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Article

Market-based solution in China to finance the clean from the dirty

Haoqi Qian[a,b], Rong Ma[c], Libo Wu[c,d,*]

[a] Institute for Global Public Policy, Fudan University, Shanghai 200433, China
[b] LSE-Fudan Research Centre for Global Public Policy, Fudan University, Shanghai 200433, China
[c] School of Economics, Fudan University, Shanghai 200433, China
[d] Shanghai Institute for Energy and Carbon Neutrality Strategy, Fudan University, Shanghai 200433, China

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ABSTRACT

Financial incentives play a key role in promoting renewable energy investments that can help China achieve the ‘dual carbon’ goal. The national emissions trading scheme (ETS) and the renewable energy portfolio standard (RPS) are two existing market-based policy instruments that can generate stable expected returns for low-carbon projects. This paper studies the interactive distribution effects of these two market-based instruments. We use the micro-level thermal power plant data to investigate the abatement effects of the national ETS, in which the details show that the existing rate-based ETS will result in higher negative impacts on power units, whose installed capacities are smaller than 400 MW. The interactive distribution effects between the two markets will occur when the permit allocation standards of the national ETS become stricter than the existing ones. Provinces in Eastern China and Northern China will face high pressure on costs in both ETS and RPS markets. When the levels of the permit allocation standards are set as 70% of the existing ones and the carbon price is assumed to be 200 yuan/ton in 2030, the annual market size of the national ETS will be nearly 100 billion yuan, and the annual market size is predicted to be 250 billion yuan. In the existing rate-based national ETS, the China Certified Emission Reduction (CCER) mechanism will have an offsetting effect, which should be taken into serious consideration during the policy-making processes in the future.

1. Introduction

The goal of "carbon peak and carbon neutralization" (hereinafter referred to as the "dual carbon" goal) has become China’s national strategy since 2020. In order to achieve the dual carbon goal, China requires a huge number of green investments along with climate policies. For example, it is estimated that China needs to invest about 22 trillion yuan by 2030 and about 139 trillion yuan by 2060. Among these investments, the annual demand for green investment to achieve the "carbon peak" from 2021 to 2030 is about 2.2 trillion yuan/year [1]. For a long time, the effectiveness of green investment and financing has been weakened by the lack of unified standards, imperfect information disclosure mechanism, low proportion of ESG investment, low project returns, etc. [2]. The basic approaches to achieving carbon peak and carbon neutralization include developing renewable energies, promoting terminal electrifications, improving energy efficiencies, and developing carbon removal technologies [3–5]. The key action that can solve these issues is to improve the expected rate of return of green investment projects by realizing the internalization of positive externalities of green projects and the financial additionality for the investors [6]. The national emissions trading scheme (ETS) and the renewable energy portfolio standard (RPS) are two existing market-based policy instruments that have the potential to achieve these targets [7,8]. Therefore, this paper attempts to study the interactive distribution effects of these two market-based instruments.

From 2022 to 2030, the market-based policy instruments such as carbon emission trading and renewable energy portfolio standards are expected to become the main driving force for China to achieve the dual carbon goal [9]. There are several reasons for this trend. Firstly, China’s policy practices show that there are disadvantages in the emissions reduction policy based on the direct intervention of the government [10]. For example, renewable energy subsidies bring pressure on the public financial system. The national feed-in-tariff subsidies for renewable energies began in 2012 and ended in 2021 due to the accumulating fund gaps. Secondly, market-based instruments can help improve the efficiencies of resource allocation and ensure that the emissions reduction constraints can be flexibly adjusted according to the economic situation. In August 2021, the Ministry of Finance made it clear in its official reply to the deputies’ suggestions on renewable en-

* Corresponding author.
E-mail address: wulibo@fudan.edu.cn (L. Wu).

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ergy subsidies that it is not appropriate to use special treasury bonds and special bonds of local governments to alleviate the subsidy burden. The environmental benefits of renewable energies should be subsidized through market-based mechanisms such as green certificate and carbon emission trading [11]. Thirdly, the imbalance in the geographical distribution of China's natural resources and energy consumption activities indicates the importance of the transfer of funds among its own regions. The economies in eastern coastal areas are relatively developed with high energy demand, while the western inland areas that are rich in natural resources are lagging behind economically. If the eastern revenues can be leveraged so they flow into the western economy by the market-based instruments, China can not only achieve an energy revolution, but also reduce the imbalance of regional economic development.

The research content and innovation points of this paper mainly lie in two aspects. First, we construct a micro-level thermal power plant dataset. Differing from the top-down analyses using macro models, which take the industry as a whole, this paper uses micro-level data to conduct the ex-ante policy evaluations. This is imperative for China's current national ETS is rate-based and depends on plant-level heterogeneities [12]. Secondly, we calculate the monetary distribution effect and summarize the policy interaction mechanisms of the national ETS and RPS. These two policies with internal interactions constitute the driving basis for the development of China's renewable energy in the future. The calculations show that if the permit allocation standards are tightened to less than 80% of the current standards, the interaction between the national ETS and the RPS market will occur. Then the emissions reduction costs borne by the central and western provinces in the ETS will be alleviated by selling renewable energy green certificates in RPS market, and the green certificate revenue can be used to support the development of renewable energy endowments in the central and western provinces. With intensive consumption, the eastern provinces will face the dual pressure of renewable energy green certificate and carbon emission permit as the outflow of provinces will support the development of renewable energy. According to the scenario of tightening permit allocation standard to 70% of the current standards by 2030, the proportion of renewable energy power in consumption is required to reach 40%, the carbon price to be 200 yuan/ton, the annual distribution scale generated by the national ETS through the power industry be close to 100 billion yuan/year, and the distribution scale of RPS and green certificate trading be close to 250 billion yuan/year. The top six provinces to gain money inflows are Yunnan, Sichuan, Fujian, Qinghai, Gansu, and Hubei, with a net inflow larger than 10 billion yuan per year. The top six provinces in terms of net outflow are Shandong, Jiangsu, Henan, Anhui, Shanghai, and Hebei, with the outflow approaching or exceeding 15 billion yuan per year. Meanwhile, the policymakers should consider relaxing the use proportion of China Certified Emission Reduction (CCER) in the ETS, and avoid double counting and distorting market incentives by local interests.

The remainder of this article is organized as follows. In Section 2, we introduce the background of China's carbon pricing mechanisms and discuss how the policies can help solve the green financing gap and promote the development of renewable energy generation. Section 3 explains the scheme of research design in this paper. Section 4 presents the main results of the simulation and the discussion of the important mechanisms. Section 5 gives the concluding remarks.

2. Literature review

The expected rate of return and risk are the key elements for investors to evaluate benefits and costs when making investment decisions. From the perspective of cost minimization of power system, renewable energies such as wind power and solar PV are less attractive than the traditional thermal power plants due to their intermittence. Renewable energies needed to bear the system consumption cost, which is caused by their volatilities, and additional actions such as bearing the costs of auxiliary services and purchasing energy storage facilities, are required to balance the market condition of the power sector [13,14]. Similar to other countries around the world, China has implemented non-market approaches to promote the development of renewable energies for a long period of time. However, high renewable energy subsidies among other non-market approaches led to overinvestment along with debt problems. Furthermore, the renewable energy policies had shifted to auction policies and the adoption of renewable portfolio standard policies [15]. The renewable energy portfolio standards (RPS) set mandatory requirements on the proportion of renewable energy power consumption on the power demand side; this mechanism is called "renewable energy power consumption responsibility weight" in China. The required weight can be accomplished by either consuming green electricity or purchasing green certificates in the RPS market. Since China's renewable energy endowments are highly spatial imbalanced, regions with less endowments are expected to pay more to purchase green certificates that are generated from the regions with more renewable energy endowments [16].

