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# Environmental and economic effects of China's carbon market pilots: Empirical evidence based on a DID model☆

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ABSTRACT

This paper investigates whether the China ETS policy has achieved carbon emission reduction at the expense of economic development. Moreover, we are interested in unmasking the role of the institutional factors adopted by the ETS pilots in their ETS effects. Using the province-level panel data during the 2008–2016 period. we employ the DID model to compare carbon emissions and economic development between the ETS and non-ETS regions and between the pre- and post-ETS periods. Some novel empirical findings emerge. First, compared with the non-ETS areas, the ETS policy has significantly reduced carbon emission in the ETS areas. This emission reduction has not come at the cost of economic development. Second, the ETS policy leads to a decline in carbon intensity and fossil fuel energy consumption relative to all energy types. Lastly, some heterogeneity across markets arise. The Beijing carbon market performs the best among all pilots in terms of achieving targets of carbon reductions, followed by the Hubei carbon market.



## 1. Introduction

To control greenhouse gas emissions, governments around the world have adopted a series of policies involving command-and-control instruments, market-based tools, and voluntary programs. Among these alternatives, the carbon emission trading scheme (ETS) is considered as the most cost-effective market instruments (Harrison et al., 2008). China has been resorting to this market-based instrument. In 2011, National Development and Reform Commission (NDRC) in China announced to launch seven regional ETS pilots including five municipal cities (i.e., Beijing, Shanghai, Chongqing, Tianjin, and Shenzhen) and two provinces (i.e., Hubei and Guangdong).[1] These pilots were then put into effect in late 2013 and early 2014. In September 2015, the Chinese government announced to launch a national carbon market during the China-US joint presidential statement on climate change. On December 19 of 2017, NDRC issued the national carbon emission trading market construction plan, marking the official announcement of launching China's unified national carbon market (Weng and Xu, 2018). China's national carbon market covering the power generation section only in the first phase has an initial quota of more than 3 billion tons, surpassing the European Union as the world's largest carbon market. The regional ETS pilots during the 2013–2017 period are served as the transition toward building a successful and effective national carbon market (Martina et al., 2016; Clayton et al., 2016; Weng and Xu, 2018). At this crossroads of transiting toward the unified national carbon market, it is particularly important to carry out post-evaluation on the pilot markets and analyze the environmental and economic achievements of each pilot, providing policy implications for designing the national carbon market.

This paper focuses on whether China's carbon market pilots have achieved certain environmental and economic effects and whether the ETS policy has achieved carbon emission reduction at the expense of economic development. The data pertain to the province-level panel data during the 2008–2016 period. We employ the DID model to compare carbon emissions and economic development between the ETS and non-ETS regions and between

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[1] Due to limited economic indicators for Shenzhen prefecture market, we could not separate it from Guangdong province. The empirical investigation only focuses on the remaining six ETS pilots.

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the pre- and post-ETS periods. Some novel empirical findings emerge. First, compared with the non-ETS areas, the ETS policy has significantly reduced carbon emission in the ETS areas. This emission reduction has not come at the cost of economic development. Second, the ETS policy leads to a decline in carbon intensity and fossil fuel energy consumption relative to all energy types. Lastly, but not least, some heterogeneity across markets arise. The Beijing carbon market performs the best among all pilots in terms of achieving targets of carbon reductions, followed by the Hubei carbon market.

The growing literature has focused on the design and operation of China's carbon market, such as the maturity of carbon market (Liu et al., 2019; Hu et al., 2017), carbon prices (Liu et al., 2020), carbon leakage (Zhu et al., 2020), carbon quota allocation (Fang et al., 2019). This paper is related to a strand of literature examining the environmental effect and economic effect of China's carbon market. Most relevant work resorts to model simulation. Zhu et al. (2015) simulate the effectiveness of the Beijing carbon market during the 2013–2015 period. Using the CO2 emission data of China's thermal power plants from 2005 to 2010, Liu et al. (2018) employ a nonparametric optimization model to estimate the potential economic benefits and carbon emission reduction under three alternative allocation strategies of carbon emission quota. The simulation results show that the jointed ETS of SO2 and CO2 could contribute to achieving the dual goal of increasing potential revenue and reducing emissions of pollutants. Mu et al. (2018) take account of both renewable energy policy and carbon ETS. Their model simulation demonstrates how China could achieve the national voluntary emission reduction target. Their findings show that a seamless combination of carbon markets and renewable quotas could be the best way to achieve China's indigenous contribution.

This paper is closely related to the empirical literature studying the ETS effects on carbon emissions and economic development (Alvarado et al., 2018; Khan et al., 2019, 2020; Zhang et al., 2020). This line of studies provides some corroborating evidence in support of the Porter Hypothesis, which states that environmental policy could encourage firms to conduct technological innovation. Moreover, the improvement of firms' productivity or competitiveness through the induced innovation could help offset environmental compliance costs, leading to a win-win situation of economic development and environmental protection (Porter and van der Linde, 1995). Whether China carbon ETS contributes to this win-win benefits is the focus of the existing literature. Zhang et al. (2017) employ the Propensity Score Matching (PSM) and Difference-in-Difference (DID) method to study the impact of China's carbon market on CO2 emissions. The research design sets the announcement year of 2011 as the ETS policy shock. They investigate the difference in carbon emissions between the ETS and non-ETS areas. Using the provincial panel data from 2000 to 2016, Wang et al. (2019) employ the PSM-DID method to examine the ETS impact on low carbon transformation. Their findings provide some evidence in support of the Porter hypothesis. Along this line, Yi et al. (2020) use the provincial panel data from 2005 to 2016 to estimate the emission reduction effect of the ETS policy. Based upon the DID method, the empirical results showed that the implementation of carbon markets in Beijing, Shanghai, and Hubei has a significant inhibitory effect on local CO2 emissions, while the Guangdong carbon market has a promoting effect.

We contribute to the existing literature in the following points. First, we use the DID method to conduct a post-evaluation of the China regional ETS pilots. We aim to examine whether the ETS policy has reduced carbon emissions and whether the emission reduction target was achieved at the cost of economic development. Second, we are further interested in exploring the mechanism of how the ETS policy has achieved the goal of carbon reduction by focusing on carbon intensity and energy consumption structure. Third, we attempt to unmask the role of specific ETS markets in meeting the carbon emission reduction target by running the market-specific DID model. Since each carbon market pilot has its discretion to implement detailed emission allocation of allowances, MRC, and other rules, we explain why some pilots could achieve better results while others may fail. Lastly, comparing with a plethora of computational general equilibrium (GGE) models that predict the ETS impact, regression analysis adopted in this paper could take advantage of the emerging panel data and estimate the causal impact of the ETS on selected outcome variables.

