

# Testing mechanisms through which China's ETS promotes a low-carbon transition

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## ABSTRACT

China regards an emission trading scheme (ETS) as the most promising approach for reducing its carbon dioxide emissions. However, there are still disagreements about the effectiveness of China's ETS (CETS). To settle this issue, we test the impact of CETS on key mechanisms driving a low-carbon transition. We use the difference-in-difference method to analyze data for coal-power plants participating in China's carbon trading pilot. This involves the use of two variables based on life-cycle indicators, namely 'energy return on energy invested' (EROI) and 'energy return on carbon invested' (EROIC). We obtain three main findings: (1) a mediating effect of supply-side reform is significant; (2) this effect is stronger for more intense technological innovation and government intervention; (3) the influence of CETS on a low-carbon transition is independent of the development of clean energy. Overall, we conclude that the scope of CETS should be extended to other emitters to fully unleash its potential for reducing carbon emissions.

## 1. Introduction

Being the largest market for carbon-emission permits worldwide, China's emissions trading system (CETS) has drawn much attention since its launch. After positive experiences with regional pilots, CETS was fully launched in 2021, with firms within the fossil-fuel power sector as the initial participants. Being the main source of electricity supply, coal-fired power plants account for 60% of electricity production, which means they are crucial for a stable power supply. Here we try to assess the impact of CETS on a low-carbon transition of coal-fired power. This is done by examining potential transmission path underlying these effects, which possibly involve indirect factors, such as technology innovation and government intervention. Insight into this will aid the design of supporting policies as well as the integration of other carbon-intensive industries in a next stage of CETS.

The effectiveness of the CETS has already been analyzed from different perspectives. Due to its market mechanism, CETS has advantages in terms of cost and systemic effectiveness compared to over carbon taxation and direct regulation (e.g., through quota or technological norms/standards) (Li et al., 2019; Mu et al., 2018). It is also noteworthy

that CETS relies on a rate-based tradable performance standard (TPS). This aims at reducing the carbon intensity of economic activities rather than the total amount of carbon emissions (Goulder et al., 2022; Yu et al., 2023). As a result of the TPS, emission allowances are allocated to the participants as the product of the benchmark of emission intensity and their actual output. Unlike in the case of cap-and-trade, the total numbers of allowances under TPS are unknown before the actual output of facilities is verified at the end of the compliance period (Li et al., 2022). To study how CETS may influence the evolution of the economy, several studies have used computable equilibrium models that simulate effects on production, households, technical progress and emissions (Liu et al., 2023; Song et al., 2021; Zhang et al., 2019). Their findings indicate that the cost of carbon generated by CETS increases the price of carbon-intensive products, in turn reducing their consumption. Additionally, the CETS can stimulate technical progress of low-carbon technologies, which will reduce future abatement costs (Lv and Bai, 2021; Rogge and Hoffmann, 2010).

Despite theoretical support and evidence, doubts remain as to whether CETS functions as desired. The main concerns include the extent of economic losses, unfair distributional effects and carbon

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leakage (Wen et al., 2021; Zhou et al., 2020). The insufficient transactions and long trading intervals also reduce the efficiency of CETS. (Chang et al., 2018). Other limitations of CETS have been suggested, such as higher profit variability and operational risk for covered industries (Li et al., 2022; Yu et al., 2022). A weak emission allowance and fluctuating carbon prices result in uncertain expectation about future carbon cost, which in turn can postpone the low-carbon upgrading of carbon intensive enterprises (Chai et al., 2022; Yu et al., 2022).

China's regional pilots show distinct trading volumes and carbon prices, which result from differences in income level, industrial structure and energy mix between regions (Xiao et al., 2015). Studies indicate that the generation efficiency and industrial structure in the participating regions were optimized during the pilot period (Li et al., 2018; Zhao et al., 2022). In addition, the influence of China's ETS has shown significant heterogeneity in that it is more effective in regions with strict environmental regulation and sufficient financial support (Wang et al., 2022; Wang and Zhang, 2022). Most studies so far have evaluated the performance of China's ETS from a regional or macro perspective (Deng and Zhang, 2019; Yang and Cheng, 2017), while few studies have addressed the direct participants of the national carbon market.

To assess the main goal of the CETS, carbon dioxide emissions and energy consumption are commonly studied (Duan et al., 2022; Lin and Huang, 2022). To provide a comprehensive perspective on economic changes, a total-factor productivity index has also been used (Chen and Hibiki, 2022). To capture lifecycle and production-chain effects, various studies have used the indicator of Energy Return on Energy Investment (EROI), which represents the ratio between energy delivered by a particular kind of fuel or source to society and the energy invested in its life-cycle process (Hall et al., 2014). Accounting for relevant life-cycle processes defines a range of EROIs, such as Standard EROI, Point of Use EROI, Extended EROI or Societal EROI (Hall et al., 2009; Murphy et al., 2011). A study by King and van den Bergh (2018) proposed the indicator of Energy Return on Carbon Investment (EROC), which considers carbon dioxide emissions as an input to energy-conversion processes. This indicator was applied in several studies on solar, wind and other energy projects (Huang et al., 2019; Liu and van den Bergh, 2020; Walmsley et al., 2017). Being based on life cycle data of energy input, EROI and EROC serve here to comprehensively measure and compare the performance of energy efficiency and carbon intensity. Compared with other indicators, EROI and EROC form a consistent set of indicators based on the same foundation, namely return on investment (ROI). When the full life cycle is accounted for, these indicators permit a thorough evaluation of the power industry in term of generation efficiency and minimum carbon emissions. Our elaboration of both indicators for this purpose is inclusive of the energy used in the generation stage, other direct energy use (e.g., auxiliary power), and indirect energy use embodied in materials and labor.

To obtain insight on the consequences of planned extension of CETS with other carbon-intensive industries in the next stage, this study undertakes a comprehensive evaluation of the influence of CETS on the economy and identifying the key factors affecting this process. To measure the low-carbon performance of the coal power sector, the two life-cycle indicators EROI and EROC will be used to evaluate generation efficiency and carbon intensity, respectively. Given that CETS was launched less than two years ago, the data for quantitative analysis cover the CETS pilots as well. This means we use data that conform to the features of a quasi-natural experiment. The difference-in-difference (DID) method is used to analyze the data, while a series of tests including propensity score matching (PSM) and placebo tests are conducted to assess the robustness. The result helps to better understand the effects of CETS and contribute to designing supporting policies. In addition, it can also serve as reference to bring more carbon intensive industries of China into CETS and thus promote the national low-carbon transition.