Another important market-based instrument is China's national ETS. China has launched nine provincial and city-level pilot ETSs since 2013 and their main target was to gain experience to prepare for the national ETS. Several studies that used firm-level data had verified that the pilot ETSs can successfully induce the firms' innovations in low-carbon technologies [17,18], and reduce carbon emissions of firms in non-power sectors [19]. Meanwhile, the abatement effects were not found in power plants that are covered in the pilot ETSs [19,20]. Considering that China has very unequal distributions of wind and solar resources and that local governments are primarily responsible for designing and implementing the pilot ETSs [21,22], the decisions made by local decision-makers can only be optimized at local level, not at national level. This disadvantage can be alleviated by the official launch of national ETS. In the initial stage of national ETS, only thermal power plants are covered, and carbon permits are allocated based on the benchmarking approach, which aims to give incentives to power plants to improve energy efficiencies [12].

In terms of revenue, the effects of the two policies are different. The theoretical foundations of ETS and RPS are pricing the environmental externalities [23,24]. The difference between the two is that ETS internalizes the negative externality cost of greenhouse gas emissions, so the emitter bears a higher cost and will be encouraged to reduce total emissions, which improves emission efficiencies. The RPS internalizes the positive externality benefits of renewable energy power generation. Compared to the fixed feed-in tariff, the advantages of market-based instruments lie in the flexibility of subsidies and fewer dependencies on government supports. Compared to the RPS's positive impacts on the development of renewable energies, the impacts of ETS on promoting renewable energies are less obvious but can be demonstrated through three aspects.

Firstly, ETS can increase the cost of fossil energy consumption through carbon price channels, reduce fossil fuel consumption, and improve the relative competitiveness of renewable energy, as shown in EU-ETS [25,26]. However, since the power plants can pass additional carbon costs through the downstream, the impacts might not be significant in practice [27]. Although the researchers found that the ETS has relatively small impacts on the development of renewable energies when compared to feed-in tariff policies, it accelerated the investment in energy efficiency innovations as well as carbon capture technologies [28–30]. Furthermore, the impacts of ETS on power plants can also bring different types of co-benefits. For example, coal-fired power plants using wet cooling technologies will bring vast pressure on local water resources, especially for regions such as Northwestern China [31]. Besides, regulating coal-fired power plants that discharge air pollutants such as SO_2 and NO_x will lead to potential co-benefits in terms of air pollutant reductions as well as health improvement [32–35]. As a result, the carbon market will bring significant benefits when all the fossil-fuel-related externalities are taken into account.

Secondly, after the introduction of permit auction in ETS, the revenues can be used to support the development of renewable energy. Generally speaking, the recycling mechanism of carbon revenue plays an important role in designing the carbon market [36, 37]. From the perspectives of welfare and public economics, a good design of recycling mechanism can definitely reduce the existing distortions in the whole society and improve social welfare. Since the long-term goal of climate policy is to actualize the low-carbon transformation process, achieving intertemporal optimization is crucial amongst other topics that deserve to be investigated. Among these topics is financing the development of renewable energies and low carbon technologies, in which will hold great value in the long-term transformation [38]. Using the revenues from the carbon market to support the low-carbon transformation is also common in practice. For example, according to the Report from the European Commission, around 80% of the revenues from 2013-2017 were used or planned to be used for climate and energy purposes [39]. Within the revenue, 37% was used for renewable energies, 36% for energy efficiency projects, 10% for sustainable transportation, 8% for research and development, and 9% was used for other domestic or EU expenditures. The California ETS and RGGI set a higher proportion of household and corporate subsidies in a broader sense, but they still set aside certain proportions of the revenue to support the development of clean energies. According to the California Climate Investments 2018 Annual Report, 7% of California ETS's revenue was used for clean energy and energy efficiency projects, 14% for natural resources and waste diversion, at least 35% to subsidize low-income families and communities, and the rest was used for sustainable transportation [40].

Finally, in order to encourage fossil energy producers and consumers to achieve low-carbon transformation, offset mechanisms, which allow emitters to offset a certain proportion of greenhouse gas emissions, are designed in the carbon market. Revenues generated by the offset mechanism such as purchasing CCER constitute a potential source of revenue for supporting renewable energies[1]. At the moment, covered power plants are allowed to adopt offset measures in the national ETS, but the upper limit is tentatively set at no more than 5% of the performance responsibility [12]. Due to the need to meet the principle of additionality, non-hydro renewable power generation companies should choose to verify their output as either CCER in ETS or green certificates in RPS, otherwise, it will cause double counting problems. Therefore, there exists an internal conflict between the two market instruments [41–45]. Until now, there have been many studies that focused on the interactions between the two markets from either the theoretical or empirical perspective at a regional level, but very few focus on the interaction mechanisms from the micro-level perspective for China's ETS and RPS.

In addition, the market-based instruments also have disadvantages that will increase the volatilities of revenues for supporting renewable energies. Under the condition of electricity price marketization, the increase in renewable energy penetration rate will reduce the value of renewable energy assets by increasing the price fluctuation [45]. This shows that clarifying policy roadmaps, measuring revenue distribution effects of the two markets, and stabilizing market expectations are of great significance for attracting investment and alleviating the gap in the field of green financing and investment.

[1] Since 2017, the National Development and Reform Commission has suspended the CCER mechanism due to problems such as the oversupply of CCERs, low pricing, and weak additionality. On August 6, 2021, the Beijing Green Exchange held a public tender for the national registration system and trading system for voluntary emission reduction of greenhouse gases, which was interpreted as the imminent restart of CCER.

3. Research design

3.1. Theoretic mechanisms

As an ex-ante policy evaluation, this paper puts forward the incentive mechanism of the national ETS and RPS to support the development of renewable energy. The incentive mechanism is composed of three channels: the demand substitution channel, the emission offset channel, and the revenue distribution channel.

3.1.1. Demand substitution channel

The renewable energy portfolio standard exerts a mandatory constraint on the structure of power sector in terms of the proportion of renewable energy power. Let $\bar{Q}^t$ denote the total electricity demand of all the generation types, which is exogenous, Q^r denote the supply of renewable energy power, Q_i^c denote the supply of thermal power plant i, and Q^0 denote the supply of other types of generation that is exogenously set.

The quantity of demand equals the total supply:

$$Q^r = \bar{Q}^t - Q^0 - \sum_i Q_i^c \tag{1}$$

The portfolio standard constraint can be shown as follows:

$$Q^r \geq \bar{Q}^t \times GCR \tag{2}$$

Enhancing GCR, which stands for green certificate ratio requirement, can directly stimulate the development of renewable energy. When the cost of renewable energy is relatively high, setting a gradually increasing GCR schedule will urge the power consumers to pay higher costs to meet the share requirements and endogenously price the financial additionality of renewable energy power.

3.1.2. Emission offset channel

When the carbon market allows the use of the emission offset mechanism for the performance responsibility, the carbon cost will drive the participating plants to actively seek to purchase offset certificates such as CCER from renewable energy power plants. In this paper, we assume that the electricity generated from renewable energies can be verified either as green certificate or CCER, and that double counting is not allowed. When the carbon market is highly constrained, the proportion of renewable energy power generation will exceed the level set by the renewable energy portfolio standard.

