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ORIGINAL ARTICLE

How does coal consumption constraint policy affect electrical energy efficiency? Evidence from 30 Chinese provinces

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Abstract In recent years, energy efficiency has been considered an extremely cost-effective way to reduce greenhouse gas emissions. China is a country with the world's largest coal consumption and heavy reliance on thermal power generation. Therefore, the relationship between the coal consumption constraint policy (CCCP) in China and electrical energy efficiency is a topic worthy of study. Based on the panel data of 30 provinces in China during 2005–2016, this paper employs the difference-in-differences (DID) to examine the impact of CCCP on electrical energy efficiency in China. The results indicate that the implementation of the CCCP reduces electrical energy efficiency in the pilot provinces. Based on the mechanism tests, the cost effect outweighs the innovation effect, which is why CCCP decreases electrical energy efficiency. The results of the heterogeneity analysis show that the influence of CCCP is more significant in the provinces with weak law enforcement and small hydropower investment and northern provinces. This study suggests that the Chinese government can promote corporate technological innovation by improving the environmental compensation system and increasing environmental law enforcement to improve electrical energy efficiency. Meanwhile, renewable energy projects should be the focus of future investment.

Keywords Coal consumption constraint policy · Electrical energy efficiency · China · DID method

JEL Classification O13 · O18 · Q50

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Introduction

With the increasing frequency of human economic activity, global warming intensifies, and the global temperature is estimated to rise by 1.5 °C between 2030 and 2052 (Ipcc, 2018). Therefore, how to reduce greenhouse gas emissions has been a perennial topic of concern for scholars (Mills, 2011; Zhang and Fan, 2019; Talaei et al., 2020). Currently, global coal consumption is the main source of greenhouse gas emissions (Zeng et al., 2021). Dieter (2012) attributed the failure of the Kyoto Protocol to the neglect of the

Fig. 1 Coal consumption (up) and carbon dioxide emissions (bottom) in China and the world. Ref. (BP, 2021)

increase in global greenhouse gas emissions because of coal consumption. Steckel et al. (2015) considered that the growth of coal consumption in China, India, and other developing countries is the main reason for the increase in energy production's carbon intensity. As the world's second-largest economy, the increasing energy consumption and environmental pollution in China have raised widespread concerns about the sustainable development of its economic growth (Bi et al., 2014). Especially in terms of its coal consumption, it has become a dominant topic in climate change mitigation (Korsbakken et al., 2016; Tang et al., 2018; Zhang, Bai, et al., 2018; Zhang, Liu, et al., 2018). According to the BP Statistical Review of World Energy 2021, China is currently the largest coal energy consumer and the largest emitter of carbon dioxide (see Fig. 1). From 2011 to 2020, China's total coal consumption accounts for approximately 50% of the world's total coal consumption (see the upper part of Fig. 1). In addition, China's total CO_2 emission is also a quarter of the world's total CO_2 emission (see the bottom part of Fig. 1). Due to many advantages such as large reserves and low prices, coal has been dominant in China's energy consumption, which far exceeds the average of 20% in developed countries (Guo et al., 2018). However, while supporting the rapid development of China's economy and society, it can also bring severe environmental problems (Hao et al., 2015). Under this background, the coal consumption constraint policy (CCCP) was proposed by the Chinese government in 2011 in order to reduce the consumption of coal and protect the environment.