## 2. Hypotheses

The Chinese government has established the goal of carbon neutrality nation-wide before 2060 and considers CETS as the primary tool for achieving this. Being a market-oriented environmental policy, the CETS will impose a financial burden on high-emission industries, which is the coal-fired power industry in the initial stage. Carbon emission allowances are granted to the facilities based on the TPS, meaning that the number of emissions in each compliance period is allocated as the product of the assigned "benchmark" and level of output. If their emissions exceed the allowances, emitters have to pay for the surplus. On the other hand, they also have the option to sell their unused allowances to other parties. To avoid a sharp increase in the cost of carbon, those with a higher carbon emissions rate than the benchmark will tend to adopt the decarbonization technology. An upgrade of generation technology (e.g., ultra-supercritical technology) is an alternative to achieve the goal of carbon reduction by improving generation efficiency. As the result of any technological upgrades, both EROI and EROC of the sectors are expected to increase. In the light of this, we propose the following hypothesis:

**Hypothesis 1.** CETS will increase the EROI and EROC of coal-fired power plants.

According to the Porter Hypothesis, environmental regulation creates a comparative advantage as it induces technological innovation (Porter, 1991). As a policy tool of environmental regulation, CETS may have a similar effect. Coal-fired power companies in the CETS pilot provinces may seek for improving productivity under the emission reduction pressure. Consequently, more investment in low-carbon technology will be flooded into the CETS pilot regions to stimulate the regional innovation and then contribute to the low-carbon transition in coal-fired power. This is captured by the following hypothesis:

**Hypothesis 2a.** China's ETS increases the EROI and EROC of coal-fired power through technological innovation.

The Notice on the Pilot Work of Carbon Emission Trading required local government in all pilot regions to attach great importance to the pilot work and arrange special funds for it. The environmental protection expenditure can capture the government intervention of government. CETS may take effect by strengthening government intervention from local government. First, it can effectively promote the energy conservation and emission reduction (Zhu and Lu, 2017). Additionally, it can reflect the environmental preference of the government and thus guide the investment of social capital (Liu and Sun, 2021; Tian et al., 2016), which also helps improve the energy efficiency of coal-fired power. Therefore, we propose the following hypothesis:

**Hypothesis 2b.** CETS increases the EROI and EROC of coal-fired power through government intervention.

With the deceleration of growth of electricity consumption and the acceleration of renewable energy development, coal-fired power is confronted with a structural surplus. This has led to low utilization rates of coal-fired power units, hindering high-efficiency units from reaching their full potential. To address this issue, the government has implemented a supply-side reform. Coal power capacity construction has been halted or delayed while the outdated units have been phased out or temporarily shut down. This reform results in fewer opportunities for inefficient units, leading to a reduction in coal-fired generation and an improvement in the performance of coal-fired power in terms of EROI and EROC. We therefore propose the following hypothesis:

**Hypothesis 2c.** CETS increases the EROI and EROC of coal-fired power through the reform of electricity generation.

Both the low-carbon transition of thermal power and the substitution of renewable energy for it are effective ways to reduce fuel consumption and carbon emission in the power system. Therefore, the development of

renewable energy can possibly influence the transition of coal-fired power. For example, provinces with favorable natural conditions for renewable energy will put more emphasis on it and thus pay less attention to the upgrading of the internal coal-fired power capacity, which may lead to the failure of the CETS in regions with more developed clean energy. We therefore propose the following hypothesis:

**Hypothesis 3.** The development level of clean energy negatively influences the effect of CETS on the EROI and EROC of coal-fired power.

### 3. Method and data

#### 3.1. Method

To study the effectiveness of climate policy, many studies use a regression model in which a dummy explanatory variable is set to represent whether the policy was implemented in a region which is then regressed on the variable of interest. However, this method can bias the estimates as it causes endogeneity problems by overlooking the difference in values of the explanatory variable between regions at the start (Meyer, 1995). To overcome this problem, the difference-in-differences (DID) model is used in this study. This model has seen wide application in econometric studies where the causal effect of a policy is estimated by comparing the longitudinal data of a treatment group and a control group (Angrist and Pischke, 2009). In our study, these groups are the pilot regions of CETS and the other regions of China, respectively. The general form of the DID model is as follows:

$$Y_{it} = \alpha_0 + \alpha_1 Treated_i \times Period_t + \sum_{k=1}^6 \beta_k X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Here subscripts  $i$  and  $t$  represent the  $i$ -th province and  $t$ -th year respectively.  $Y_{it}$  represents the EROI or EROC of the coal-fired power industry in each region. The core explanatory variable is the effect of CETS identified by the interaction term of *Treated* and *Period*. *Treated* = 1 denotes that the province belongs to the CETS pilot group, and zero otherwise. *Period* = 1 denotes that it is in the implementation period of the CETS, and zero otherwise.  $X$  represents a series of control variables. We control for two fixed effects in the model, where  $\mu_i$  represents the region fixed effect that captures regional characteristics that remain unchanged when time  $t$  changes and  $\lambda_t$  represents the time fixed effect that captures time characteristics that remain unchanged when region  $i$  changes. Standard errors are clustered at the provincial level.

Based on the baseline DID model, this paper adopts a mediator model using the causal steps regression approach (Baron and Kenny, 1986). The central idea of this model is that the effects of stimuli on behavior are mediated by various transformation processes internal to the organism. Therefore, the mediator-oriented research gives more attention to the mechanism through which the independent variable influences the dependent variable than a model with an exogenous dependent variable (the policy effect *TP* as in this study). The baseline DID model displayed by Eq. (1) examines the influence of CETS on the low-carbon transition of China's coal-fired power industry, while the mediator model explores the influencing mechanism behind it. Therefore, the mediator model can be considered as an extension of our baseline DID model. Next to Eq. (1), the mediator model includes Eq. (2) and Eq. (3):

$$ME_{it} = \alpha_0 + \alpha_1 Treated_i \times Period_t + \sum_{k=1}^6 \beta_k X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

$$Y_{it} = \alpha_0 + \alpha_1 Treated_i \times Period_t + \alpha_2 ME_{it} + \sum_{k=1}^6 \beta_k X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

The first step is to examine the coefficient  $\alpha_1$  of policy effect variable *TP* of China's ETS through Eq. (1). If it is statistically significant, the tests based on Eqs. (2) and (3) should be conducted as the second step. In that case, if both the regression coefficient  $\alpha_1$  in Eq. (2) and  $\alpha_2$  of mediator

variable *ME* in Eq. (3) are significant, it indicates the existence of a mediation effect. If only one of them is significant, a Sobel test should be done to examine the mediation effect again. The third step is to test whether the coefficient  $\alpha_1$  of Eq. (3) is significant or not. If not, it indicates that there is only one mediation effect called the complete mediation effect. On the contrary, it means the direct effect is still significant after adding the mediating variable, which is called the partial mediation effect.

As another extension of the baseline DID model, a moderator model is used to identify factors that specify the conditions for the operation of the independent variable (Baron and Kenny, 1986), namely the CETS in this study. The model is displayed in Eq. (4). The most relevant coefficient is  $\alpha_3$  of the interaction term between *TP* and the moderator variable *MO*. If  $\alpha_3$  is statistically significant, it indicates the presence of a moderation effect, namely *MO* moderating the influence of CETS on EROI and EROC.

$$Y_{it} = \alpha_0 + \alpha_1 Treated_i \times Period_t + \alpha_2 MO_{it} + \alpha_3 Treated_i \times Period_t \times MO_{it} + \sum_{k=1}^6 \beta_k X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

#### 3.2. Data

The CETS pilot was launched in 6 regions. To examine its impact on the life-cycle performance of the coal-fired power capacity, this paper used the panel data of 30 provinces across China from 2011 to 2020, before the implementation of China's national CETS in July 2021. The data used in this study is from the China Electric Power Yearbook, China Railway Yearbook, China Statistical Yearbook, China Environmental Yearbook, China Electric Power Yearbook, China Labor Statistical Yearbook, China Statistical Yearbook of Science and Technology, and Chinese Research Data Services Platform (CNRDS).

The explained variables are EROI and EROC, which are derived from the calculation in Section 4. The influencing factors of the power system efficiency has been well explored, and we select control variables accordingly (Guang, 2020; Xu et al., 2022). For the control variables, this paper selects the GDP per capita (PGDP) to measure provincial affluence, population density (PD) to measure the residential power demand, proportion of the urban population in total population to measure the urbanization rate (UR), proportion of secondary industry GDP in total GDP to measure the industrial structure (IS), proportion of mining workers in total employment to measure the provincial coal mining industry status (CM), and the ratio of electricity production to electricity consumption to measure the local electricity self-sufficiency (ES).