Let CCER_i denote the quantity of offset emission of plant i using CCER, Q_i^c denote the output level of the thermal plant i, $ef_{i,bench}^c$ denote the benchmark coefficient of permit officially allocated with unit as tCO_2/MWh, and ef_i^c denote the emission factor of plant i with unit as tCO_2/MWh. Then the market clearance condition of carbon market will be as follows:

$$\sum_i Q_i^c \times ef_{i,bench}^c = \sum_i \left(Q_i^c \times ef_i^c - \text{CCER}_i\right) \tag{3}$$

When the certificate market of the renewable portfolio standard is cleared, the output used for offset equals the total output of renewable energy power minus the output used to fulfill the performance responsibility of renewable portfolio standard $\bar{Q}^t \times GCR$. Let ef_{gc} denote the conversion coefficient from electricity output to CCER with the unit of tCO_2/MWh. Then the market clearance condition of CCER market will be as follows:

$$\sum_i \text{CCER}_i = \left(Q^r - \bar{Q}^t \times GCR\right) \times ef_{gc} \tag{4}$$

Eq. 4 shows that the two markets are endogenously related. With the constraint of carbon emission trading scheme surpassing the financial additionality required to support renewable energy power investment, the power output of renewable energy driven by the offset mechanism will exceed the requirements of renewable energy portfolio standard. Simultaneously, more renewable energy power will reduce offset demand and achieve endogenous equilibrium through the demand substitution effect.

Table 1
Sample representativeness.

Fuel type	Variable	Official Statistics in 2018(≥6 MW)	Sample	Coverage
Coal	Capacity (GW)	1007.94	861.87	85.5%
	Power Generation(Billion MWh)	4.48	3.88	86.6%
Gas	Capacity (GW)	83.13	64.78	77.9%
	Power Generation(Billion MWh)	0.21	0.17	81.9%

Let baseline and equilibrium output level of thermal power plant be $\bar{Q}_i^c$ and Q_i^c, respectively. Assume each individual power plant's output level will be adjusted proportionally. Q_i^c could be written as $\overline{Q}_i^c \times k$, where k ranges between 0 and 1. Combining Eqs. 1–4, we can get the clearance of the two markets will be as follows:

$$\sum_i \left(\overline{Q}_i^c \times k \times ef_{i,bench}^c\right) = \sum_i \left(\overline{Q} \times k \times ef_i^c\right) - \left[\overline{Q}^t \times (1 - GCR) - Q^0 - \sum_i \left(\overline{Q}_i^c \times k\right)\right] \times ef_{ge} \quad (5)$$

The left-hand side of Eq. 5 is the supply of permits in ETS, which includes free permits and auctioned permits. The sum of the officially allocated permits can be treated as the cap of emission. The right-hand side of the equation is the demand of permits in the national carbon market, which includes the carbon dioxide emission and offset emission by CCER. The adjustment parameter k can be solved endogenously as follows:

$$k = \frac{\bar{Q}^t \times (1-GCR) \times ef_{gc} - Q^0 \times ef_{gc}}{\sum_i (\bar{Q}_i^c \times ef_{gc}) + \sum_i \bar{Q}_i^c \times ef_i^c - \sum_i \bar{Q}_i^c \times ef_{i,bench}^c} \quad (6)$$

The parameter k can be interpreted in two ways. k in Eq. 6 is the adjustment parameter for thermal power plant's output, and its relationship with the benchmark coefficient can be shown as $\partial k / \partial ef_{i,bench}^c > 0$. As a result, changes in k can be viewed as the emissions reduction effect from the ETS. In the second case, k is the coefficient in the process of realizing endogenous equilibrium in the model, and it represents the degree of internal correlation between the two markets. In the extreme case of ETS setting the strictest allocation rules, the benchmark coefficients would approach zero. Even then, the parameter k will still be greater than zero, because electricity generated from thermal power plants still exists. The gap between allocated permits and actual emissions is filled by CCERs[2]. Moreover, we can calculate the impacts of adjusting benchmark coefficients on electricity generations from thermal power plants and renewable energies as $\partial Q_i^c / \partial ef_{i,bench}^c > 0$ and $\partial Q^r / \partial ef_{i,bench}^c < 0$, respectively.

3.1.3. Revenue distribution channel

The "paid auction" mechanism of carbon permit is expected to be introduced gradually in the national carbon market rules [12]. Let α_{auc} denote the ratio of auctioned permits, then the total amount of permits that will be auctioned to thermal power plants equals $\alpha_{auc} \times \sum_i Q_i^c \times ef_{i,bench}^c$. The revenue from the auction can be used to provide sufficient funds to facilitate China's low-carbon transformations by promoting renewable energies, supporting low-carbon innovations, subsidizing low-income families, and etc.

3.2. Data

In 2021, the Ministry of Ecology and Environment announced the list of 2,225 power plants to be included in the national ETS. The 2,225 power plants are mainly composed of coal-fired and gas-fired power plants. In this paper, we construct a micro-level thermal power plants dataset, and collect the plant-level and unit-level data from various sources including *Annual Compilation of Power Industry Statistics (2018), Manual of National Power Units (2019), National Thermal Power Unit Benchmarking and Competition (2018), Annual Compilation of China Huaneng Group (2018) and Annual Compilation of China Huadian Group (2018)* [46–50]. After comparing our dataset with the official list, a total of 964 power plants with installed capacities greater than or equal to 100 MW are matched. Around 67% of the matched plants have unit-level data, and around 2500 units are included in the dataset. Table 1 shows that our dataset is a good representative sample with high coverage. For coal-fired power plants, the total installed capacity and the power generation of the sample data cover 85.5% and 86.6% of national total values, respectively. The thermal power plants excluded from the sample data are mainly small size and captive power plants.

3.3. Scenario settings

3.3.1. Carbon market and permit allocation

According to the official rule, China's national ETS adopts a rate-based permit allocation approach [12]. Total permits allocated to power plants contain two components: permits for heat supply and for electricity supply. The permits for heat supply are calculated by multiplying the benchmark for heat supplied and the actual heat supplied. Similarly, the permits for electricity supply are first calculated by multiplying the corresponding benchmark for electricity supplied and the actual electricity supplied[3], then multiplying the following three adjustment factors. Benchmarks adopted in the current national ETS are shown in Table 2.

First adjustment factor is the cooling method. This factor equals 1 for the water cooling mode and equals 1.05 for the air cooling mode. Choices of the cooling mode are highly dependent on water resource constraints in different regions [31], and power units with air cooling mode generally have higher coal consumption rates of power supply. The introduction of cooling method adjustment factor reflects the circumstance that environmental benefits have also been taken into consideration.

Second is the heating adjustment factor. This factor equals 1-0.22 × *HR* for coal-fired units and equals 1-0.6 × *HR* for gas-fired units, where *HR* represents the heating ratio.

Third adjustment factor is the load rate. The load rate is calculated by a piecewise function of the unit's load rate. A unit's load rate is equal to its utilization hours divided by its operation hours. As the load rate decreases, the load rate adjustment factor increases. From the technical point of view, a unit's efficiency will increase as the load rate increases. Therefore, this coefficient is set to eliminate the negative impacts of load rate on efficiencies. In China, the rapid development of renewable energies is leading to continuous declines in thermal power plants' utilization hours. The load rate adjustment factor can be viewed as a certain kind of compensation for provinces that actively develop and consume renewable energies. However, it undermines the restraint effect of the carbon market on inefficient and uncompetitive units.

[2] It is worth noting that the amount of CCERs that are allowed to be used in ETS may be limited. For example, China's national ETS set the proportion of CCER that can be used to offset emissions at 5%. If the proportion limits are reached, then the stable relationships between market equilibrium prices of CCER and permits will no longer exist.

[3] Benchmarks for electricity supplied depend on the category of the unit. Specifically, the units participating in the national ETS are divided into four categories including coal-fired units (below 400 MW), coal-fired units (above 400 MW), coal-fired units (using circulating fluidized bed), and gas-fired units.