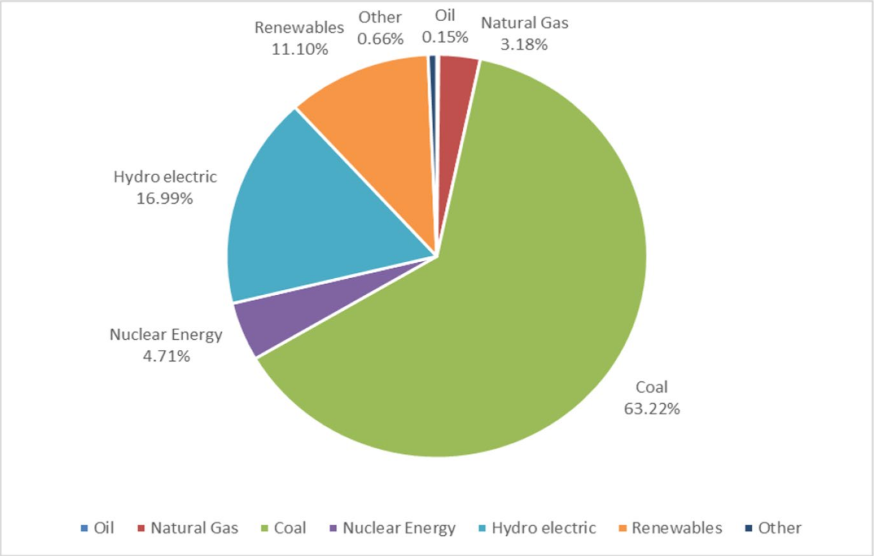

Fig. 2 Fuel sources for electricity generation in China in 2020. Ref. (BP, 2021)

Previous studies have investigated various topics related to the CCCP, which mainly focused on two aspects. One is to explore the relationship between CCCP and economic growth (Bloch et al., 2012; Xu et al., 2018; Chai et al., 2019). The other is to predict the peak of coal consumption and future coal demand under the Chinese control plan (Hu et al., 2014; Li, Liang, et al., 2015; Li, Lin, et al., 2015; Zhang, Bai, et al., 2018; Zhang, Liu, et al., 2018). However, there are few studies in the literature considering the relationship between CCCP and electricity. To improve environmental quality and change energy structure, China has implemented a strategy of "electricity energy substitution"[1] to achieve sustainable development. It cannot be ignored that, as a country that relies heavily on thermal power generation, coal accounts for 63.22% of all power generation fuels in China (see Fig. 2). Consequently, China's coal power generation will inevitably release large amounts of greenhouse gases (Bi et al., 2014).

Additionally, the electricity consumption in China has now entered a "new normal" stage. During this stage, the electricity consumption shifts from high-speed growth to low-speed growth. The improvement of electrical energy efficiency has become the development focus and an important guarantee to drive green development in China's electric power industry. It can directly reduce coal consumption and pollutant emissions (Guang, 2020) and meet the objective of China's energy development strategy to promote energy efficiency (Lin & Zhu, 2020). In light of this, it is important to study the relationship between CCCP and China's electrical energy efficiency.

This study aims to examine the impact of CCCP on electrical energy efficiency in 30 provinces of China and investigate the mechanisms of its impact. Considering that the CCCP aims to reduce coal consumption by replacing coal with clean and efficient energies (Guo et al., 2020). Therefore, renewable energy projects such as water, wind, and solar will target a new investment round. In this case, this study will further explore the impact of CCCP on electrical energy efficiency at different levels of renewable energy investment. Finally, we give practical policy recommendations to provide direction for the improvement of CCCP and the development of each province under this constraint.

Specifically, this paper adopts the DID model to examine the overall impact of CCCP on electrical energy efficiency in the CCCP-covered provinces. Then, we discuss the impact of law enforcement, hydropower investment, and region heterogeneity and use the mediating effects model to explore the economic channel through CCCP on electrical energy

[1] Replacing coal by electricity and replacing oil by electricity are the new ideas advocated in the strategy of "electrical energy substitution.".

Table 1 Current study of the impact of CCCP on the field of electricity

Authors	Findings
Fu and Wu (2018)	Under the background of the CCCP, the power transmission scale will still increase, whereas the ratio between coal and electricity transmission will display a downward trend
Ji et al. (2018)	The CCCP will stimulate renewable energy generation, especially in wind power
Chen and Chen (2019)	The natural gas and electricity consumption would be increased by implementing CCCP, contributing 15% and 4% to national SO2 and NOx emission control targets
Guo et al. (2020)	The CCCP has a positive impact on the share of electricity consumption in total energy consumption. The proportion will be increased by 4.898%

efficiency in the CCCP-covered provinces. Our evidence shows that, first, the CCCP has a negative impact on electrical energy efficiency. Second, the innovation effect cannot wholly offset the adverse effects caused by cost effects after the implementation of the CCCP, which leads to a decrease in electrical energy efficiency. Finally, provinces with weak law enforcement and small hydropower investment and northern provinces in China are vulnerable to the adverse effects of CCCP.