The energy consumption and carbon emission for electricity generation have fell greatly in recent years. In China, the coal consumption has decreased from 325 g/kwh in 2012 to 305 g/kwh in 2021, which is partly due to the technological innovation such as the ultra-supercritical (USC) technology (Fan et al., 2018). To examine whether the technological innovation mediates the impact of CETS on the low-carbon transition of coal-fired power, this study introduces the indicator of research and development level (RD), and conducts a mediation effect test on it. Besides, the government's commitment on environmental regulation can determine whether an environmental policy works or not (Wang and Shen, 2009; Wei et al., 2023), so we introduce the indicator of government intervention (GI) to explore its mediation effect as well. Furthermore, China's supply-side reform has mandated that electricity supply be as environmentally friendly as possible, disallowing the use of low-efficiency units. This has resulted in a reduction in coal-fired generation (CG). To measure the success of the reform, we will use CG as an indicator, with lower CG values indicating greater success, and explore its mediation effect.

Last, the proportion of clean energy in total electricity production is

**Table 1**  
Variables and data description.

| Type                              | Variable       | Definition                          | Description                                                  |
|-----------------------------------|----------------|-------------------------------------|--------------------------------------------------------------|
| Explained variable                | <i>EROI</i>    | Energy return on energy investment  | Energy return / energy invested                              |
|                                   | <i>EROC</i>    | Energy return on carbon investment  | Energy return / carbon invested                              |
| Explanatory variable              | <i>Treated</i> | Whether it is a CETS pilot province | It is equal to 1 if it is a pilot province, and 0 otherwise. |
|                                   | <i>Period</i>  | Whether CETS has been implemented   | It is equal to 1 in 2014–2020, and 0 in 2011–2013.           |
| Control variable                  | <i>PGDP</i>    | GDP per capita                      | Ln (GDP / population)                                        |
|                                   | <i>PD</i>      | Population density                  | Ln (population / provincial area)                            |
|                                   | <i>UR</i>      | Urbanization rate                   | Urban population / total population                          |
|                                   | <i>IS</i>      | Industrial structure                | Secondary industry GDP / total GDP                           |
|                                   | <i>CM</i>      | Coal mining industry status         | Number of mining workers / total labor force                 |
| Mediating and moderating variable | <i>ES</i>      | Electricity self-sufficiency        | Electricity production / electricity consumption             |
|                                   | <i>RD</i>      | Research and development level      | Research and development expenditure input / GDP             |
|                                   | <i>GI</i>      | Government intervention             | Environmental protection cost / total government expenditure |
|                                   | <i>CG</i>      | Coal-fired generation               | Ln (coal-fired power production)                             |
|                                   | <i>CE</i>      | Clean energy development            | Clean energy production / total power production             |

**Table 2**  
Descriptive statistics.

| Variable    | N   | Mean  | S.D.  | Min   | P50   | Max   |
|-------------|-----|-------|-------|-------|-------|-------|
| <i>PGDP</i> | 300 | 1.578 | 0.438 | 0.464 | 1.534 | 2.798 |
| <i>PD</i>   | 300 | 0.044 | 0.060 | 0.001 | 0.028 | 0.331 |
| <i>UR</i>   | 300 | 0.590 | 0.122 | 0.350 | 0.570 | 0.900 |
| <i>IS</i>   | 300 | 0.410 | 0.081 | 0.160 | 0.420 | 0.620 |
| <i>CM</i>   | 300 | 0.038 | 0.040 | 0.000 | 0.030 | 0.222 |
| <i>ES</i>   | 300 | 1.054 | 0.313 | 0.320 | 0.988 | 1.930 |
| <i>RD</i>   | 300 | 1.730 | 1.127 | 0.410 | 1.400 | 6.440 |
| <i>GI</i>   | 300 | 0.030 | 0.010 | 0.012 | 0.028 | 0.068 |
| <i>CG</i>   | 300 | 6.855 | 0.911 | 4.218 | 6.826 | 8.477 |
| <i>CE</i>   | 300 | 0.239 | 0.247 | 0.002 | 0.138 | 0.924 |

used to denote the local clean energy development (*CE*) in the moderation effect analysis, with *RD* and *GI* used as well. To alleviate the heteroscedasticity of data, some variables are treated through log transformation. Table 1 shows the definition and description of all variables, and Table 2 reports the descriptive statistical results.

#### 4. EROI and EROC

In this study, EROI and EROC were used to evaluate the life cycle of the coal-fired power plants including the stages of the manufacture, transport, construction, operation and decommissioning. For each stage, the direct and indirect inputs were included. As the research subject of this study is the coal-fired power, the system boundary is confined to the combination of fuel cycle and plant cycle. The fuel cycle includes fuel transportation, combustion and waste disposal in this study, and the plant cycle includes production and transportation of electric power systems, and construction, operation and decommissioning of power plants, as shown in Fig. 1. Most of the energy consumption and carbon footprint happen in the fuel combustion stage and they can be derived from the provincial coal consumption statistics in China Electric Power Yearbook. For the same reason, provincial energy consumption and carbon footprint can also be estimated in the fuel transportation and the operation of power plants. However, they are unmeasurable in other stages for the lack of statistics. Thankfully, Wang et al. (2021a) did the life cycle analysis for a typical coal-fired power plant in China and offered the energy and material (coal, oil, gas, electricity, concrete, steel, copper and aluminum) consumption data in these stages. With the energy conversion factors provided by China Energy Statistical Yearbook

**Table 3**  
Data sources.

| Life cycle  | Specific stage                                          | Data source                                              |
|-------------|---------------------------------------------------------|----------------------------------------------------------|
| Fuel cycle  | Coal transportation                                     | China Railway Yearbook and China Electric Power Yearbook |
|             | Coal combustion                                         | China electric power yearbook                            |
|             | Waste disposal                                          | Wang et al. (2021a) and China Electric Power Yearbook    |
| Plant cycle | Production and transportation of electric power systems | Wang et al. (2021a) and China Electric Power Yearbook    |
|             | Construction of power plants                            | Wang et al. (2021a) and China Electric Power Yearbook    |
|             | Operation of power plants                               | China Electric Power Yearbook                            |
|             | Decommission of power plants                            | Wang et al. (2021a) and China Electric Power Yearbook    |
|             |                                                         |                                                          |