Table 2
Benchmarks adopted in the national ETS in China (2019-2020).

Type	Capacity	Benchmark for electricity supplied (tCO_2/MWh)	Benchmark for heat supplied (tCO_2/GJ)
Conventional coal-fired unit	<400 MW	0.979	0.126
	>=400 MW	0.877	0.126
Unconventional coal-fired unit	-	1.146	0.126
Gas-fired unit	-	0.392	0.059

Table 3
Parameters used in simulation.

Parameters	Notation	Setting
Total power generation	$\bar{Q}^t$	According to the National Energy Administration's "Letter on the Proposal for the 2021 Renewable Energy Power Consumption Responsibility Weight and 2022-2030 Expected Targets" (hereinafter referred to as the "Expected Targets"), the electricity consumption target for the whole society in 2030 is set as 11 billion MWh [54].
Power generation of other types	Q^0	We set the nuclear power generation accounts for 10% of total generation (the expected target of China Nuclear Society and State Grid Energy Research Institute [55]), which is set at 1.1 billion MWh. We set the annual growth rate of gas-fired power generation as 10% after 2019 [53]. Gas-fired generation accounts for 6% of total generation which equals 0.66 billion MWh in 2030.
Coal-fired power generation	$\sum_i(\bar{Q}_i^c)$	Coal-fired power generation will increase by 6.2% in 2030 from 2019.
Required ratio in RPS	GCR	According to the "Expected Goals", renewable energy accounts for at least 40% of total generation, of which non-hydro renewable energy accounts for at least 25.9% of total generation [54].
Benchmark in ETS	$ef^c_{i,bench}$	The benchmarks are set based on the 2019-2020 national carbon market permit allocation scheme [12]. We retain the differences between the various types, and tighten the benchmarks by multiplying them by a certain proportion, such as 70% and 80%.
Emission factor	ef^c_i	The emission factor for coal-fired power generation is set as 2.6603 tCO_2/MWh. The emission factor for gas-fired power generation is set as 1.6257 tCO_2/MWh.
CCER conversion factor	ef_{gc}	According to the substitutions between renewable energy power generation and coal-fired power generation, we set the conversion factor as 0.8 tCO_2/MWh.
Price of permit in ETS	P	The exogenous carbon market price is set as 200 yuan/tCO_2, and the equilibrium price of green certificate is set as 160 yuan/MWh.

3.3.2. RPS and CCER

China's RPS is designed by following a top-down method and is named as "renewable energy power consumption responsibility weight". Electricity entities that cannot consume the minimum required proportion of electricity generated from renewable energies must purchase corresponding green certificates to meet the requirements. The provincial renewable energy excess consumption permit trading has been gradually launched since 2021. According to a draft document issued by the National Energy Administration, in order to ensure the completion of the target of non-fossil energy proportion in 2030, the total weight of renewable energy electricity should be set at 40% for all regions, and the weight of non-hydro renewable energy electricity at 25.9% in 2030[4].

China's renewable energy endowments are distributed unequally, in which results the central and the western regions having more renewable energy endowments compared to the other regions. In 2019, a total of eight provinces have already met the 40% weight requirement [51]. Among these provinces, Yunnan, Sichuan, Hubei, Tibet, Qinghai are rich in hydropower due to their abundant water resources and large terrain differences. As a result, they are expected to generate more green certificates in the RPS market. In contrast, it is quite difficult for the eastern coastal provinces to fulfill the 40% target due to the shortages in renewable energy endowments.

For the CCER market, the National Development and Reform Commission had publicized a total of 2856 CCER projects for review at the end of year 2021. Among these projects, 287 of them had been issued and 254 projects representing 52.94 $MtCO_2$ had released certification reports [52]. These projects can be categorized into four different types. The first type is the voluntary emission reduction project developed using the methodology filed by the national competent department, with an emission reduction of 18.9 million tons. The remaining three types are clean development mechanism (CDM) projects, with a total emission reduction of 34.04 million tons. Among them, the non-hydro power projects (wind power, solar power generation, biomass power generation, and biogas) accounted for 45.7%, hydropower projects accounted for 25.4%, and thermal power related projects accounted for more than 23.8%. With the further decline in the costs of solar PV and wind power, the share of CCERs from non-hydro power projects is expected to increase continuously in the future.

The intrinsic link between the RPS market and the CCER market has been discussed in previous sections. In our model, we set no offset limit for CCER usage so that the maximum offsetting effects can be investigated. Moreover, we also assumed that only CCERs from non-hydro power projects can be used in ETS[5].

3.3.3. Long-term macro variables

The target year for the simulation is 2030, and the parameters for the key variables in 2030 are summarized in Table 3. China's natural gas consumption in 2020 was 316.3 billion cubic meters, of which natural gas power generation accounts for 17% [53]. China's natural gas consumption is expected to be 520 billion cubic meters in 2030, of which natural gas power generation accounts for 26%. We set the average an-

[4] Details can be found in Letter on Requesting the 2021 Renewable Energy Power Consumption Responsibility Weight and 2022-2030 Expected Target Suggestions, https://news.bjx.com.cn/html/20210210/1135968.shtml.

[5] For most of the pilot ETSs, CCERs from hydropower projects are not allowed to be used.

Table 4
Scenario of provinces in year 2030.

Provinces	Electricity consumption (million MWh)	GCR	GCR (non-hydro)
Yunan	275.13	40.0%	28.2%
Sichuan	400.24	40.0%	19.2%
Fujian	364.83	40.0%	20.2%
Qinghai	108.71	40.0%	39.2%
Gansu	195.95	40.0%	33.2%
Hubei	336.65	40.0%	23.2%
Xinjiang	437.24	40.0%	27.2%
Liaoning	365.58	40.0%	26.7%
Guangxi	290.12	40.0%	23.2%
Ningxia	165.33	40.0%	35.2%
Inner Mongolia	557.25	40.0%	33.7%
Hainan	54.42	40.0%	21.2%
Guangdong	1018.14	40.0%	18.7%
Jilin	118.97	40.0%	34.2%
Tibet	11.8	0.0%	0.0%
Guizhou	234.02	40.0%	22.7%
Heilongjiang	151.06	40.0%	34.2%
Zhejiang	717.78	40.0%	21.7%
Hunan	283	40.0%	27.7%
Shanxi	343.91	40.0%	33.2%
Chongqing	176.43	40.0%	17.2%
Shaanxi	256.76	40.0%	28.2%
Tianjin	134.89	40.0%	30.2%
Jiangxi	233.28	40.0%	25.7%
Beijing	176.84	40.0%	30.7%
Hebei	587.07	40.0%	29.2%
Shanghai	238.4	40.0%	17.7%
Anhui	350.86	40.0%	27.7%
Henan	512.25	40.0%	33.2%
Jiangsu	951.99	40.0%	24.2%
Shandong	951.06	40.0%	25.7%
Total	11000	40.0%	25.9%

nual growth rate of gas consumption for natural gas power generation as 10%, which is close to the prediction mentioned.

For the growth of coal-fired power generation, we adopted an indirect calculation approach. First, the electricity consumption target for the whole society in 2030 is set as 11 billion MWh and the minimum proportion requirement for renewable energy is set as 40% [54]. Nuclear power is assumed to account for 10% of the power generation in 2030 according to China Nuclear Power Society and State Grid Energy Research Institute [55]. By subtracting the predicted power generation from other types of power, we get the prediction of coal power generation in 2030. The coal-fired power generation is expected to increase by 6.2% in 2030 from 2019 as the baseline.