The remaining of this paper is structured as follows. Section 2 briefly summarizes China ETS background, while Section 3 introduces data sources, construction of variables, and descriptive statistics. Section 4 presents the empirical strategy, empirical results, robustness checks, and mechanism discussion. The last section concludes.

## 2. China ETS background

In late 2011, China announced to launch the regional ETS pilots covering "Two Provinces and Five Cities" (i.e., Hubei, Guangdong, Beijing, Shanghai, Tianjin, Chongqing, and Shenzhen). Since June 2013, seven carbon market pilots have been formally launched and started trading carbon emission allowance. Following some general guidelines from NDRC, each regional ETS pilot has the discretion to design their own carbon market rules including covered sectors, emissions target, allowance allocation, and monitoring, reporting and verification (MRV). Table A1 in the appendix provides a summary of region ETS policy across pilots.

First, regional ETS pilots vary across covered sectors. The Beijing ETS pilot covers industries such as power, heat, cement, petrochemical, automobile, and public construction. Besides these, the Shanghai pilot includes steel, chemical, metal, textile and paper printing, rubber, and chemical fiber industries. Covered sectors in the Tianjin pilot are carbon-intensive ones, including iron and steel, chemicals, power, petrochemicals, and oil refining. The Chongqing and Hubei pilots mainly cover industries such as cement, steel, and power, while the Guangdong pilot includes six industries: power, cement, steel, petrochemical, paper, and civil aviation.

Second, each ETS pilot has its own rule for the inclusion of carbon-intensive firms into the ETS system based upon their historical emissions during the 2009–2011 period. The Beijing pilot requires all firms with annual emissions of more than 10,000 tons CO2 to participate in the ETS. The Shanghai pilot set different standards. For firms in non-manufacturing sectors, only those with annual emissions of 10,000 tons CO2 and above are included in the ETS, while for firms in the manufacturing sectors, the threshold is 20,000 tons. Similarly, both Chongqing and Guangdong adopt the same threshold of 20,000 tons CO2. The Hubei pilot raises the threshold to 60,000 tons of annual CO2 emissions for all industrial firms, while the Shenzhen ETS pilot has a lower threshold of 3000 tons CO2 for all manufacturing firms.

Third, the allocation of carbon allowance varies across pilots. Among the seven pilots, Tianjin, Chongqing, and Hubei adopt free distribution, while the remaining pilots have mixed between the free distribution and paid distribution (mainly including auctions and fixed price sales).

## 3. Data

### 3.1. Data sources

The data pertain to the provincial-level panel data during the 2008–2016 period, covering 30 provinces in mainland China except for Tibet due to a lack of relevant data. The data sources include China Energy Statistical Yearbook and China Statistics Yearbook. The former provides detailed energy consumption information for each province, while the latter supplies the economics characteristics and environmental investment during the study period.

### 3.2. Variable construction

#### 3.2.1. Outcome variables

The primary interest of this paper is to examine whether the ETS implementation could contribute to the environmental and economic effects on China. Two main outcome variables are carbon emissions and GDP. The former is measured by energy consumption and carbon emissions rates by energy types. To avoid double-counting, the annual consumption of various energy sources in each province is eliminated from the input and loss of energy processing and conversion processes and the industrial production as raw materials and materials to obtain the net consumption of 30 provinces. Following the "2006 IPCC Guidelines for National Greenhouse Gas Inventories" published by Intergovernmental Panel on Climate Change (IPCC), we use method 1 based on the amount of fuel burned and default emission factors in three ways to estimate carbon emissions from fossil fuel combustion. The logarithm fashion is accounted for. Next, we take the logarithmic value GDP of each province as a proxy for economic development.

Moreover, we are interested in exploring the mechanism of how the ETS policy is associated with changes in carbon intensity and energy structure at the province level. The former is measured by carbon emission per unit of GDP, while the latter is the proportion of coal consumption in total energy consumption.

#### 3.2.2. Policy variables

The core explanatory variable is the ETS policy. We define $ETS_j$ as a binary indicator of the ETS region, taking a value of region j is one of the ETS pilots (i.e., Beijing, Shanghai, Tianjin, Hubei, Chongqing, and Guangdong), and zero otherwise. Among these carbon markets, Hubei and Chongqing carbon markets were implemented in 2014, while the remaining four markets were put into effect in 2013. For convenience, we set the year 2013 as the launching year of the ETS policy. *Post* denotes the policy dummy, equaling one if the year is 2013 and afterwards, and zero otherwise.

#### 3.2.3. Other control

In line with existing work (Zha et al., 2010; Kaya, 1989; Yang et al., 2018), we include a set of the province-level control to capture their potential impacts on carbon emissions and economic development. Specifically, industrial value-added captures production activities in the manufacturing, mining and public utility sectors. We also include foreign direct investment (FDI) and import/export values to measure how trade and FDI would affect carbon emission and energy structure. Besides, innovation proxied by the number of granted patents is included to control for the technology effect on carbon emissions. Lastly, we control for industrial pollution abatement investments and energy sector investment, as these two are crucial to carbon emission abatement and energy structure. The former could be conducive to a reduction in carbon emissions, while the latter may set as an obstacle to achieving the carbon reduction target.

### 3.3. Descriptive statistics

Table 1 shows the descriptive statistics of selected variables. The last two columns present the mean values by the ETS regions. Relative to the non-ETS regions, the ETS regions on average have lower carbon emissions, carbon intensity, and energy structure, but higher GDP. Table 2 further illustrates the mean values of outcome variables by the ETS period and ETS regions During the pre-ETS period, there is a small difference in carbon emissions between the ETS and non-ETS regions. The difference becomes larger during the post-ETS period. A similar pattern persists for GDP and energy structure. As one may worry about the systematical differences in outcome variables during the pre-ETS period, we resort to the PSM approach to select non-ETS regions to match with the ETS ones as a robustness check in the empirical section.

## 4. Empirics

### 4.1. Baseline model

This paper aims to estimate the environmental and economic effects of the ETS regional pilots. The empirical model employs the DID approach, comparing outcome variables of interests between the ETS regions and the non-ETS regions and between the pre- and post-ETS periods. For province j at year t, the baseline model is proposed as follows,

$$Y_{jt} = \beta_0 + \beta_1 ETS_j \times Post + X_{jt} + \delta_j + \gamma_t + \varepsilon_{jt} \quad (1)$$

where $\delta_j$ and $\gamma_t$ captures the industry fixed effect and year fixed effect, respectively. $X_{jt}$ is the province-level control variables including value added, FDI, population, patent innovation, investment in industrial pollution abatement, import, export, and energy industry investment. $\varepsilon_{jt}$ denotes the disturbance term.