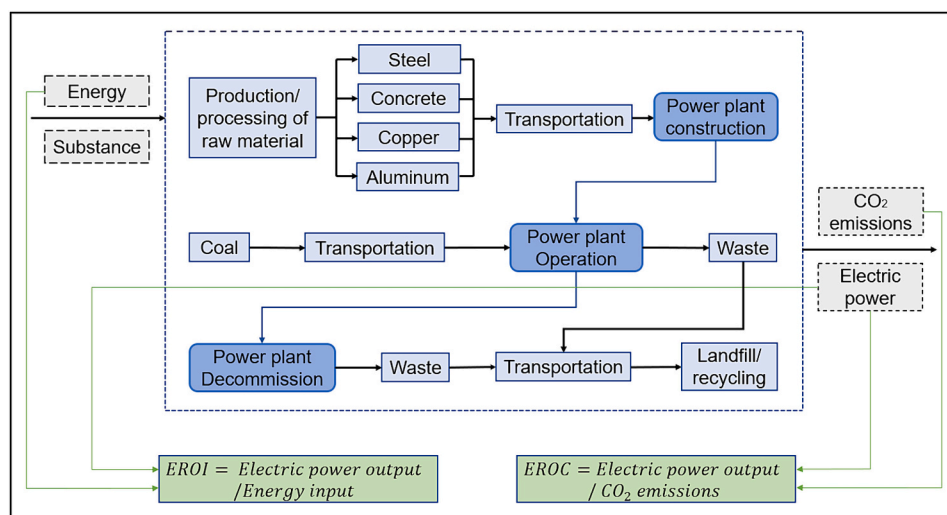


**Fig. 1.** System boundary of the life cycle analysis of coal-fired power.

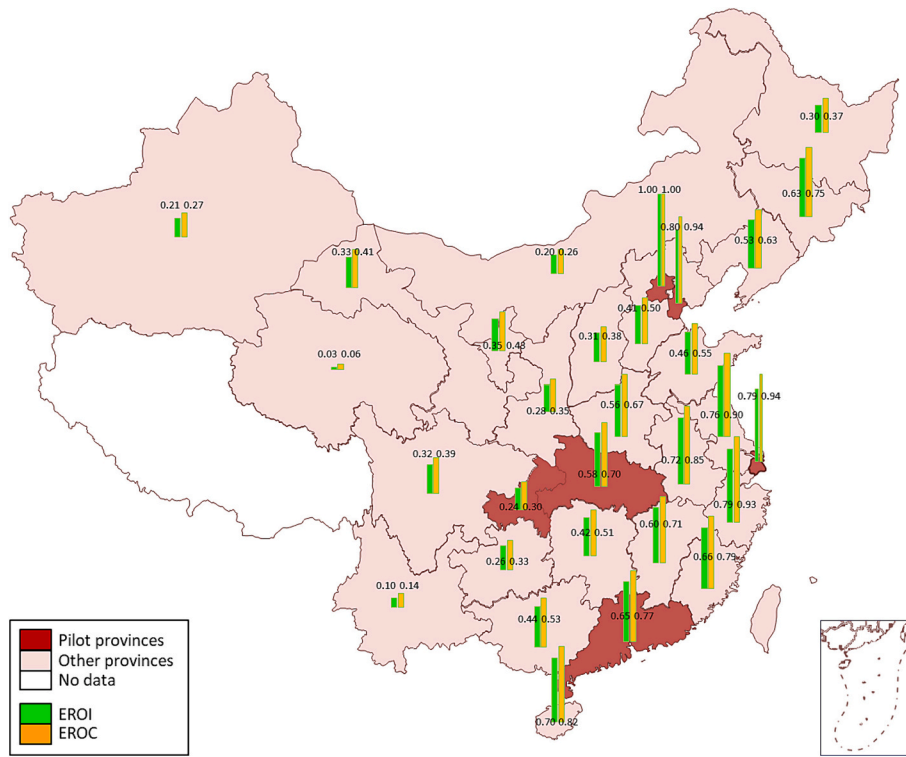


Fig. 2. Average EROI and EROC in 2011–2020 for 30 provinces.

and material conversion factors collected by Yin et al. (2017), they are converted to standard coal and carbon emission equivalent. Thus, the energy consumption and carbon footprint in the rest stages can be estimated. Table 3 shows the system boundary and data source of evaluating EROI and EROC.

The energy consumption and carbon footprint in the fuel combustion depend on the coal consumption, and they depend on the electricity consumption for self-use in the operation stage. Both the coal and self-use electricity consumption data are provided by China Electric Power Yearbook. They are also converted to standard coal and carbon emission equivalent.

To measure the energy consumption and carbon footprint during the fuel transportation, we use data from China Railway Yearbook. In China, coal is mainly delivered by railway, using locomotives that are either

diesel or electric. This is captured by the following equation:

$$T_{it} = Coal_{it} \sum_{j=1}^2 p_{ij} e_{ij} k \quad (5)$$

Here  $i$ ,  $t$  and  $j$  denote provinces, years and types of locomotive respectively;  $T$  is the energy consumption or carbon footprint during the fuel transportation;  $Coal$  denotes the coal consumption in the power generation.  $p$  represents the proportion of the transportation of the  $j$ -th type of locomotive in the total transportation.  $e$  represents the energy consumption of the locomotive for delivering per unit of coal.  $k$  represents the conversion factor from certain energy to coal equivalent when calculating energy consumption, while it represents the carbon emission factor of certain energy when calculating the carbon footprint. The former factors are from China Energy Statistical Yearbook, and the latter

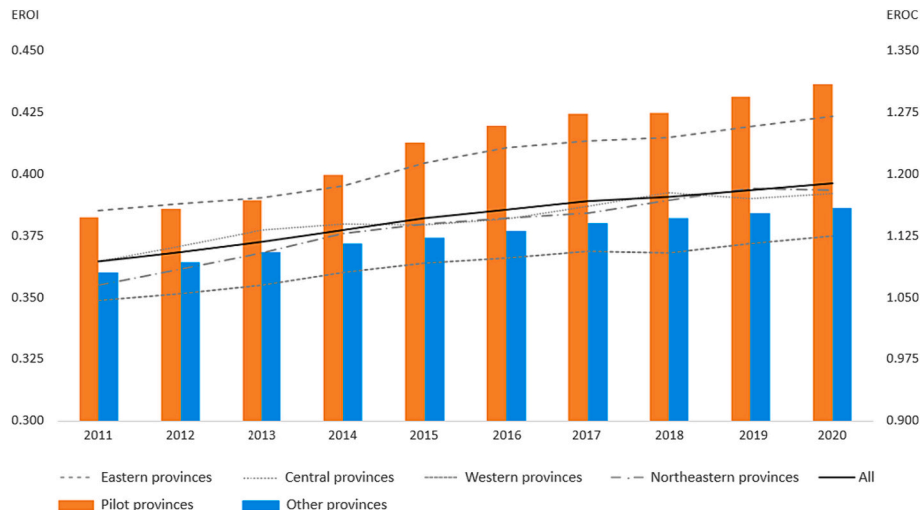


Fig. 3. Trend of EROI and EROC in different groups.

are calculated following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006):

$$C_i = NCV_i \cdot CC_i \cdot O_i \cdot \frac{M_{CO_2}}{M_C} \quad (6)$$

Here  $NCV_i$  represents the lower calorific value of the  $i$ -th fuel,  $CC_i$  represents its carbon content per unit calorific value,  $O_i$  represents its carbon oxidation rate during the combustion, and  $M_{CO_2}$  and  $M_C$  represent the molecular weight of  $CO_2$  and Carbon, respectively. The lower calorific value data is collected from the China's General Principles for Calculation of the Comprehensive Energy Consumption. The carbon content per unit calorific value and the carbon oxidation rate of each fuel are from the China's Guidelines for the Preparation of Provincial Greenhouse Gas Inventories.

After the calculation of the energy consumption and carbon footprint in all stages, the EROI and EROC can be derived in the following way:

$$EROI_{it} = \frac{P_{it}k}{\sum EC_{it}} \quad (7)$$

$$EROC_{it} = \frac{P_{it}}{\sum CE_{it}} \quad (8)$$

Here  $i$  and  $t$  denote the  $i$ -th province and the  $t$ -th year respectively;  $P$  represents the coal-fired power output;  $k$  is the conversion factor from electricity to standard coal equivalent;  $EC$  and  $CE$  represent the energy consumption (converted to standard coal equivalent) and carbon emission in each stage respectively.

To explore the spatial difference of coal-fired power efficiency, Fig. 2 shows the average EROI and EROC in 2011–2020 for both pilot provinces and others. The data is normalized to better display the differences across provinces. According to the national bureau of statistics, all provinces are divided into 4 groups by location, including eastern, central, western and northeastern provinces. We find that the pilot provinces are primarily located in the east and that the EROI and EROC are higher in eastern provinces. In China, these provinces enjoy geographic advantages and a relatively open business environment. Consequently, they tend to have more development opportunities and enjoy more prosperity than regions in central or western China. Such differences are also reflected in company performance regarding low-carbon transition (Wang et al., 2021b).