The price of the permit in ETS is an important variable in estimating the market size based on the market interactions. In this paper, the carbon price is exogenously set rather than endogenously determined. It is because the marginal abatement cost curve (MACC) cannot be directly estimated at a micro-level. For this consideration, we used an exogenously determined carbon price that equals 200 yuan/ton to conduct the analyses. The price will not affect the result of the structural impact we are concerned about, but only affect the market sizes from market interactions. A recent survey, conducted on relevant parties in the carbon market, has supported the price level we set [52]. According to the survey results, the average expected carbon price in 2030 is 139 yuan/ton, the 20% quantile expected carbon price is 200 yuan/ton, and the 80% quantile expected carbon price is 50 yuan/ton. The survey also pointed out that the market expectations on carbon prices have been gradually improving over time.

Table 4 provides the provincial parameters that are calculated based on assumptions and settings in Table 3 for ETS and RPS market. Total electricity consumption and renewable energy power generation of the provinces are allotted by using their 2019 value as the weights.

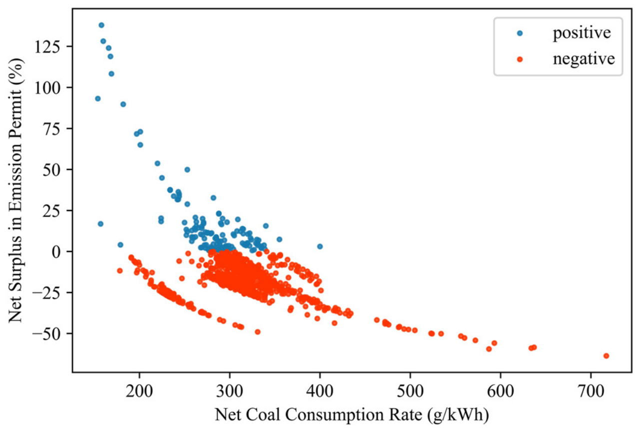

Fig. 1. Permit surplus of power plants on different efficiency level.

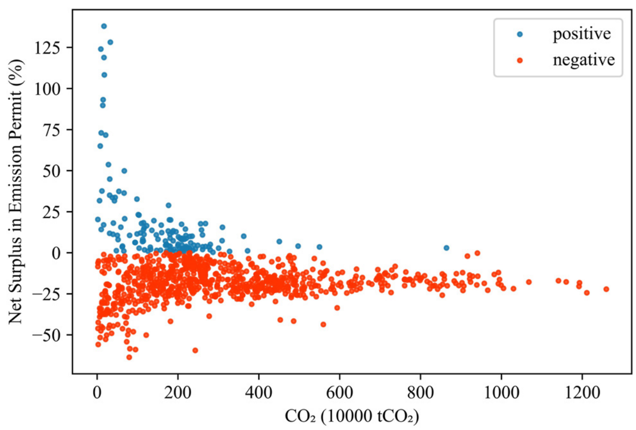

Fig. 2. Permit surplus of power plants on different scales.

4. Results

4.1. Plant-level distribution effect

The constraints of national ETS will tighten when the benchmarks decrease. If the benchmarks are reduced proportionally to close to 80% of the current standards, our results show that there will be shortages of permits supply in the ETS, and the power plants will start to purchase CCERs to offset their emissions. When the benchmarks are reduced proportionally to 70% of the current standards, they are equivalent or close to the efficiencies of gas-fired power plants. This is a strict constraint imposed on coal-fired power plants because even the ultra-supercritical coal-fired power units will have to purchase permits or CCERs in the ETS for compliance if their allocated permits are not adjusted by adjustment factors. In the remaining part of the paper, the results are derived from the scenario that the benchmarks are set as 70% of the current standards[6].

The plant-level net surplus of permits when benchmarks are reduced to 70% of the current standards are illustrated in Figs. 1,2. We can see from Fig. 1 that more efficient power plants generally have higher net surpluses of permits, but this correlation does not always hold up because the allocated permits may be affected by other factors. For example, if the low efficiencies of some power units are caused by low load rates, adjusting the load rate adjustment factor will significantly

[6] Setting benchmarks to other standards such as 75%, 65%, or 60% level of the current standards will not affect the structural problems that have been discussed in this paper.

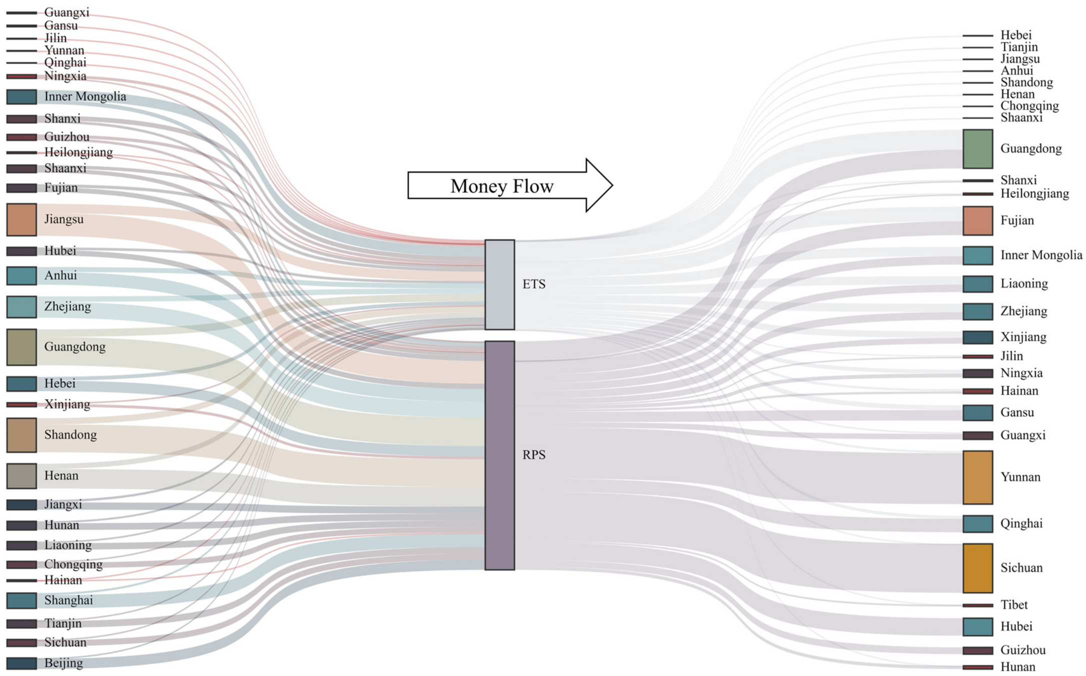

Fig. 3. Money flow of province-level distribution effect.

reduce the gaps in these units. Similar adjustments can be used to prevent the carbon market from having a greater impact on coal-fired units undertaking peak shaving functions. On the other hand, this feature also protects the units whose low load rates are caused by intrinsic inefficiencies.

The variance of net surplus ratio decreases as the size of power plant increases. Fig. 2 shows that the variance of the permit surplus ratio of the units below 400 MW is large, indicating that the small units are more heterogeneous in terms of efficiency. The reason for this result can partly be explained that the units below 400 MW include not only subcritical units, but also a large number of ultra-high pressure and high voltage units, and these units have quite different efficiencies. Another reason is that even for the units below 400 MW with similar technologies, some of them are constructed in the early period, so the older units tend to have relatively low efficiencies. The rate-based scheme is expected to accelerate the phase out procedure for small units with low efficiencies. However, since many small-scale power plants take the responsibility to supply heat, some of them may receive high compensations in permits that will lead to higher ratios of net permits which can be found in Fig. 2.