A vector of outcome variables, denoted by $Y_{jt}$, include carbon emissions, GDP, carbon intensity, and energy structure all at the province level. The core explanatory variable is captured by $ETS_j$, an indicator of the ETS region. This binary indicator takes a value of one of region j is one of the ETS pilots (Beijing, Shanghai, Tianjin, Hubei, Chongqing and Guangdong), and zero otherwise. *Post* denotes the policy dummy, equaling one if the year is 2013 and afterwards, and zero otherwise. The key coefficient of interest denoted by $\beta_1$ indicates the environmental and economic effects of the ETS policy.

### 4.2. Baseline results

Table 3 presents the ETS effects on carbon emissions and GDP based upon the baseline model specification (1). All columns consist of the province-level control including FDI, trade, population, patent, pollution abatement, and energy investment. Besides, a set of year fixed effect, province fixed effect, and/or province linear trend are included. Standard errors presented in the parenthesis are clustered at the province level.

Columns (1) and (2) present the results on carbon emissions. The coefficient for the interaction term between the ETS and post indicators is negative and statistically significant at the 1% level. Adding additional province linear year trend in column (2) does not alter this main result. The estimated coefficient is negative and statistically significant at the 5% level. The magnitude becomes smaller due to the explanatory power absorbed by the additional province linear trend. The estimated coefficient of −0.157 indicates that the ETS policy leads to a 15.7% decline in carbon emissions in the ETS regions relative to the non-ETS regions.

Columns (3) and (4) of Table 3 further explore whether the reduction in carbon emissions would be achieved at the expense of economic development. Both columns report the positive estimated coefficient for the interaction terms between the ETS and post indicators. Neither of these estimates are statistically significant at the conventional levels. There is little evidence suggesting

**Table 1**
Descriptive statistics.

| Variable | Observations | Means | Std. Dev. | Min | Max | ETS mean | Non-ETS mean |
|---|---|---|---|---|---|---|---|
| Carbon emissions | 270 | 10.126 | 0.769 | 7.778 | 11.461 | 9.942 | 10.172 |
| GDP | 270 | 9.503 | 0.887 | 6.926 | 11.300 | 9.862 | 9.413 |
| Carbon intensity | 270 | 0.623 | 0.556 | −1.045 | 1.932 | 0.080 | 0.758 |
| Energy structure | 270 | 0.465 | 0.108 | 0.010 | 0.636 | 0.375 | 0.488 |
| $ETS_j$ | 270 | 0.200 | 0.401 | 0 | 1 | 1 | 0 |
| Post | 270 | 0.444 | 0.498 | 0 | 1 | 0.444 | 0.444 |
| Value added | 270 | 8.550 | 0.993 | 5.706 | 10.394 | 8.830 | 8.480 |
| FDI | 270 | 9.963 | 1.578 | 4.600 | 12.327 | 11.021 | 9.698 |
| Population | 270 | 8.184 | 0.742 | 6.317 | 9.306 | 8.087 | 8.208 |
| Patents | 270 | 10.059 | 1.519 | 6.066 | 13.147 | 10.220 | 10.019 |
| Pollution abatement | 270 | 2.685 | 0.948 | −1.032 | 4.953 | 2.900 | 2.631 |
| Import | 270 | 5.153 | 1.802 | 0.425 | 10.231 | 5.174 | 5.147 |
| Export | 270 | 5.339 | 1.742 | 0.920 | 10.596 | 5.453 | 5.310 |
| Energy investment | 270 | 6.470 | 0.764 | 3.584 | 8.006 | 6.680 | 6.417 |

Note: all province-level control variables including value added, FDI, population, pollution abatement, import, export, energy investment, and patent innovation are defined in the logarithm fashion.

**Table 2**
Comparison of mean values for outcome variables.

| Period | Regions | Carbon emissions | GDP | Energy structure |
|---|---|---|---|---|
| Pre-ETS period | ETS pilots | 9.927 | 9.638 | 0.397 |
| | Non-ETS pilots | 10.088 | 9.194 | 0.493 |
| Post-ETS period | ETS pilots | 9.961 | 10.141 | 0.348 |
| | Non-ETS pilots | 10.276 | 9.688 | 0.480 |

Note: Carbon emissions, GDP, and energy structure are defined in the logarithm.

**Table 3**
ETS effects on CO2 emissions and GDP.

| | Total CO2 | | GDP | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| ETS × Post | −0.184*** | −0.157** | 0.005 | 0.031 |
| | (0.058) | (0.064) | (0.029) | (0.025) |
| GDP | 0.602 | 0.024 | | |
| | (0.383) | (0.439) | | |
| Value added | −0.174 | −0.031 | 0.477*** | 0.358*** |
| | (0.203) | (0.199) | (0.042) | (0.035) |
| FDI | −0.024 | −0.016 | −0.005 | −0.004 |
| | (0.018) | (0.020) | (0.010) | (0.008) |
| Population | 0.495 | 0.372 | 0.119 | −0.053 |
| | (0.636) | (0.593) | (0.189) | (0.126) |
| Patent | −0.015** | −0.021** | −0.002 | −0.000 |
| | (0.006) | (0.009) | (0.002) | (0.003) |
| Pollution abatement | 0.008 | 0.008 | −0.000 | 0.000 |
| | (0.012) | (0.015) | (0.004) | (0.004) |
| Import | −0.019** | −0.010 | 0.003 | 0.002 |
| | (0.008) | (0.008) | (0.003) | (0.002) |
| Export | 0.028** | 0.022** | −0.001 | −0.004 |
| | (0.011) | (0.010) | (0.003) | (0.003) |
| Energy investment | −0.018 | −0.014 | −0.008** | −0.000 |
| | (0.013) | (0.022) | (0.004) | (0.006) |
| Observations | 270 | 270 | 270 | 270 |
| R-squared | 0.711 | 0.737 | 0.991 | 0.995 |
| Year FE | Y | Y | Y | Y |
| Province FE | Y | Y | Y | Y |
| Province linear trend | | Y | | Y |

Note: Post is a binary indicator for year 2013, taking a value of one if the years is 2013 and afterwards, and zero otherwise. $ETS_j$ is an indicator of ETS region, equaling one if the region is one of the pilots, and zero otherwise. The standard errors in parenthesis are clustered at the province level. *, **, and *** represent statistical significance levels at the 10%, 5%, and 1%, respectively.

that the ETS policy would sacrifice economic development while accomplishing the carbon emission reduction target.