As shown in Fig. 3, a combination chart is made to show the trend of EROI and EROC. Five lines are plotted to represent the trend in the eastern, central, western, northeastern provinces, and all provinces. Overall, all lines have an upward trend, indicating the better environmental performance over time. The EROI increased by 0.038 in both eastern provinces and northeastern provinces during 2011–2020, which is beyond the average increase of 0.032. By contrast, it increased by 0.028 and 0.026 in central provinces and western provinces respectively, which is below average. Similarly, the increase of EROC in eastern provinces and northeastern provinces is also higher than the average level of 0.094, which is 0.113 and 0.115 respectively. The increase of EROC is by comparison lower in central provinces and western provinces, which is 0.082 and 0.078 respectively. Therefore, the eastern provinces have more successful performance regarding the low-carbon transition of coal-fired power compared to central and western provinces. The difference can be attributed to the side effect of low-carbon transition. Since environmental regulation have some negative influences on economy in the short run (Wang and Feng, 2014), less developed regions are unlikely to promote the transition at the price of economic development.

The columns in Fig. 3 show the growth of EROI and EROC in both pilot provinces and other provinces. It is obvious that there was a gap between pilot provinces and other provinces from the beginning, and it tended to enlarge in the given period. Specifically, the EROI has an average rise of 0.161 in pilot provinces during 2011–2020, which is more than twice of the rise of 0.077 in other provinces. Similarly, the

**Table 4**

Impact of CETS on coal-fired power industry.

| VARIABLES                           | EROI                  | EROC                 |
|-------------------------------------|-----------------------|----------------------|
|                                     | (1)                   | (2)                  |
| <i>TP</i>                           | 0.0191**<br>(0.00723) | 0.0567**<br>(0.0215) |
| <i>GDP per capita</i>               | −0.0323<br>(0.0257)   | −0.0960<br>(0.0767)  |
| <i>Population density</i>           | −1.281<br>(1.034)     | −3.815<br>(3.082)    |
| <i>Urbanization rate</i>            | −0.217<br>(0.190)     | −0.647<br>(0.565)    |
| <i>Industrial structure</i>         | 0.0489<br>(0.0710)    | 0.145<br>(0.212)     |
| <i>Coal mining industry status</i>  | −0.153<br>(0.136)     | −0.456<br>(0.406)    |
| <i>Electricity self-sufficiency</i> | 0.0147<br>(0.0196)    | 0.0437<br>(0.0583)   |
| <i>Constant</i>                     | 0.888***<br>(0.0985)  | 2.644***<br>(0.293)  |
| <i>Observations</i>                 | 300                   | 300                  |
| <i>Region FE</i>                    | YES                   | YES                  |
| <i>Year FE</i>                      | YES                   | YES                  |

Notes: robust standard errors in parentheses are clustered at the provincial level; \*\*\*, \*\* and \* represent the significance levels at 1%, 5% and 10%, respectively.

EROC increased by 0.054 in pilot provinces and only 0.026 in other provinces. To some extent, such results might imply that the CETS pilot scheme has a positive influence on the low-carbon transition of coal-fired power in pilot provinces. However, it still entails further verification in the following empirical analyses.

## 5. Empirical analyses

### 5.1. Benchmark regression results

In this section, the impacts of the CETS on EROI and EROC are estimated based on Eq. (1). The results in Table 4 show that the regression coefficients of *TP* in the EROI model ( $\beta = 0.019, p < 0.05$ ) and EROC model ( $\beta = 0.057, p < 0.05$ ) are both positive and have passed the significance test. This indicates the CETS has a positive effect on the low-carbon transition of coal-fired power in China. This means we can accept Hypothesis 1.

### 5.2. Parallel trend test and dynamic effect analysis

The most important prerequisite for the employment of DID model is to pass the parallel trend test (Marcus and Sant'Anna, 2020; Qiao and Li, 2018). This test requires that the treatment group and the control group have a consistent trend before the treatment. In other words, the EROI and EROC in pilot regions should have the same trend as non-pilot regions before the intervention from the CETS. This premise can support the comparability of the two groups and thus ensure the feasibility of our study. The parallel trend test for EROI and EROC is conducted respectively with the following estimation model:

$$Y_{it} = \alpha_0 + \sum_{j=1}^3 \alpha_{-j} D_{i,t-j} + \sum_{j=1}^6 \alpha_j D_{i,t+j} + \sum_{k=1}^6 \beta_k X_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (9)$$

Here  $i$  and  $t$  denote province and year respectively;  $D_{i,t-j}$  and  $D_{i,t+j}$  are dummy variables. If the year  $t$  is  $j$  years prior to the pilot year of the province  $i$ , then  $D_{i,t-j}$  will be set to 1; otherwise, it will be set to 0. If the year  $t$  is  $j$  years after the pilot year of the province  $i$ , then  $D_{i,t+j}$  will be set to 1; otherwise, it will be set to 0. The coefficient  $\alpha_{-j}$  and  $\alpha_j$  indicate the difference between the treatment group and the control group before and after the pilot policy respectively. If  $\alpha_{-j}$  is close to 0, then it implies the two groups have similar trends before the pilot scheme; otherwise, the sample cannot pass the parallel trend test.

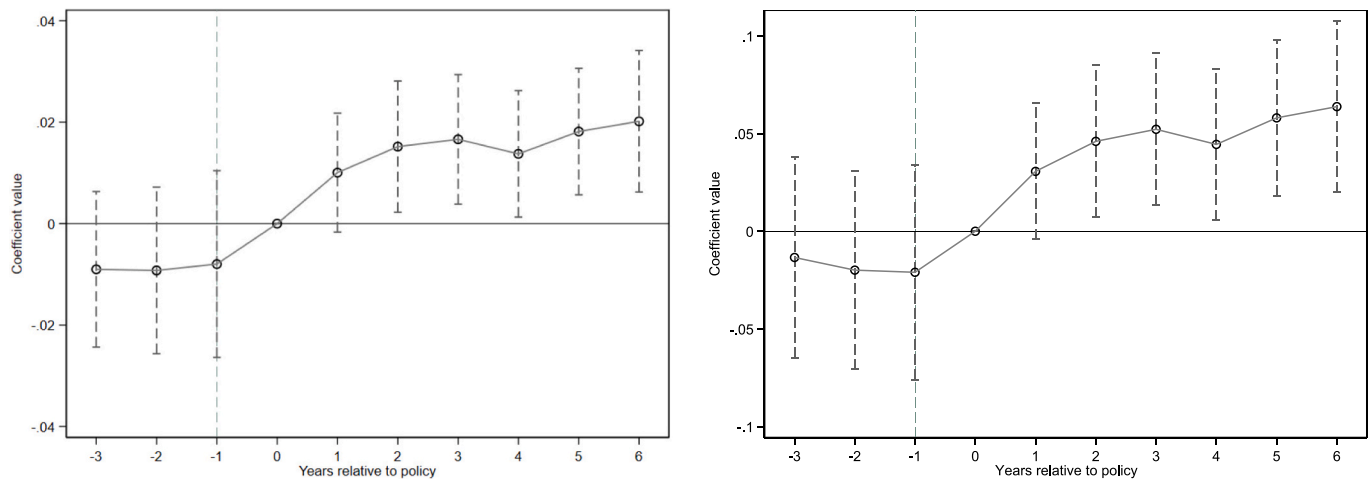


Fig. 4. Dynamic effect of CETS on EROI and EROC.