4.2. Province-level distribution effect

The province-level distribution effect is illustrated in Fig. 3 and Table 5 provides the detailed information. With the price of carbon permit being at 200 yuan/ton, total market size of the two markets will exceed 300 billion yuan, of which the market size of the RPS reaches 245.45 billion yuan, and the market size of the ETS reaches 96.25 billion yuan (including CCERs). It is reasonable that the market size of the RPS market is larger than that of the ETS, because the RPS market involves the stock of all types of renewable energies, while the ETS is mainly based on the gap between the allocated permits and the actual emissions.

The expected renewable energy generation reaches 45.2% (which exceeds the 40% requirement) due to the pulling effect from ETS through mechanisms proposed in the theoretical analysis. Assuming that the CCER or other nationally unified carbon emission offset mechanisms can convert renewable energy power generation into carbon market emission offsets, the tightening of carbon market permits will endogenously lead to the decline in thermal power generation and the growth in renewable energy generation (including incremental renewable energy generation used to offset emissions).

According to the scale of net money inflow shown in Table 5, the top six provinces in order are Yunnan, Sichuan, Fujian, Qinghai, Gansu, and Hubei, and the net money inflow scale of these six provinces is more than 10 billion yuan per year mainly because of the abundance in hydropower, wind power, and solar power The top six provinces in terms of net money outflow are Shandong, Jiangsu, Henan, Anhui, Shanghai, and Hebei, with money outflow approaching or exceeding 15 billion yuan per year. These provinces are mainly in the eastern and central provinces since their renewable energy endowments are lower than that of the western provinces, so it is necessary to purchase green certificates to meet the requirements of RPS. In general, the interactions between national ETS and RPS can alleviate the cost pressures in central and western provinces. These revenues can be used to support the further development of renewable energy endowments in central and western provinces. By contrast, eastern provinces will face dual pressures from both the ETS and RPS market.

4.3. Regional distribution effect

The regional distribution effect of the ETS and RPS market is illustrated in Fig. 4. Consistent with the provincial-level results, electricity consumers in Eastern China, Northern China and Central China will become the main fund contributors after the tightening of ETS. Table 6 shows that Southwestern China relies on their abundant hydropower resources to obtain the highest money inflow, and the northwest ranks second because of their wind and solar resources. The reasons for the surplus in the South and Northeastern can be explained by their high thermal power efficiencies and moderate natural resource endowments.

4.4. Discussion

4.4.1. The impact of market design on policy interaction mechanisms

Different market designs can affect the mechanism of policy interaction and change the incentives of the two types of market-based instruments.

Table 5
Province-level Distribution Effect through the Interacted Markets.

Provinces	Money from ETS	Money into ETS	Money from RPS	Money into RPS	Total surplus
Yunnan	2.4	0.5	54.6	0.0	56.4
Sichuan	0.0	0.9	52.5	6.4	45.2
Fujian	15.7	3.3	14.9	5.1	22.1
Qinghai	3.2	0.3	14.5	0.0	17.4
Gansu	5.1	1.5	11.1	0.0	14.7
Hubei	0.0	2.8	18.8	5.8	10.2
Xinjiang	6.9	1.2	6.3	3.0	9.1
Liaoning	8.9	1.8	8.1	7.0	8.3
Guangxi	1.9	1.5	5.9	0.0	6.3
Ningxia	4.3	3.0	4.1	0.8	4.5
Inner Mongolia	10.0	10.5	9.1	4.5	4.2
Hainan	2.6	0.3	2.4	1.4	3.3
Guangdong	21.3	8.1	20.2	30.4	2.9
Jilin	1.5	0.6	1.3	0.0	2.2
Tibet	0.4	0.0	1.8	0.0	2.2
Guizhou	0.0	3.4	7.2	2.8	1.0
Heilongjiang	1.2	0.8	0.7	0.9	0.2
Zhejiang	8.9	5.8	8.2	17.1	-5.7
Hunan	0.0	2.0	3.5	7.2	-5.7
Shanxi	1.1	5.0	0.6	2.8	-6.1
Chongqing	0.0	1.3	0.0	6.0	-7.3
Shaanxi	0.0	3.6	0.0	4.3	-7.9
Tianjin	0.0	1.1	0.0	7.2	-8.4
Jiangxi	0.0	2.5	0.0	7.8	-10.2
Beijing	0.0	0.9	0.0	10.9	-11.8
Hebei	0.3	4.0	0.0	11.3	-15.0
Shanghai	0.0	2.2	0.0	14.2	-16.4
Anhui	0.1	5.3	0.0	13.8	-19.0
Henan	0.1	5.6	0.0	20.9	-26.3
Jiangsu	0.2	9.9	0.0	24.4	-34.1
Shandong	0.1	6.6	0.0	29.8	-36.3
Total	96.3	96.3	245.5	245.5	0.0

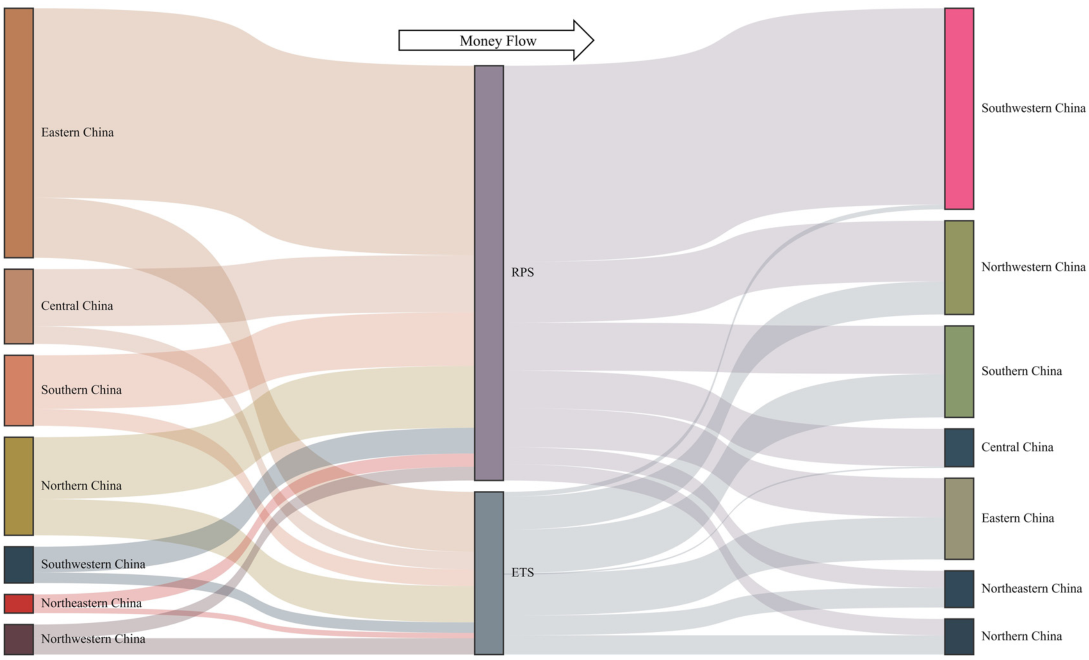

Fig. 4. Money flow of regional distribution effect.

The first design incorporates the proportion limits of CCER in ETS. Currently, the national ETS limits the use of CCER to 5%. When there is a cap on CCER, the further reduction in benchmarks means that the market needs to introduce paid auctions to fill the permit gap. If the paid auction revenue funds can be used to support the development of renewable energy, they will also tend to flow into the regions with higher renewable energy endowments. Therefore, even with the CCER limitations, the redistribution effects shown in this paper are of general significance. Moreover, the theory of this paper also highlights that the appropriate relaxation of CCER will weaken the mitigation effect of the ETS, but it can strengthen the role of the carbon market by driving the development of renewable energy. A key conclusion of this paper shows

Table 6
Regional Distribution Effect through the Interacted Markets.