### 4.3. Mechanism discussion

Reducing carbon intensity has been a key constraint on achieving the climate change mitigation goal in both the Kyoto Protocol and the Paris agreement. Under the framework of the Paris Agreement, the Chinese government submitted to the United Nations on June 30, 2015, “Strengthening Action to Address Climate Change China’s National Independent Contribution.” According to its national conditions, development stages, sustainable development strategies, and international responsibilities, China has set the target of 2030, that is, carbon dioxide emissions will peak around 2030, the annual decline is expected to be around 60%–65%, the proportion of non-fossil energy in primary energy consumption would reach about 20%, and the forest stock would increase by about 4.5 billion cubic meters compared with 2005. Besides the reduction of CO2 emissions, China has pledged to reduce carbon intensity and adjust energy structure in response to climate change. To achieve these goals, one way is to adjust the energy consumption structure, develop renewable energy, and reduce fossil energy, especially coal consumption. In this paper, we further examine whether the ETS leads to a decline in carbon intensity and a change in energy structure. The former is measured by CO2 emission per unit of GDP, while the latter is proxied by the proportion of coal consumption in total energy consumption. Both are defined in the logarithm fashion. Table 4 presents the corresponding results. Columns (1) and (2) reports the results for carbon intensity, while the remaining columns presents the results for energy structure.

In columns (1)–(2) of Table 4, the interaction term coefficients are negative and statistically significant at the level of 1%, indicating that the carbon market pilot policy has significantly reduced carbon intensity. Taking column (2) as an example, after adding year fixed effect, year fixed effect and province time trend effect, the policy reduced carbon intensity by 18.7%, indicating that the carbon market pilot policy is conducive to realizing a low-carbon development model in the pilot area. When it comes to energy structure, columns (3) and (4) reports that the estimated coefficients for the interaction terms are negative and statistically significant at the 5% level. These findings indicate that the ETS policy contributes to a 2.9% decline in coal consumption relative to the total energy consumption. The ETS policy helps improve the energy consumption structure by consuming cleaner non-fossil fuel energy.

### 4.4. Robustness checks

#### 4.4.1. Pre-trend test

To further ensure the stability of main results, we further run the parallel trend test. For each year, we consider a year-specific indicator and interact it with the ETS dummy based upon the baseline DID model. A variant of the DID model is then proposed as follows,

$$Y_{jt} = \beta_0 + \sum_t \beta_t ETS_j \times Post_t + X_{jt} + \delta_j + \gamma_t + \varepsilon_{jt} \tag{2}$$

where $Post_t$ is the year t-specific dummy variable, taking a value of 1 if year is at t, and 0 otherwise. A series of year-specific coefficients for the interaction term is of the central interest of this test. We expect that the coefficients are not statistically significant from 2009 to 2012 during the pre-ETS period, indicating the ETS regions and the non-ETS regions do to have systematically and statistically difference in the outcome variables during the pre-ETS period. In the meanwhile, we would expect the estimated coefficients during the post-ETS period starts to show the statistical significance after 2013, shedding light on the change in outcome variables was indeed due to the implementation of the carbon market pilot policy in 2013.

Table 5 presents the corresponding results. Columns (1) and (3) show that for total CO2 emissions and carbon intensity, the estimated coefficients are negative but not statistically significant during the pre-ETS period of 2009–2012. The estimated negative coefficients start to be statistically significant from 2013 onward. This is in line with our expectations indicating that the reduction in total CO2 emissions and carbon intensity arise from the introduction of the ETS policy in 2013. Moreover, the magnitudes become larger, indicating that with the gradual implementation of the carbon market pilot, the improvement of the trading mechanism and the expansion of the coverage, the policy impact of the carbon market pilot is also increasing.

For the energy structure shown in column (4), the estimated coefficients are positive but not statistically significant at conventional level during the pre-ETS period, while the coefficients turn to be negative and remain statistically insignificance during the post-ETS period. The adjustment of the energy consumption structure in response to the ETS does not have the short-term effect.

#### 4.4.2. Placebo test

Moreover, a placebo test is conducted by random sampling the ETS regions as the pseudo regions. Specifically, we randomly select 6 out of 24 non-pilot provinces and treat them as the pseudo ETS areas. The corresponding indicator is considered. We then rerun the variant of the baseline DID model with the pseudo ETS indicators interacting with the post dummy. This procedure is conducted 50 times starting from the random sampling of the pseudo ETS regions. Fig. 1 depicts the scatter plots of the estimate coefficients for the pseudo ETS regions and the corresponding p-values. Most of the estimated coefficients are not statistically significant at conventional levels, providing further corroborating evidence in support of the main conclusion. The reduction of carbon emissions and carbon intensity are indeed brought by the ETS policy.

#### 4.4.3. PSM-DID test

Lastly, we employ the PSM and DID method to further examine the environmental and economic effects of the ETS policy. Table 6 presents the corresponding results.[2] The results of PSM-DID are basically consistent with the results of our baseline regression and mechanism discussion. For the three main explanatory variables of total CO2 emissions, carbon intensity and energy structure, the interaction term coefficients are significantly negative, indicating that the policies of pilot carbon market have reduced CO2 emissions, reduced carbon intensity, and achieved the improvement of energy structure. For GDP, the interaction term coefficient is significantly positive at the 10% level, the significance level is low and the symbol is consistent with the benchmark regression result, indicating that China's pilot carbon market policy has achieved emission reduction without at the expense of economic development.

### 4.5. Heterogeneity by pilots

Due to the different environmental backgrounds of carbon market pilot projects in different provinces, different policies and measures have been adopted, resulting in different results for each pilot project. It is worth discussing which pilot methods and policy measures should be used for reference in the establishment of a national carbon market. Based on the baseline model, we interact the ETS region-specific dummy variable with the post indicator. A variant of the baselined DID model is proposed,

**Table 4**
ETS Effects on Carbon intensity and Energy Structure.

| | Carbon intensity | | Energy structure | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| ETS × Post | −0.186*** | −0.187*** | −0.036** | −0.029** |
| | (0.061) | (0.067) | (0.014) | (0.011) |
| GDP | | | 0.133 | −0.009 |
| | | | (0.081) | (0.104) |
| Value added | −0.364*** | −0.380*** | −0.117** | −0.068 |
| | (0.064) | (0.110) | (0.048) | (0.050) |
| FDI | −0.022 | −0.013 | 0.004 | 0.008 |
| | (0.016) | (0.019) | (0.005) | (0.007) |
| Population | 0.447 | 0.423 | −0.055 | −0.083 |
| | (0.613) | (0.576) | (0.131) | (0.117) |
| Patent | −0.014** | −0.021** | −0.003 | −0.002 |
| | (0.006) | (0.009) | (0.002) | (0.002) |
| Pollution abatement | 0.008 | 0.007 | 0.003 | −0.003 |
| | (0.012) | (0.017) | (0.003) | (0.004) |
| Import | −0.020** | −0.012 | −0.001 | −0.000 |
| | (0.008) | (0.009) | (0.002) | (0.002) |
| Export | 0.028** | 0.026** | 0.002 | 0.001 |
| | (0.011) | (0.011) | (0.003) | (0.002) |
| Energy investment | −0.015 | −0.014 | −0.006 | −0.001 |
| | (0.013) | (0.024) | (0.004) | (0.006) |
| Observations | 270 | 270 | 270 | 270 |
| R-squared | 0.866 | 0.871 | 0.394 | 0.468 |
| Year FE | Y | Y | Y | Y |
| Province FE | Y | Y | Y | Y |
| Province linear trend | | Y | | Y |