Table 5

Mediation effect of research and development level (RD).

| VARIABLES    | RD                | EROI                    | EROC                  |
|--------------|-------------------|-------------------------|-----------------------|
|              | (1)               | (2)                     | (3)                   |
| TP           | 0.112<br>(0.0993) | 0.0174**<br>(0.00722)   | 0.0518**<br>(0.0215)  |
| RD           |                   | −0.00827**<br>(0.00400) | −0.0246**<br>(0.0119) |
| Constant     | −5.600<br>(6.156) | 0.709***<br>(0.254)     | 2.111***<br>(0.756)   |
| Observations | 300               | 300                     | 300                   |
| Region FE    | YES               | YES                     | YES                   |
| Year FE      | YES               | YES                     | YES                   |
| Control      | YES               | YES                     | YES                   |

As shown in Fig. 4, the number 0 is used to represent the pilot year and we use corresponding numbers to represent certain years before and after the pilot scheme. The estimation results of  $\alpha_{-j}$  are shown in the figure and the confidence intervals cover the 0 level in both the EROI model (left) and EROC model (right), which indicates there is little difference between the two groups regarding the trend of EROI and EROC before the implementation of the CETS. Without the pilot scheme, this trend is likely to last for more years. Therefore, the parallel trend test is passed.

The benchmark regression results have shown the average effect of the CETS on EROI and EROC. By contrast, the  $\alpha_j$  in this section implies the annual effect and thus reveals the change of CETS impact on the coal-fired power industry over the 5 years. The policy effect was not significant for the first year after the pilot scheme though it was positive. However, it became significant and positive in the next 5 years and the coefficient size had an upward trend, which implied the increasing positive impact of the CETS over time.

The delayed effect is partly due to market processes. The initial weak emission allowance contributes to over-supply which suppresses permit trading activity. Additionally, similar to the EU-ETS price, CETS price fluctuated heavily during the initial stage. Most participating companies tended to adopt a wait-and-see attitude and purchased emission permits only just before the end of the annual commitment period, which led to a sluggish market. With the reduction of total allowances and the increase in transaction volume, the fluctuations of carbon price became milder, which improved the effectiveness of the CETS on the low-carbon transition of domestic coal power.

Table 6

Mediation effect of government intervention (GI).

| VARIABLES    | GI                    | EROI                   | EROC                  |
|--------------|-----------------------|------------------------|-----------------------|
|              | (1)                   | (2)                    | (3)                   |
| TP           | 5.84e-05<br>(0.00207) | 0.0165***<br>(0.00524) | 0.0490***<br>(0.0156) |
| GI           |                       | 0.222<br>(0.155)       | 0.660<br>(0.461)      |
| Constant     | −0.0263<br>(0.0730)   | 0.761***<br>(0.162)    | 2.266***<br>(0.481)   |
| Observations | 300                   | 300                    | 300                   |
| Region FE    | YES                   | YES                    | YES                   |
| Year FE      | YES                   | YES                    | YES                   |
| Control      | YES                   | YES                    | YES                   |

### 5.3. Mediation analysis

We verify the positive impact of China's ETS on the low-carbon transition of its domestic coal-fired power industry. In this section, we further investigate the influential mechanisms that correspond to examining hypotheses 2a, 2b, and 2c. Specifically, we determine whether transmission channels have been established through technological innovation, government intervention, and the reform of electricity generation.

#### 5.3.1. Hypothesis 2a: technological innovation

In this section, Research and development level (RD) is used to denote the strength of technological innovation. Its mediation effect on the impact of CETS on EROI and EROC is shown in Table 5. Column (1) and (2) show the mediation effect test of RD on EROI. Column (1) and (3) show the mediation effect test of RD on EROC. It can be found from Column (1) that the coefficient  $\alpha_1$  of the key explanatory variable TP is not significant, though  $\alpha_2$  of RD is significant at the 5% level in Column (2) and (3). In this instance, a Sobel test should be conducted to examine whether the mediation effect of RD exists or not. Based on the reports from the Sobel test, there is a lack of statistical significance which negates its role as a mediator. Therefore, Hypothesis 2a is rejected.

Technological advances are of critical importance for the improvement of the production and the transformation of the energy and the efficiency of its use (Streimikiene et al., 2012). Unfortunately, limited progress in coal-fired power technology has hindered significant improvements in low-carbon or decarbonization performance and reduced upgrade costs. For example, the carbon capture, utilization, and storage (CCUS) turns out to be effective but its high cost has hindered its application on a large scale (Xiao et al., 2022). It is estimated that the

**Table 7**  
Mediation effect of reform of coal-fired generation (CG).

| VARIABLES    | CG                 | EROI                  | EROC                 |
|--------------|--------------------|-----------------------|----------------------|
|              | (1)                | (2)                   | (3)                  |
| TP           | 0.215**<br>(0.104) | 0.0143**<br>(0.00694) | 0.0425**<br>(0.0207) |
| CG           |                    | 0.0102<br>(0.00656)   | 0.0304<br>(0.0195)   |
| Constant     | 3.732<br>(2.485)   | 0.717***<br>(0.255)   | 2.136***<br>(0.757)  |
| Observations | 300                | 300                   | 300                  |
| Region FE    | YES                | YES                   | YES                  |
| Year FE      | YES                | YES                   | YES                  |
| Control      | YES                | YES                   | YES                  |

**Table 8**  
Moderation effect of clean energy development (CE).

| VARIABLES    | EROI                  | EROC                 |
|--------------|-----------------------|----------------------|
|              | (1)                   | (2)                  |
| TP           | 0.0166**<br>(0.00725) | 0.0493**<br>(0.0216) |
| CE           | −0.0179<br>(0.0174)   | −0.0534<br>(0.0519)  |
| TP×CE        | −0.0208<br>(0.0316)   | −0.0620<br>(0.0943)  |
| Constant     | 0.779***<br>(0.270)   | 2.320***<br>(0.805)  |
| Observations | 300                   | 300                  |
| Region FE    | YES                   | YES                  |
| Year FE      | YES                   | YES                  |
| Control      | YES                   | YES                  |

large-scale investment of CCUS will not happen until 2035 (Guo and Huang, 2020). With a low return on investment currently, CETS pilot provinces have not promoted the development of related technologies.

#### 5.3.2. Hypothesis 2b: government intervention

In this section, we introduce the indicator of government intervention (GI) and test its mediation effect. This indicator captures environmental protection expenditures of local governments, which can be seen as complementary to CETS. The results are shown in Table 6. Column (1) and (2) show the mediation effect test of GI on EROI. Column (1) and (3) show the mediation effect test of GI on EROC. Both the  $\alpha_1$  in Column (1) and the  $\alpha_2$  in Column (2) and (3) are not significant, which indicates that GI fails to mediate the CETS impact on EROI and EROC. Therefore, Hypothesis 2b is rejected.

The CETS is carried out by setting up local carbon emission trading system in the pilot regions. Hypothetically, the local government will provide ongoing support for the low-carbon transition of coal-fired power plants through subsidies for facility upgrades and other means. However, this trial has shown that the government has not provided sufficient support or implemented complementary policies for the CETS, and thus has not gotten the best out of it.

