbon leakage would be :

$$L = \left( \Delta D - \frac{\beta}{\alpha + \beta} \cdot \Delta D \right) \cdot \tau \quad L_{rate} = \frac{L}{\Delta D \cdot \tau} = \frac{\alpha}{\alpha + \beta}$$

The supply and demand map below shows the problem more intuitively



## Appendix B

### B.1 Derivation of $L_{rate1}$

From Eq.(6) we have  $Q_{e0} = \frac{\xi \varphi Q_{c0}}{\omega}$ , let Eq.(2)=Eq.(3) and Eq.(4)=Eq.(5), then inserting the relationship in Eq.(6) into them, suppose  $A = Q_{c0} \frac{\Delta P_e}{P_{e0}}$ ,  $B = Q_{c0} \frac{\Delta P_c}{P_{c0}}$  we get,

$$\text{coal market: } E_c^S B = (1-\varphi) E_c^{dotr} B + \varphi (E_c^{de} A + E_c^{dc} B) - \Delta D \quad (18)$$

$$\text{electricity market: } \varphi E_c^{de} A + \varphi E_c^{dc} B + \frac{(1-\omega) E_e^{Srew} \varphi A}{\omega} - \Delta D = \frac{E_e^d \varphi A}{\omega} \quad (19)$$

from Eq.(19),

$$A = \frac{\omega \Delta D - \omega \varphi E_c^{dc} B}{\omega \varphi E_c^{de} + (1-\omega) \varphi E_e^{Srew} - \varphi E_e^d} \quad (20)$$

Inserting Eq.(20) into (18),

$$B = \frac{[E_e^d - (1-\omega) E_e^{Srew}] \Delta D}{[\omega E_c^{de} + (1-\omega) E_e^{Srew} - E_e^d] [E_c^S - (1-\varphi) E_c^{dotr}] + \varphi E_c^{dc} [E_e^d - (1-\omega) E_e^{Srew}]}$$

thus,

$$L_{rate1} = 1 + \frac{\Delta Q_c}{\Delta D} = 1 + \frac{E_c^S B}{\Delta D} = 1 + \frac{E_c^S [E_e^d - (1-\omega) E_e^{Srew}]}{[\omega E_c^{de} + (1-\omega) E_e^{Srew} - E_e^d] [E_c^S - (1-\varphi) E_c^{dotr}] + \varphi E_c^{dc} [E_e^d - (1-\omega) E_e^{Srew}]}$$

### B.2 Derivation of $L_{rate2}$

Also let Eq.(2)=Eq.(3) and Eq.(9)=Eq.(10), then inserting the relationship  $Q_{e0} = \frac{\xi \varphi Q_{c0}}{\omega}$  into them,

suppose  $A_1 = Q_{c0} \frac{\Delta P_{e1}}{P_{e0}}$ ,  $B_2 = Q_{c0} \frac{\Delta P_{c1}}{P_{c0}}$  we get,

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$$\text{coal market: } E_c^s B_1 = (1-\varphi) E_c^{dotr} B_1 + \varphi(E_c^{de} A_1 + E_c^{dc} B_1) - \Delta D \quad (21)$$

$$\text{electricity market: } \varphi E_c^{de} A_1 + \varphi E_c^{dc} B_1 + \frac{(1-\omega) E_e^{Srew} \varphi A_1}{\omega} - \frac{E_e^d \varphi A_1}{\omega} \quad (22)$$

from Eq.(22),

$$A_1 = \frac{-\omega \varphi E_c^{dc} B_1}{\omega \varphi E_c^{de} + (1-\omega) \varphi E_e^{Srew} - \varphi E_e^d} \quad (23)$$

Inserting Eq.(23) into Eq.(21),

$$B_1 = \frac{[E_e^d - (1-\omega) E_e^{Srew} - \omega E_c^{de}] \Delta D}{[\omega E_c^{de} + (1-\omega) E_e^{Srew} - E_e^d][E_c^s - (1-\varphi) E_c^{dotr}] + \varphi E_c^{dc} [E_e^d - (1-\omega) E_e^{Srew}]}$$

Thus

$$L_{rate2} = 1 + \frac{\Delta Qc1}{\Delta D} = 1 + \frac{E_c^s B_1}{\Delta D} = 1 + \frac{E_c^s [E_e^d - (1-\omega) E_e^{Srew} - \omega E_c^{de}]}{[\omega E_c^{de} + (1-\omega) E_e^{Srew} - E_e^d][E_c^s - (1-\varphi) E_c^{dotr}] + \varphi E_c^{dc} [E_e^d - (1-\omega) E_e^{Srew}]}$$

### B.3 Derivation of $L_{rate3}$

Similarly, let Eq.(12)=Eq.(13) and Eq.(14)=Eq.(15), then inserting the relationship  $Q_{eo} = \frac{\xi \varphi Q_{c0}}{\omega}$

into them, suppose  $A_2 = Q_{co} \cdot \frac{\Delta Pe2}{Pe0}$ ,  $B_2 = Q_{co} \cdot \frac{\Delta Pc2}{Pc0}$  we get,

$$\text{coal market: } E_c^s B_2 = (1-\varphi) E_c^{dotr} B_2 + \varphi(E_c^{de} A_2 + E_c^{dc} B_2) \quad (24)$$

$$\text{electricity market: } \xi \varphi E_c^{de} A_2 + \xi \varphi E_c^{dc} B_2 + \frac{\xi (1-\omega) E_e^{Srew} \varphi A_2}{\omega} = \frac{\xi E_e^d \varphi A_2}{\omega} - \Delta D \quad (25)$$

from Eq.(25),

$$A_2 = \frac{-\omega \Delta D - \xi \varphi B_2 \omega E_c^{dc}}{\omega \xi \varphi E_c^{de} + (1-\omega) E_e^{Srew} \xi \varphi - E_e^d \xi \varphi} \quad (26)$$

Inserting Eq.(26) into Eq.(24),

$$B_2 = \frac{-\Delta D E_c^{de} \omega}{[\xi \omega E_c^{de} + \xi (1-\omega) E_e^{Srew} - \xi E_e^d][E_c^s - (1-\varphi) E_c^{dotr}] + \varphi E_c^{dc} [\xi E_e^d - \xi (1-\omega) E_e^{Srew}]}$$

Thus,

$$L_{rate3} = 1 + \frac{\Delta Qc2}{\frac{\omega \Delta D}{\xi}} = 1 + \frac{E_c^S B2}{\frac{\omega \Delta D}{\xi}} = 1 + \frac{-E_c^S E_c^{de}}{[\omega E_c^{de} + (1-\omega)E_c^{Srew} - E_c^d][E_c^S - (1-\phi)E_c^{dotr}] + \phi E_c^{dc}[E_c^d - (1-\omega)E_c^{Srew}]}$$

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