Note: Post is a binary indicator for year 2013, taking a value of one if the years is 2013 and afterwards, and zero otherwise. $ETS_j$ is an indicator of ETS region, equaling one if the region is one of the pilots, and zero otherwise. The standard errors in parenthesis are clustered at the province level. *, **, and *** represent statistical significance levels at the 10%, 5%, and 1%, respectively.

[2] The balancing test is performed. The corresponding results are presented in Table A2 in appendix.

**Table 5**
Robustness check for Pre-trend Test.

| Variables | Total CO2 emissions | GDP | Carbon intensity | Energy structure |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| ETS × $POST_{2009}$ | −0.012 | 0.012 | −0.023 | 0.000 |
| | (0.037) | (0.009) | (0.039) | (0.009) |
| ETS × $POST_{2010}$ | −0.041 | 0.006 | −0.047 | 0.008 |
| | (0.064) | (0.011) | (0.068) | (0.017) |
| ETS × $POST_{2011}$ | −0.064 | 0.012 | −0.075 | 0.011 |
| | (0.073) | (0.014) | (0.079) | (0.021) |
| ETS × $POST_{2012}$ | −0.101 | 0.015 | −0.115 | 0.013 |
| | (0.083) | (0.024) | (0.093) | (0.023) |
| ETS × $POST_{2013}$ | −0.188* | 0.034 | −0.219** | −0.012 |
| | (0.095) | (0.033) | (0.106) | (0.022) |
| ETS × $POST_{2014}$ | −0.215** | 0.038 | −0.251** | −0.016 |
| | (0.098) | (0.034) | (0.106) | (0.025) |
| ETS × $POST_{2015}$ | −0.244* | 0.043 | −0.284** | −0.031 |
| | (0.120) | (0.040) | (0.124) | (0.031) |
| ETS × $POST_{2016}$ | −0.263* | 0.065 | −0.323** | −0.038 |
| | (0.139) | (0.045) | (0.141) | (0.036) |
| Observations | 270 | 270 | 270 | 270 |
| R-squared | 0.742 | 0.995 | 0.875 | 0.480 |
| Other Province control | Y | Y | Y | Y |
| Year FE | Y | Y | Y | Y |
| Province FE | Y | Y | Y | Y |
| Province linear trend | Y | Y | Y | Y |

Note: POSTt is a year specific binary indicator. $ETS_k$ is an indicator of ETS region, equaling one if the region is one of the pilots, and zero otherwise. The province-level control including FDI, export, import, population, patent, pollution abatement, and energy investment are included but are not reported due to the limited space. The standard errors in parenthesis are clustered at the province level. The standard errors in parenthesis are clustered at the province level. *, **, and *** represent statistical significance levels at the 10%, 5%, and 1%, respectively.

$$Y_{jt} = \beta_0 + \sum_{k=\{bj,hb,tj,sh,gd\}} \beta_k ETS_k \times Post + X_{jt} + \delta_j + \gamma_t + \varepsilon_{jt} \quad (3)$$

where $ETS_k$ is the ETS region k-specific indicator. k belongs to a set of six ETS region including Beijing, Hubei, Tianjin, Shanghai, and Guangdong.

Table 7 shows the corresponding results. Columns (1)–(3) show that in all the pilot areas, the estimated coefficient for the Beijing carbon market is negative and statistically significant. Among five pilot markets, the Beijing carbon market achieve the greatest reduction in carbon emissions by 24.4%, carbon intensity by 22.7%, and energy structure by 8.6%. For the Hubei carbon market, the estimated coefficient for carbon emissions and carbon intensity are negative and statistically significant at the 1% level, suggesting that the Hubei ETS leads to a reduction in carbon emissions and carbon intensity. However, the Hubei carbon market does not significantly alter the energy consumption structure, as shown by the insignificant coefficient in column (3).

The carbon market in Shanghai is prominent in terms of improving the energy consumption structure. The estimated coefficient is negative and statistically significant at the 1% level for energy structure, while the coefficients are negative but not statistically significant at conventional levels for carbon emission and carbon intensity. For the remaining ETS pilots, the coefficients for the Tianjin carbon market are negative but not statistically significant, so do the coefficients for the Guangdong carbon market.

The success of the carbon market pilot policy in Beijing and Hubei is naturally inseparable from the system used in the carbon market in Beijing and Hubei. Looking at the seven pilot carbon markets across the country, it can be seen that Beijing's carbon quota accounts for 4.3%, trading volume accounts for 19%, and the trading amount accounts for 20%. According to relevant specific studies on the carbon market in Beijing, compared with other pilot carbon markets, the construction of the carbon market in Beijing focuses on the top-level design and establishes a relatively complete policy and regulation system. Including the Beijing municipal people's congress legislation released on December 27, 2013, local government regulations dated on May 28, 2014, and more than 20 supporting policy documents and technical support documents issued by Beijing Municipal Development and Reform Commission (MDRC) and other relevant departments, including the quota verification method, the management method of the verification institution, the trading rules, the supporting rules, the discretionary power of administrative penalty, the carbon emission trading rules and rules issued by Beijing environmental exchange in recent years. The systematic policy and regulation system makes the pilot construction of the Beijing carbon market orderly and provides a solid foundation for the healthy development of the Beijing carbon market.

In terms of MRV system construction, Beijing is also at the forefront of relevant pilot provinces and cities. Beijing takes the lead in implementing carbon assessment for new fixed-asset investment projects to reduce emissions at source. Beijing also takes the lead in implementing the double-filing system for verification agencies and inspectors, and conduct third-party verification, expert review, and cross-checking of carbon emissions reports by the fourth party of verification agencies, to ensure the quality of carbon emissions data. In addition to these, Beijing takes the lead in exploring the development of a carbon emission management system, support key emitters in controlling carbon emissions by strengthening refined management, and gradually transition from government procurement of historical carbon emission data to enterprise procurement of third-party verification services. In June 2018, the Beijing MDRC carried out a special inspection on the third-party verification institutions of the city's carbon emission trading.