Provinces	Money from ETS	Money into ETS	Money from RPS	Money into RPS	Total surplus
Southwestern China	2.82	6.22	116.14	15.22	97.53
Northwestern China	19.55	9.64	35.88	8.11	37.68
Southern China	25.77	9.89	28.39	31.79	12.47
Northeastern China	11.66	3.16	10.03	7.84	10.69
Central China	0.12	10.36	22.24	33.80	-21.80
Northern China	11.38	21.46	9.67	36.58	-36.99
Eastern China	24.95	35.52	23.10	112.11	-99.58

that as long as the carbon market constraints are tight enough, relaxing the limit of 5% of CCER offset ratio can stimulate the development of new energy. At the same time, due to the substitution effect of the new energy on thermal power, the offset mechanism will not produce the uncontrolled growth of thermal power.

The second market design focuses on the double-counting issue. Allowing the double-counting of renewable energy generation would distort carbon market prices. On the one hand, renewable electricity will obtain double benefits, but on the other hand, the sharp increase in the supply of CCER will significantly reduce the equilibrium prices in the ETS and RPS, resulting in fewer incentives. Therefore, policymakers should clarify the linkage between renewable energy power generation in two markets as early as possible to avoid the double-counting issue.

The third design touches upon the hydropower issue. In this paper, we assume that CCERs are all derived from non-hydro renewable energy sources. However, Yunnan, Sichuan and other provinces can still receive large money inflows, which can be explained by the high proportion of hydropower endowments in the local power structure. Currently, China's CCER mechanisms are still in the process of restarting. According to historical experience and requirement of additionality, we allow non-hydro renewable power generation such as wind power and solar power that can be verified as CCER. Although hydropower generation cannot be verified as CCER, it can be transformed into green certificates that can be traded in the RPS market. According to the current setting of China's official documents, the renewable energy portfolio standard (RPS) sets two objectives: the minimum proportion requirement of non-hydro renewable energy power generation (excluding hydropower) and the minimum proportion requirement of all types of renewable energy power generation (including hydropower). Although provinces with abundant hydropower cannot obtain revenue through CCER from the national carbon market, they can still obtain revenue through trading in the RPS market. From the perspective of non-hydro renewable endowments, the advantages of the southwestern provinces may be less significant because the development space is quite limited in southwestern provinces [56].

4.4.2. The impact of intra-province transaction on policy interactions

Incentives of local governments are also important in the dynamic process of transition [57,58]. We further consider that the local governments may require power plants to give priority to trading within the province. The intra-province trading will not change the scales of net money inflow and outflow, but reduce the incentives level of the ETS for local plants. On the one hand, the heterogeneities among power plants within each province make it possible to induce intra-provincial trading. For example, under 80% of current standards, the intra-province trading volume will be 15.2 billion yuan annually, which accounts for 37.1% of the market size of ETS. On the other hand, as the number of free permits decreases, the importance of intra-province trading will be reduced. For example, under 70% of current standards, the intra-province trading volume only accounts for 4% of the market size of ETS.

5. Conclusion

This paper studies the policy interaction mechanisms between China's two market-based policy instruments, one is the national ETS and the other is the RPS market. We conducted simulation analyses to investigate the distribution effects caused by the interactions between the two markets. Plant-level analyses show that permits allocations vary greatly among power units due to the different efficiencies as well as the adjustment factors. Strict constraints in ETS will lead to greater impacts on small-scale power units below 400 MW. The provincial-level results show that policy interactions between ETS and RPS market will occur when the benchmarks of ETS are tightened to 80% of the current standards. When this ratio is further tightened to 70%, with the carbon price as high as 200 yuan/ton, the annual market size of the national ETS is expected to be close to 100 billion yuan, and the annual market size of the RPS market to be close to 250 billion yuan in 2030. Regional results show that eastern and northern provinces will face dual pressures from both ETS and RPS market, but money outflow from the provinces in these regions can be used to support the nationwide development of renewable energies.

This study reveals the importance of market design of the market-based instruments in both fields of mitigating carbon emissions as well as promoting renewable energies. Firstly, different benchmark settings can be viewed as an important force to induce the interactions between the two markets. As a result, the lax standards adopted in the current national ETS should be reconsidered in the future to increase the effectiveness of the ETS. Secondly, offsetting mechanisms, including CCER, play an important role in connecting different markets. It is not only the results generated by the markets, but also the important sources of revenue that can be used to develop renewable energies. Thirdly, RPS market itself is an important market player in terms of its sheer market size. To avoid uncertainties that may occur in these markets, issues such as double counting and hydropower qualification should be studied and clarified as early as possible.

Declaration of competing interest

The authors declare that they have no conflicts of interest in this work.

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References

[1] Z. Zhou, S. Zhang, Z. Yao, et al., Green Finance: Promoting Services with Guidance and Turning Challenges into Opportunities, CICC, 2021.
[2] J. Ma, On the construction of China's green finance system (in Chinese), Finance Forum (5) (2015) 18–27.
[3] D. Guan, K. Hubacek, C.L. Weber, et al., The drivers of Chinese CO_2 emissions from 1980 to 2030, Glob. Environ. Change-Human Policy Dimens. 18 (4) (2008) 626–634.
[4] Z. Liu, D. Guan, W. Wei, et al., Reduced carbon emission estimates from fossil fuel combustion and cement production in China, Nature 524 (7565) (2015) 335–338.
[5] Z. Mi, J. Zheng, F. Green, et al., Decoupling without outsourcing? How China's consumption-based CO_2 emissions have plateaued, iScience 24 (10) (2021) 103–130.
[6] T. Dietz, P.C. Stern, New tools for Environmental Protection: Education, Information, and Voluntary Measures, The National Academies Press, Washington, 2002 DC.
[7] H. Demsetz, The core disagreement between Pigou, the profession, and Coase in the analyses of the externality question, Eur. J. Polit. Econ. 12 (4) (1996) 565–579.