#### 5.3.3. Hypothesis 2c: reform of electricity generation

In this section, we use the variable CG (coal-fired generation) to examine its mediation effect. The result is shown in Table 7. Column (1) and (2) show the mediation effect test of CG on EROI. Column (1) and (3) show the mediation effect test of CG on EROC. The  $\alpha_1$  in Column (1) is significant at the 5% level, indicating that the CETS has caused a decline of coal-fired generation in pilot provinces. However, the  $\alpha_2$  is not significant in Column (2) and (3), so we conduct a Sobel test to examine it again. The Sobel test shows a 5% significance and thus supports the mediation effect of CG. Therefore, the CETS has contributed to the shift of generation opportunities and then improve the EROI and EROC in pilot provinces. Because the  $\alpha_1$  is still significant in Column (2) and (3),

**Table 9**  
Moderation effect of research and development level (RD).

| VARIABLES    | EROI                    | EROC                   |
|--------------|-------------------------|------------------------|
|              | (1)                     | (2)                    |
| TP           | −0.0234<br>(0.0198)     | −0.0698<br>(0.0589)    |
| RD           | −0.0135***<br>(0.00440) | −0.0403***<br>(0.0131) |
| TP×RD        | 0.0145**<br>(0.00584)   | 0.0432**<br>(0.0174)   |
| Constant     | 0.678***<br>(0.239)     | 2.021***<br>(0.711)    |
| Observations | 300                     | 300                    |
| Region FE    | YES                     | YES                    |
| Year FE      | YES                     | YES                    |
| Control      | YES                     | YES                    |

this is a partial mediation effect. Hypothesis 2c is verified.

### 5.4. Moderation analysis

In this section, we utilize the moderator model to test Hypothesis 3. Additionally, we continue to explore the possible roles of technological innovation and government intervention in the low-carbon transition of China's coal-fired power industry. The above analysis has rejected their positive mediation effect. Hypothetically, however, they may still be conducive to the effect of CETS somehow. With the moderator model, we can test whether they have a moderation effect on the impact of CETS.

#### 5.4.1. Hypothesis 3: clean energy development

In this section, the proportion of clean power production in total energy production is used as the indicator of clean energy development (CE). Column (1) and (2) in Table 8 are the results of CE moderating the impact of CETS on EROI and EROC, respectively. The focus coefficient of the interaction term of TP and CE is not significant in both the EROI model and the EROC model. Therefore, no matter in regions with a high or low level of clean energy development, the CETS can always have a positive impact on the low-carbon transition of coal-fired power. This rejects the possible moderation effect of clean energy development, as stated in Hypothesis 3.

Due to the fluctuating output of renewable energy, the position of coal power to ensure the security of national electricity supply is still irreplaceable. As a result, the low-carbon transition of coal power is not in conflict with the development of renewable power at this stage, which is demonstrated by the insignificant moderation effect of CE.

#### 5.4.2. Technological innovation

In this section, research and development level (RD) is used as the indicator of technological innovation. Table 9 shows the moderation

**Table 10**  
Moderation effect of government intervention (GI).

| VARIABLES    | EROI                   | EROC                  |
|--------------|------------------------|-----------------------|
|              | (1)                    | (2)                   |
| TP           | 0.0158***<br>(0.00494) | 0.0470***<br>(0.0147) |
| GI           | −0.164<br>(0.200)      | −0.490<br>(0.594)     |
| TP×GI        | 0.981**<br>(0.406)     | 2.922**<br>(1.209)    |
| Constant     | 0.734**<br>(0.274)     | 2.185**<br>(0.814)    |
| Observations | 300                    | 300                   |
| Region FE    | YES                    | YES                   |
| Year FE      | YES                    | YES                   |
| Control      | YES                    | YES                   |

**Table 11**

Test of propensity score matches.

| Variable                     | Mean treated | Mean control | t     | P > t |
|------------------------------|--------------|--------------|-------|-------|
| GDP per capita               | 1.688        | 1.725        | −0.36 | 0.718 |
| Population density           | 0.034        | 0.036        | −0.48 | 0.633 |
| Urbanization rate            | 0.601        | 0.622        | −1.14 | 0.263 |
| Industrial structure         | 0.438        | 0.415        | 1.04  | 0.304 |
| Coal mining industry status  | 0.014        | 0.014        | 0.06  | 0.949 |
| Electricity self-sufficiency | 1.076        | 0.943        | 1.59  | 0.119 |

analysis of *RD*. Column (1) and (2) are the results for EROI and EROC, respectively. The focal coefficient of the interaction term of *TP* and *RD* is positive and significant at the 5% level in both the EROI model and the EROC model. This indicates *RD* has positively moderated the impact of CETS on coal-fired power, i.e., CETS has better performance in provinces with higher technological innovation level. Therefore, technological innovation has ensured a more effective implementation of CETS.

A possible explanation is that coal-fired power industry in high-*RD* regions has easier access to more affordable and better performing technologies that can help improve energy efficiency and alleviate carbon emissions. After the adoption of CETS, they are more likely to introduce these technologies than those in low-*RD* regions.

#### 5.4.3. Government intervention

In this section, *GI* is used to denote government intervention. Column (1) and (2) in Table 10 are the results of *GI* moderating the CETS effect on EROI and EROC respectively. The focal coefficient of the interaction term of *TP* and *GI* is positive and significant at the 5% level in both the EROI model and the EROC model. This indicates *GI* has positively moderated the impact of CETS on coal-fired power. Therefore, government intervention has ensured a more effective implementation of CETS.

Government intervention is important for the government to improve both the economic and environmental performance of enterprises (Fronzel et al., 2007; Wang et al., 2016). On one hand, coal-fired power plants and other related enterprises in high-*GI* regions will face penalties for breaching regulations. Moreover, the government there provides ample support to organizations attempting to reduce pollution, including financial and administrative assistance. On this basis, the effectiveness of environmental policy (CETS in this case) will be enhanced when participating enterprises believe the investment in carbon reduction and environmental production can be sufficiently compensated (Korhonen et al., 2015).

## 6. Robustness checks

### 6.1. PSM-DID model

The selection of pilot regions is usually dependent on various factors, which might give rise to self-selection bias. To address this concern, we adopt a difference-in-differences method combined with propensity score matching (PSM-DID) to reassess the effect of the CETS on EROI and EROC. The basic idea of PSM-DID is to find the best control group for the experimental group based on the observable characteristic variables, so that the paired experimental group and the control group are as close as possible. Based on this idea, the differences in a series of characteristics across provinces are evaluated and the pilot provinces are matched with those similar to them. The change of EROI and EROC in pilot provinces is compared only with their matched counterparts. Thus, the quasi natural experiment of the pilot scheme can be considered random and a more accurate result is expected. Specifically, we conduct a caliper 1:3 matching with the probit regression. On this basis, a balancing test that reveals the difference between the treatment group and new control group in the selected attributes is operated. As shown in Table 11, all the *t*-test results after matching are insignificant. This indicates there is no systematic difference between the treatment group and the matched

**Table 12**

PSM-DID estimation based on the matched sample.

| VARIABLES                    | EROI                 | EROC                 |
|------------------------------|----------------------|----------------------|
|                              | (1)                  | (2)                  |
| <i>TP</i>                    | 0.013**<br>(0.005)   | 0.040**<br>(0.014)   |
| GDP per capita               | −0.060**<br>(0.024)  | −0.177**<br>(0.073)  |
| Population density           | 3.034*<br>(1.541)    | 9.035*<br>(4.582)    |
| Urbanization rate            | −0.170<br>(0.205)    | −0.507<br>(0.610)    |
| Industrial structure         | 0.021<br>(0.113)     | 0.063<br>(0.335)     |
| Coal mining industry status  | −1.566***<br>(0.296) | −4.665***<br>(0.880) |
| Electricity self-sufficiency | −0.029<br>(0.030)    | −0.087<br>(0.090)    |
| Constant                     | 0.481***<br>(0.101)  | 1.432***<br>(0.301)  |
| Observations                 | 57                   | 57                   |
| Region FE                    | YES                  | YES                  |
| Year FE                      | YES                  | YES                  |

**Table 13**

Estimation results of placebo test I.

| VARIABLES                    | EROI                | EROC                |
|------------------------------|---------------------|---------------------|
|                              | (1)                 | (2)                 |
| <i>TPpseudo</i>              | 0.006<br>(0.004)    | 0.017<br>(0.011)    |
| GDP per capita               | 0.051<br>(0.071)    | 0.150<br>(0.212)    |
| Population density           | −1.926**<br>(0.849) | −5.735**<br>(2.525) |
| Urbanization rate            | −0.100<br>(0.183)   | −0.296<br>(0.544)   |
| Industrial structure         | −0.298**<br>(0.125) | −0.888**<br>(0.372) |
| Coal mining industry status  | 0.041<br>(0.165)    | 0.122<br>(0.491)    |
| Electricity self-sufficiency | −0.007<br>(0.017)   | −0.021<br>(0.050)   |
| Constant                     | 0.725***<br>(0.209) | 2.156***<br>(0.623) |
| Observations                 | 90                  | 90                  |
| Region FE                    | YES                 | YES                 |
| Year FE                      | YES                 | YES                 |

control group.