For trading risks, the Beijing carbon market also adopts mechanisms such as good faith margin system, supervision and inspection system, trading dispute resolution system, rise and fall limit system, maximum position limit system, risk warning system, and natural person investor education system. Due to these unique

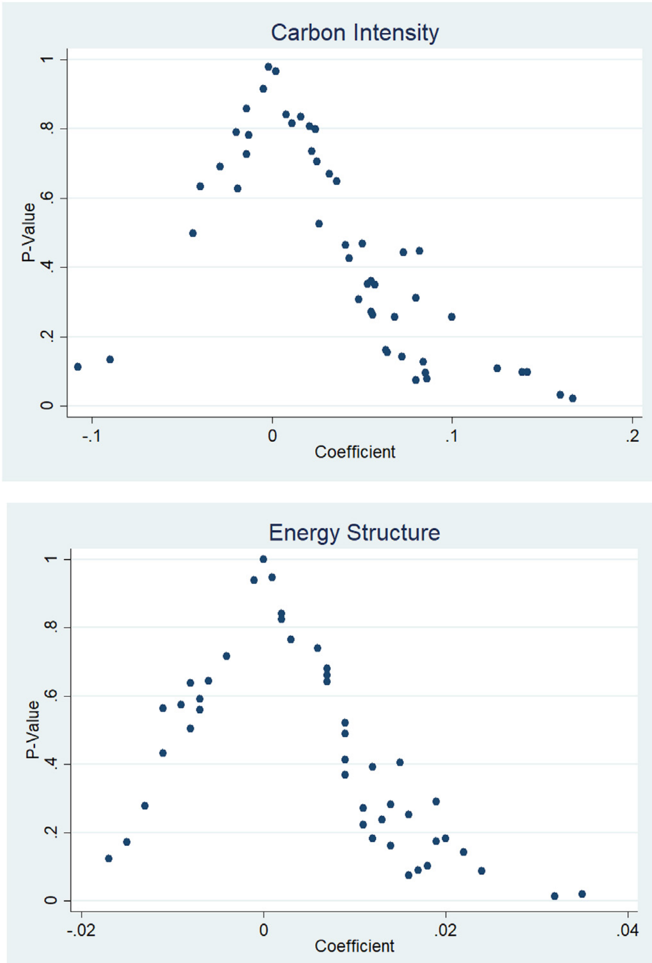


**Fig. 1.** Scatter plots for placebo tests.

mechanisms, the Beijing carbon market, which covers a wide set of manufacturing sectors and has stable carbon prices, becomes an outstanding market in China carbon market in the past few years (Clayton et al., 2016; Hu et al., 2017; Yi et al., 2018; Liu et al., 2015).

As of June 30, 2019, the secondary market of carbon quota in Hubei had a total turnover of 322 million tons, with a total amount of 7.437 billion yuan, accounting for 55.31% and 62.18% of the national gross, respectively. Market transaction scale, transaction continuity, number of participants in the market, the amount of introduced social capital, and the participation of enterprises in controlling and discharging all ranked first in China. The Hubei carbon market has been leading the country in carbon price stability and carbon quota management. Based on relevant experience and lessons and research results, the Hubei carbon market has designed a set of mechanisms to stabilize carbon price, including quota classification management and automatic cancellation, quota ex-post adjustment, quota release, and repurchase.

Emission trading quota in the Hubei carbon market consists of three categories: the initial quota for existing enterprises, the reserved quota for new enterprises, and the reserved quota for the government. Among them, the initial quota for existing enterprises accounts for the majority followed by the proportion of government reserved quota fixed at 8% and the reserved quota for new enterprises. The latter two essentially act as a "safety valve" to avoid excessive quota shortage. The reserved quota for new enterprises is used to adjust the serious deviation between the initial quota and actual emission, while the quota reserved by the government is mainly used for market regulation and price discovery through the release and recovery of quota. Moreover, it could help avoid a serious imbalance between supply and demand in the trading market and excessive price fluctuation. At the same time, in consideration of short-term market fluctuations, the Hubei carbon market formulates a mechanism to limit the price rise and fall of the carbon trading market. Because the increased predictability and institutional reliability of carbon prices are critical to carbon markets, it will determine whether they can be an effective policy tool. These innovative designs have ensured the good operation of the

**Table 6**
Robustness check with the PSM-DID method.

| Variables | Total CO2 emissions | GDP | Carbon intensity | Energy structure |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| ETS × Post | −0.142*** | 0.026* | -.0161*** | −0.016** |
| | (0.027) | (0.013) | (0.027) | (0.008) |
| GDP | 0.395** | | | 0.022 |
| | (0.172) | | | (0.050) |
| Value added | −0.044 | 0.455*** | −0.332*** | −0.062** |
| | (0.097) | (0.030) | (0.060) | (0.028) |
| FDI | −0.013 | 0.012 | −0.017 | 0.005 |
| | (0.023) | (0.012) | (0.023) | (0.007) |
| Population | −0.610 | −0.091 | -.0707* | -.0276** |
| | (0.431) | (0.212) | (0.426) | (0.127) |
| Patents | −0.016** | −0.005 | −0.011 | −0.005** |
| | (0.008) | (0.004) | (0.008) | (0.002) |
| Pollution abatement | 0.010 | 0.000 | 0.007 | 0.004 |
| | (0.009) | (0.005) | (0.010) | (0.003) |
| Import | −0.011 | 0.004 | −0.012 | 0.001 |
| | (0.008) | (0.004) | (0.008) | (0.002) |
| Export | 0.019** | −0.000 | 0.018 | 0.000 |
| | (0.009) | (0.005) | (0.010) | (0.003) |
| Energy investment | −0.015 | −0.004 | −0.011 | −0.007** |
| | (0.011) | (0.006) | (0.011) | (0.003) |
| Observations | 163 | 167 | 167 | 163 |
| R-squared | 0.724 | 0.989 | 0.924 | 0.484 |
| Year FE | Y | Y | Y | Y |
| Industry FE | Y | Y | Y | Y |

Note: Post is a binary indicator for year 2013, taking a value of one if the years is 2013 and afterwards, and zero otherwise. $ETS_k$ is an indicator of ETS region, equaling one if the region is one of the pilots, and zero otherwise. The standard errors in parenthesis are clustered at the province level. *, **, and *** represent statistical significance levels at the 10%, 5%, and 1%, respectively.