[8] G.B. Upton Jr, B.F. Snyder, Funding renewable energy: An analysis of renewable portfolio standards, Energy Econ. 66 (2017) 205–216.
[9] J. Meckling, T. Sterner, G. Wagner, Policy sequencing toward decarbonization, Nat. Energy 2 (12) (2017) 918–922.
[10] S. Chen, D. Chen, Dynamic evolution of resource allocation efficiency in China: A new approach incorporating energy factors, Soc. Sci. China (4) (2017) 67–83.
[11] Ministry of Finance of the People's Republic of China, Reply to recommendation No. 9142 of the fourth session of the 13th National People's Congress. Access at: http://jjs.mof.gov.cn/jytafwgk_8360/2021jytafwgk_1/rddbjyfwgk/202108/t20210805_3743186.htm, (2021).
[12] X. Zhang, D. Zhang, R. Yu, Theory and practice of China's national carbon emissions trading system (in Chinese), Manage. World 37 (8) (2021) 80–95.
[13] R. Sioshansi, Increasing the value of wind with energy storage, Energy J. 32 (2) (2011) 1–30.
[14] A.J. Cavicchi, P.H. Ross, When the wind doesn't blow: The limits of intermittent resources and battery storage in the decarbonization of New England's power system under increased electrification, Electricity J. 33 (10) (2020) 106867.
[15] M. Auffhammer, M. Wang, L. Xie, et al., Renewable electricity development in China: Policies, performance, and challenges, Rev. Env. Econ. Policy 15 (2) (2021) 323–339.
[16] M. Wang, M. Yao, S. Wang, et al., Study of the emissions and spatial distributions of various power-generation technologies in China, J. Environ. Manage. 278 (1) (2021) 111401.
[17] J. Cui, J. Zhang, Y. Zheng, Carbon pricing induces innovation: Evidence from China's regional carbon market pilots, AEA Papers and Proceedings 108 (2018) 453–457.
[18] J. Zhu, Y. Fan, X. Deng, et al., Low-carbon innovation induced by emissions trading in China, Nat. Commun. 10 (2019) 4088.
[19] J. Cui, C. Wang, J. Zhang, et al., The effectiveness of China's regional carbon market pilots in reducing firm emissions, Proc. Natl. Acad. Sci. U. S. A. 118 (52) (2021) e2109912118.
[20] J. Cao, M.S. Ho, R. Ma, et al., When carbon emission trading meets a regulated industry: Evidence from the electricity sector of China, J. Public Econ. 200 (2021) 104470.
[21] X. Yu, A.Y. Lo, Carbon finance and the carbon market in China, Nat. Clim. Chang. 5 (1) (2015) 15–16.
[22] J. Cao, H. Dai, S. Li, et al., The general equilibrium impacts of carbon tax policy in China: A multi-model comparison, Energy Econ. 99 (2021) 105284.
[23] D.C. Matisoff, The adoption of state climate change policies and renewable portfolio standards: Regional diffusion or internal determinants? Rev. Policy Res. 25 (6) (2008) 527–546.
[24] Y. Zhang, Y. Wei, An overview of current research on EU ETS: Evidence from its operating mechanism and economic effect, Appl. Energy 87 (6) (2010) 1804–1814.
[25] B. Lin, Z. Jia, Impacts of carbon price level in carbon emission trading market, Appl. Energy 239 (2019) 157–170.
[26] R. Martin, L.B. De Preux, U.J. Wagner, The impact of a carbon tax on manufacturing: Evidence from microdata, J. Public Econ. 117 (2014) 1–14.
[27] A.D. Ellerman, C. Marcantonini, A. Zaklan, The European Union emissions trading system: Ten years and counting, Rev. Env. Econ. Policy 10 (1) (2016) 89–107.
[28] K.S. Rogge, V.H. Hoffmann, The impact of the EU ETS on the sectoral innovation system for power generation technologies–findings for Germany, Energy Policy 38 (12) (2010) 7639–7652.
[29] V.H. Hoffmann, EU-ETS and investment decisions: The case of the German electricity industry, Eur. Manag. J. 25 (6) (2007) 464–474.
[30] K.S. Rogge, M. Schneider, V.H. Hoffmann, The innovation impact of the EU emission trading system—findings of company case studies in the German power sector, Ecol. Econ. 70 (3) (2011) 513–523.
[31] C. Zhang, LJ. Zhong, J. Wang, Decoupling between water use and thermoelectric power generation growth in China, Nat. Energy (3) (2018) 792–799.
[32] L Tang, J Qu, Z Mi, et al., Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards, Nat. Energy (4) (2019) 929–938.
[33] H Qian, S Xu, J Cao, et al., Air pollution reduction and climate co-benefits in China's industries, Nat. Sustain. 4 (5) (2021) 417–425.
[34] J. Li, S. Zhou, W. Wei, et al., China's retrofitting measures in coal-fired power plants bring significant mercury-related health benefits, One Earth 3 (6) (2020) 777–787.
[35] M. Jiang, J. Li, W. Wei, et al., Using existing infrastructure to realize low-cost and flexible photovoltaic power generation in areas with high-power demand in China, iScience 23 (12) (2020) 101867.
[36] B. Lin, Z. Jia, Is emission trading scheme an opportunity for renewable energy in China? A perspective of ETS revenue redistributions, Appl. Energy 263 (2020) 114605.
[37] L. Wu, S. Zhang, H. Qian, Distributional effects of China's national emissions trading scheme with an emphasis on sectoral coverage and revenue recycling, Energy Econ. 105 (2022) 105770.
[38] R. Ma, H. Qian, Plant-level evaluation of China's national emissions trading scheme: Benchmark matters, Clim. Chang. Econ. 13 (1) (2022) 2240009.
[39] European Commission (EC), Report from the Commission to the European Parliament and the Council EU and the Paris Climate Agreement: Taking stock of progress at Katowice COP. (2018).
[40] California Air Resources BoardAnnual Report, 2018.
[41] P. Linares, F.J. Santos, M. Ventosa, Coordination of carbon reduction and renewable energy support policies, Clim. Policy 8 (4) (2008) 377–394.
[42] Y. Chang, Y. Li, Renewable energy and policy options in an integrated ASEAN electricity market: Quantitative assessments and policy implications, Energy Policy 85 (2015) 39–49.
[43] E. Delarue, K. Van-den-Bergh, Carbon mitigation in the electric power sector under cap-and-trade and renewables policies, Energy Policy 92 (2016) 34–44.
[44] B. Yi, J. Xu, Y. Fan, Coordination of policy goals between renewable portfolio standards and carbon caps: A quantitative assessment in China, Appl. Energy 237 (2019) 25–35.
[45] L. Hirth, The market value of variable renewables: The effect of solar wind power variability on their relative price, Energy Econ. 38 (2013) 218–236.
[46] China Electricity CouncilThe Statistical Compilation of China's Electricity Industry, 2018.
[47] China Electricity Council, Manual of National Power Units. (2019).
[48] China Electricity CouncilNational Thermal Power Unit Efficiency Competition, 2018.
[49] China Huaneng Group, The Statistical Compilation of China Huaneng Group. (2018).
[50] China Huadian Group, The Statistical Compilation of China Huadian Group. (2018).
[51] China Electricity CouncilThe Statistical Compilation of China's Electricity Industry, 2019.
[52] H. Slater, D. Boer, G. Qian, et al., China Carbon Pricing Survey, ICF, Beijing, 2021.
[53] B. Xu, H. Jin, Y. Xiang, et al., Analysis of natural gas consumption trend in China during the 14th Five-Year Plan (in Chinese), World Petroleum Industry 28 (1) (2021) 10–19.
[54] National Energy Administration, Letter on the Proposal for the 2021 Renewable Energy Power Consumption Responsibility Weight and 2022-2030 Expected Targets. (2021).
[55] China Nuclear Society, State Grid Energy Research Institute, Research on nuclear power development planning in China. (2019).
[56] J. Yan, Y. Yang, P.E. Campana, et al., City-level analysis of subsidy-free solar photovoltaic electricity price, profits and grid parity in China, Nat. Energy 4 (8) (2019) 709–717.
[57] J. Xu, Conflicts in multi-level governance: An analysis of international climate policy implementation at the sub-national level, Global Public Policy Governance 1 (4) (2021) 401–420.
[58] J. Xu, Y. Zhang, Has the international climate regime promoted climate justice? Evidence from clean development mechanism projects in China, Clim. Policy (2021) 1–14.

Haoqi Qian (BRID: 05962.00.91523) is an assistant professor from Institute for Global Public Policy, Fudan University. His research interests are energy and environmental policy analysis, policy simulation and modelling, big data analysis of energy and economics. He has developed the Dynamic Regional Economy-Energy-Environment Analysis Model (DREAM) to conduct large-scale policy modelling, analysis and evaluation at both global and national level. His recent articles appear in *Nature Sustainability, Energy Economics, Applied Economics, Climate Policy*, etc.

Libo Wu (BRID: 03107.00.79808) is a professor from School of Economics and Institute for Big Data, Fudan University. Her research interests are energy and environmental economics, development economics and big data analysis. She has been the principal investigator for dozens of projects funded by the National Natural Science Foundation of China, the National Ministry of Science and Technology, and National Development and Reform Commission. Her recent articles appear in *PNAS, Nature Sustainability, Nature Climate Change, Energy Economics, China Economic Review*, etc.