Based on the same estimation method as Eq. (1) and a selected sample, the results of the PSM-DID are shown in Table 12. The coefficients are similar to the previous results in Table 4, and they all pass the significance level test of 5%. Therefore, the new estimation results support the initial estimation in the benchmark regression that the CETS has a positive impact on the EROI and EROC of coal-fired power capacity.

### 6.2. Placebo test I: pseudo assignment of pilot time

Another concern with our estimation is that the increase in EROI and EROC of the treatment group may not be attributed to the pilot scheme but simply a time trend triggered by technological innovation. To mitigate this concern, this study further adopts a placebo test where a counterfactual experiment is conducted. Specifically, we use the pre-policy period data (2011–2013) and reset the policy adoption year to 2012. Correspondingly, the previous variable *TP* is replaced with *TPpseudo*, which is set to 1 if the region *i* is a pilot region and the year *t* is after 2012, and set to 0 otherwise. If our estimation simply results from a time trend, then a similar result to the initial estimation will be

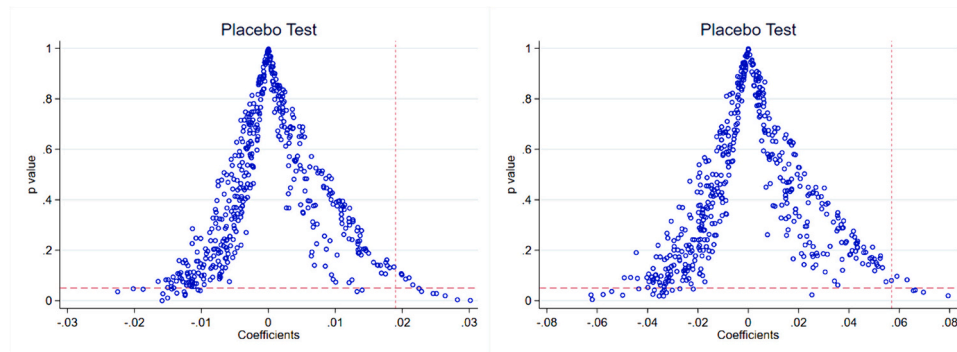


Fig. 5. Placebo test II results repeating 500 times.

observed. As shown in Table 13, the coefficients of  $TPpseudo$  for both EROI and EROC are insignificant. This implies that there is no such a time trend as mentioned above and our initial estimation is still robust.

### 6.3. Placebo test II: pseudo selection of pilot regions

Except for the pseudo setting of pilot time, another placebo test is conducted where the pilot regions are selected randomly 500 or more times. If the size and significance of the new coefficients are frequently similar to our initial estimation results, then the previous estimation might not be robust. Specifically, we randomly draw 6 provinces out of the total of 30 and reset them as the treatment group. Thus, the effects of the CETS on EROI and EROC are re-estimated and the size and significance of the new coefficients are recorded. We repeat such a process for 500 times and plot the results for EROI and EROC respectively in Fig. 5. The distribution centers are at 0 and our true estimates (0.019 for EROI and 0.057 for EROC) are well beyond them. Also, most of the estimation results do not reach the original 5% significance and the coefficients are less than the true estimates. This implies that our initial analysis is not random and the CETS has a credible positive influence on EROI and EROC.

## 7. Conclusions and policy implications

Research on the effectiveness of carbon trading on the low-carbon transition of coal-fired power plants – the only participant of China's national CETS at present – can provide insight into how best to frame the inclusion of additional carbon-intensive industries in the future. To undertake a comprehensive evaluation, the indicators of EROI and EROC were used as they capture generation efficiency and carbon intensity, respectively. On this basis, the DID model was applied to assess the impact of CETS on the low-carbon transition of coal-fired power in pilot provinces. In addition, we identified the key mechanisms and supporting factors of CETS. The main insights and conclusions are as follows.

Both EROI and EROC have improved nationwide in recent years. Compared with other regions, coal-fired power in eastern regions has better progressed in terms of EROI and EROC, which may be due to steeper increases in economic prosperity. To identify the effect of the CETS on this process, a DID analysis was conducted with results showing that the implementation of CETS improved the generation efficiency and reduced the carbon intensity of coal-fired power in the pilot regions, which was confirmed by the robust tests. We further find that the above influences had a time lag: the policy effect was not significant in the first year due to the immaturity of the market mechanism, but became significant and reinforced later. In term of mechanisms studied, the CETS influence the EROI and EROC of the coal-fired power plant through a supply-side reform which reallocated the generation opportunity from the backward units to the efficient ones. In contrast, it was observed that the impact of technological innovation and government intervention on

this process was not significant. Nevertheless, the CETS did perform better in pilot provinces with a higher level of technological innovation and government intervention. This indicated that these two factors have supported the effectiveness of CETS.

Based on the above conclusions, we provide some suggestions for relevant government departments and enterprises to modify the CETS for potential future integration to the global market. Though the benefits of the carbon trading for coal-fired power have been verified in this study, China's ETS still needs to be refined. Currently, the turnover rate of the national CETS is <5%, which is closely related to the weak emission cap. In addition, the decisions on low-carbon investments are largely determined by expectations about the future cost of carbon. Therefore, a flexible and contractionary allocation plan of emission allowances which can maintain the steadily increase of carbon price is needed. In this context, companies would be compelled to carefully consider their emission patterns and make more conscious decisions on upgrading technology. Additionally, more carbon-intensive sectors should be included into the CETS. With such measures, the imbalance between supply and demand will be overcome, in turn driving the carbon price up in the long run with needed emissions reduction as the final outcome.

In addition, it would be useful to innovate and adopt relevant technologies of energy conservation and emission reduction for application in the coal-fired power industry. According to the results, the CETS did not stimulate technological innovation so far, and possibly compensatory policies and financial support are needed for this. As a result, abatement is expensive and power enterprises preferred not to apply relevant technologies. Therefore, the government would do well to redirect the incentive system for innovative institutions and enterprises towards a low-carbon transition. Specifically, enterprises that actively adopt energy-saving and emission-reduction technologies might be supported by tax exemptions, subsidies, or preferential credit. Apart from the domestic technical development, it is also feasible to introduce advanced technology from abroad to accelerate needed technological upgrading. In the context of CETS, the carbon-intensive plants are less economically competitive compared to the low-carbon alternatives. Therefore, the reform of electricity marketization could serve as an auxiliary measure to reconfigure the thermal power sector by reallocating the generation opportunities from the carbon intensive plants to those conducting the low-carbon upgrading, and thus encourage the development of the low-carbon technologies indirectly.

### CRediT authorship contribution statement

**Feng Liu:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology. **Jeroen van den Bergh:** Project administration, Resources. **Yihang Wei:** Software, Visualization.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.eneco.2024.107494>.

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