**Table 7**
Heterogeneous results by pilots.

| Variables | Total CO2 emissions | Carbon intensity | Energy structure |
|---|---|---|---|
| | (1) | (2) | (3) |
| $ETS_{bj} \times Post$ | −0.244** | −0.227** | −0.086*** |
| | (0.098) | (0.105) | (0.020) |
| $ETS_{hb} \times Post$ | −0.198*** | −0.200*** | −0.010 |
| | (0.035) | (0.036) | (0.007) |
| $ETS_{tj} \times Post$ | −0.053 | −0.071 | −0.016 |
| | (0.130) | (0.138) | (0.025) |
| $ETS_{sh} \times Post$ | −0.038 | −0.043 | −0.050*** |
| | (0.069) | (0.071) | (0.017) |
| $ETS_{gd} \times Post$ | −0.029 | 0.054 | 0.016 |
| | (0.118) | (0.129) | (0.026) |
| Observations | 270 | 270 | 270 |
| R-squared | 0.739 | 0.867 | 0.517 |
| Other province control | Y | Y | Y |
| Year FE | Y | Y | Y |
| Province FE | Y | Y | Y |
| Province year trend | Y | Y | Y |

Note: Post is a binary indicator for year 2013, taking a value of one if the years is 2013 and afterwards, and zero otherwise. $ETS_k$ is an indicator of ETS region, equaling one if the region is one of the pilots, and zero otherwise. We use the subscript bj, hb, tj, sh, and gd to represent Beijing, Tianjin, Shanghai, and Guangdong provinces, respectively. The province-level control including FDI, export, import, population, patent, pollution abatement, and energy investment are included but are not reported due to the limited space. The standard errors in parenthesis are clustered at the province level. *, **, and *** represent statistical significance levels at the 10%, 5%, and 1%, respectively.

Hubei carbon market, making it the largest and most active carbon market among all the pilot carbon markets (Clayton et al., 2016; Weng and Xu, 2018; Fan et al., 2019).

On the whole, Beijing and Hubei are at the forefront of several carbon market trials in terms of transaction volume and turnover. Moreover, due to a large number of included enterprises, large emissions, complete, advanced and flexible market mechanisms, the pilot policies have achieved remarkable results. The establishment of a national carbon market should refer to the relevant system design of Beijing and Hubei carbon markets to achieve a better policy effect.

## 5. Conclusions

Using the provincial panel data of 30 provinces in mainland China from 2008 to 2016, we conduct an empirical study on the environmental and economic effects of pilot policies on China's carbon market. The empirical results of the benchmark analysis show that China's carbon market pilot policies have achieved a certain environmental effect, that is, reached a target of carbon emissions reduction, and this reduction was not at the expense of economic development. In the meanwhile, the ETS policy has reduced carbon intensity and improved the energy consumption structure, achieving certain far-reaching results. The results of further analysis of ETS pilots show that Beijing and Hubei carbon markets have made remarkable achievements in reducing carbon emission, carbon intensity, and energy structure.

The empirical findings of this paper provide profound policy implications for China's national carbon market. As a policy-oriented market, establishing clear and complete management methods and forming strict performance management as well as supervision mechanism is crucial to the national carbon market. The success of the market in Beijing and Hubei is closely related to the sane and complete policy and regulation systems. At present, the construction of the national carbon market mainly based on the relevant approval of the State Council and NDRC. These rules and regulations have a low legal level, which will lead to the failure to establish relevant key provisions required for the effective implementation of the carbon emission trading system, such as the qualification requirements for third-party verification institutions and the economic penalties for higher quotas, thus making it difficult to guarantee the effectiveness and authority of the system implementation.

Moreover, the allocation of carbon market quota is crucial to the construction of the carbon market. The mechanism of quota allocation in Hubei province is the key to success. Therefore, how to construct a scientific and fair initial quota allocation method for the national carbon market has a fundamental effect on the construction of the carbon market. Relative to a single standard allocation approach, a multi-standard quota allocation helps to reduce the variance between the minimum and maximum objectives of different entities and bridge the gap between developed and developing regions.

## CRediT authorship contribution statement

**Shaozhou Qi:** Conceptualization, Writing - review & editing. **Shihan Cheng:** Data curation, Methodology, Formal analysis, Writing - original draft. **Jingbo Cui:** Conceptualization, Methodology, Writing - original draft.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix

**Table A1**
Policy Summary of China Seven Pilot Carbon Markets

| Pilots | Selection criteria | The quota allocation | Sectors |
|---|---|---|---|
| Beijing | From 2009 to 2011, the average annual direct or indirect emission of more than 10,000 tons of CO2 from the fixed facility emission enterprises | Free distribution and paid distribution (sell at a fixed price or auction coexist, there is a quota buyback mechanism) | power, heat, cement, petrochemical, automobile manufacturing and public construction |
| Shanghai | Industrial enterprises emitting more than 20,000 tons of CO2 or non-industrial enterprises emitting more than 10,000 tons of CO2 in any one year from 2010 to 2011 | Free distribution and paid distribution (sell at a fixed price or auction) coexist | steel, petrochemical, chemical, metal, power, building materials, textile, paper, rubber and chemical fiber industries |
| Chongqing | Industrial enterprises with emissions of 20,000 tons of CO2 in any of the years 2008–2012 | Free distribution | cement, steel, power and other industries |
| Hubei | Industrial enterprises with a combined energy consumption of more than 60,000 tons in any one year, 2010–2011 | Free distribution | steel, chemical, cement, power and other industries |
| Tianjin | Enterprises that emit more than 20,000 tons of CO2 in key emission industries and civil construction fields in any year since 2009 | Free distribution | Steel, chemical, power, petrochemical, oil refining and other industries |
| Guangdong | Industrial enterprises that emit more than 20,000 tons of CO2 (or 10,000 tons of comprehensive energy consumption) in any year from 2010 to 2012 | Free distribution and partial paid distribution. The free quota ratio of power companies is 95%, and the free quota ratio of steel, petrochemical, cement, paper and aviation companies is 97%. | electricity, cement, steel, petrochemical, papermaking and civil aviation |
| Shenzhen | Enterprises and institutions that emit more than 3000 tons of CO2 in any year from 2009 to 2011; large public buildings of more than 10,000 square meters | Free distribution and paid distribution (sell at a fixed price or auction) coexist | Manufacturing and public utility sectors |

Note: information is obtained from the websites of each pilot province' DRC (Beijing: http://fgw.beijing.gov.cn/; Shanghai: http://fgw.sh.gov.cn/; Chongqing: http://fzggw.cq.gov.cn/; Hubei: http://fgw.hubei.gov.cn/; Tianjin: http://fzgg.tj.gov.cn/; Guangdong: http://drc.gd.gov.cn/; and Shenzhen: http://fgw.sz.gov.cn/).

**Table A2**
Balancing Test for the PSM Approach

| Variables | Mean Values in the ETS Regions | Mean Values in matched no-ETS Regions | P-Value for the Mean Differences |
|---|---|---|---|
| GDP | 9.899 | 9.982 | 0.620 |
| Value added | 8.933 | 9.071 | 0.478 |
| FDI | 10.873 | 11.078 | 0.342 |
| Population | 8.340 | 8.461 | 0.398 |
| Patent | 10.306 | 10.269 | 0.918 |
| Pollution abatement | 5.291 | 5.076 | 0.609 |
| Import | 5.619 | 5.489 | 0.756 |
| Export | 6.619 | 6.654 | 0.838 |
| Energy investment | 2.790 | 2.965 | 0.460 |

## References


Alvarado, Rafael, Ponce, Pablo, Alejandra, Criollo, Karina, Córdova, Kamran, Khan Muhammad, 2018. Environmental degradation and real per capita output: new evidence at the global level grouping countries by income levels. J. Clean. Prod. 189, 13–20.

Clayton, Munnings, Morgenstern, Richard D., Wang, Zhongmin, Liu, Xu, 2016. Assessing the design of three carbon trading pilot programs in China. Energy Pol. 96, 688–699.

Fan, Xinghua, Lv, Xiangxiang, Yin, Jiuli, Tian, Lixin, Liang, Jiaochen, 2019. Multifractality and market efficiency of carbon emission trading market: analysis using the multifractal detrended fluctuation technique. Appl. Energy 251.

Fang, Kai, Zhang, Qifeng, Yin, Long, Yoshida, Yoshikuni, Sun, Lu, Zhang, Haoran, Dou, Yi, Li, Shuai, 2019. How can China achieve its Intended Nationally Determined Contributions by 2030? A multi-criteria allocation of China's carbon emission allowance. Appl. Energy 241, 380–389.

Harrison, David, Klevnas, Per, Nichols, Albert L., Radov, Daniel, 2008. Using emissions trading to combat climate change: programs and key issues. Environ. Law Rep.: News & Analysis 38 (6), 10367–10384.

Hu, Yujie, Li, Xiaoyi, Tang, Baojun, 2017. Assessing the operational performance and maturity of the carbon trading pilot program: the case study of Beijing's carbon market. J. Clean. Prod. 161, 1263–1274.

Kaya, Yoichi, 1989. Impact of carbon dioxide emission on GNP growth: interpretation of proposed scenarios. In: Presentation to the Energy and Industry Subgroup," Response Strategies Working Group. IPCC.

Khan, Muhammad Kamran, Teng, Jianzhou, Khan, Muhammad Imran, 2019. Effect of energy consumption and economic growth on carbon dioxide emissions in Pakistan with dynamic ARDL simulations approach. Environ. Sci. Pollut. Res. 26 (23), 23480–23490.

Khan, Muhammad Kamran, Khan, Muhammad Imran, Rehan, Muhammad, 2020. The relationship between energy consumption, economic growth and carbon dioxide emissions in Pakistan. Financial Innovation 6 (1), 1–13.

Liu, Liwei, Chen, Chuxiang, Zhao, Yufei, Zhao, Erdong, 2015. "China's carbon-emissions trading: overview, challenges and future. Renew. Sustain. Energy Rev. 49, 254–266.

Liu, Xiaoning, Wang, Bing, Du, Minzhe, Zhang, Ning, 2018. Potential economic gains and emissions reduction on carbon emissions trading for China's large-scale thermal power plants. J. Clean. Prod. 204, 247–257.

Liu, Xianfeng, Zhou, Xinxing, Zhu, Bangzhu, He, Kaijian, Wang, Ping, 2019. Measuring the maturity of carbon market in China: an entropy-based TOPSIS approach. J. Clean. Prod. 229, 94–103.

Liu, Jian, Huang, Yuying, Chang, Chunping, 2020. Leverage analysis of carbon market price fluctuation in China. J. Clean. Prod. 245.

Martina, Linnenluecke, Smith, Tom, Brent, McKnight, 2016. Environmental finance: a research agenda for interdisciplinary finance research. Econ. Modell. 59, 124–130.

Mu, Yaqian, Wang, Can, Cai, Wenjia, 2018. The economic impact of China's INDC: distinguishing the roles of the renewable energy quota and the carbon market. Renew. Sustain. Energy Rev. 81 (2), 2955–2966.

Porter, Michael E., van der Linde, Claas, 1995. Toward a new conception of the environment-competitiveness relationship. J. Econ. Perspect. 9 (4), 97–118.

Wang, Han, Chen, Zhoupeng, Wu, Xingyi, Nie, Xin, 2019. Can a carbon trading system promote the transformation of a low-carbon economy under the framework of the porter hypothesis? —empirical analysis based on the PSM-DID method. Energy Pol. 129, 930–938.

Weng, Qingqing, Xu, He, 2018. A review of China's carbon trading market. Renew. Sustain. Energy Rev. 91, 613–619.

Yang, Baochen, Liu, Chuanze, Gou, Zehao, Man, Jiacheng, Su, Yunpeng, 2018. How will policies of China's CO2 ETS affect its carbon price: evidence from Chinese pilot regions. Sustainability 10 (3), 605.

Yi, Lan, Li, Zhaopeng, Yang, Li, Liu, Jie, Liu, Yiran, 2018. Comprehensive evaluation on the 'maturity' of China's carbon markets. J. Clean. Prod. 198, 1336–1344.

Yi, Lan, Ning, Bai, Yang, Li, Li, Zhaopeng, Wang, Fei, 2020. Evaluation on the effectiveness of China's pilot carbon market policy. J. Clean. Prod. 246.

Zha, Donglan, Zhou, Dequn, Zhou, Peng, 2010. Driving forces of residential CO2 emissions in urban and rural China: an index decomposition analysis. Energy Pol. 38 (7), 3377–3383.

Zhang, Yuejun, Peng, Yulu, Ma, Chaoqun, Shen, Bo, 2017. Can environmental

innovation facilitate carbon emissions reduction? Evidence from China. Energy Pol. 100, 18–28.
Zhang, Jie, Zhang, Ke, Zhao, Feng, 2020. Spatial effects of economic growth, energy consumption and environmental pollution in the provinces of China—an empirical study of a spatial econometrics model. Sustain. Dev. 1–12.
Zhu, Ying, Li, Yongping, Huang, Gordon, Fan, Yurui, Nie, Songlin Ling, 2015. A dynamic model to optimize municipal electric power systems by considering carbon emission trading under uncertainty. Energy 88, 636–649.
Zhu, Bangzhu, Zhou, Xinxing, Liu, Xianfeng, Wang, Haifang, He, Kaijian, Wang, Ping, 2020. Exploring the risk spillover effects among China's pilot carbon markets: a regular vine copula-CoES approach. J. Clean. Prod. 242.