The main contributions of this paper include the following three aspects: firstly, in recent years, the CCCP's impact (Bloch et al., 2012; Chai et al., 2019; Zhang, Bai, et al., 2018; Zhang, Liu, et al., 2018) and electrical energy efficiency (Çankaya & Pekey, 2020; Guang, 2020; Wang & Brown, 2014; Zurn et al., 2017) have been studied separately by many scholars. However, the causal relationship between CCCP and electrical energy efficiency has not been examined. Hence, this study regards the CCCP's introduction as a quasi-natural experiment and employs the DID model to address the endogenous problem. Secondly, for research in the field of electricity, the impact of CCCP on electricity consumption, renewable energy generation, and the pattern of power transmission has been explored in previous literature (see Table 1). This paper focuses on electrical energy efficiency and examines the impact of CCCP on electrical energy efficiency, which expands existing research and provides new evidence on CCCP. Finally, this paper further illustrates the impact mechanism of CCCP on electrical energy efficiency from the perspective of the super-position of cost effect and innovation effect, which makes up for the gap between the CCCP and energy efficiency in the field of mechanism research.

The rest of this paper is organized as follows. "CCCP and its influence on electrical energy efficiency in theory" provides a brief overview of China's coal consumption constraint policy and its theoretical effects on electrical energy efficiency. "Data and methodology" introduces the data and methodology. "Empirical results" shows the empirical results and offers robustness checks. "Further discussion" explores the mechanism and conducts a heterogeneity analysis. "Conclusion and policy implications" provides the main findings and policy implications.

CCCP and its influence on electrical energy efficiency in theory

Coal consumption constraint policy in China

Coal consumption constraint policy (CCCP) consists of a series of specific policies, aiming to promote its industrial restructuring, change the way of economic development, and improve environmental quality at source. In 2011, the "Twelfth Five-year Plan for Energy Conservation and Emission Reduction" defined a group of CCCP pilot areas, including the Jing-Jin-ji Region (Beijing, Tianjin, and Hebei), Yangtze River Delta (Shanghai, Zhejiang, and Jiangsu), and Pearl River Delta (Guangdong). Until 2013, the macro-policy requirements on CCCP were basically established. However, no specific technical programs or measures were put in place. From 2014 to 2016, the government issued specific measures, and the coal equivalent substitution was included in the environmental impact assessment. Coal consumption management in China entered the phase of "coal equivalent substitution." During this phase, the thermal power sector becomes the main target of treatment. The replacement of coal comes mainly from implementing centralized heating, energy-saving technology for coal-consuming equipment and the use of clean energy, etc. After 2016, coal consumption management in China shifted from "coal equivalent substitution" to "coal reduction substitution." Liaoning province, Shandong province, and Henan province were added to the CCCP pilot areas. The focus of this phase extends from the thermal power sector to non-electricity sectors such as the iron and steel sector, cement sector, and plate glass sector. In addition, this phase further promotes the implementation of "coal to electricity" and "coal to gas" and gradually reduces the direct burning of coal and the use of coking coal.

Theoretical effect of CCCP on electrical energy efficiency

The coal consumption constraint policy belongs to the category of environmental regulation. At present, two competing academic perspectives regarding the impact of environmental regulation on energy efficiency are prevailing. The first academic perspective is based on the Porter hypothesis (Porter 1991). The prominent argument of this view is that environmental regulation has incentives to induce technological innovation in the regulated firms, generating a compensatory effect of innovation and improving energy efficiency (Berman & Bui, 2001; Bi et al., 2014; Telle & Larsson, 2007). Specifically, reasonable environment regulation can change the impact of price effect and market scale effect on energy factors, which shifts the preference of technological innovation (Acemoglu et al., 2014). There are opportunity costs[2] associated with the use of energy factors in the context of environmental regulation. If the opportunity cost is more significant than zero, the relative price of energy factors will increase, promoting technological innovation in favor of energy conservation.

Additionally, the implementation of environmental regulation leads to external constraints on the energy use of market subjects and inhibits their impulse investment and blind expansion of scale. This will weaken the impact of the market scale effect on energy use and thus discourages technological innovation in favor of energy use. As an external constraint, CCCP can raise coal prices and accelerate the closing or reconstruction of small power plants, facilitating efficient technologies (Li, Liang, et al., 2015; Li, Lin, et al., 2015; Yu et al., 2011). The continuous innovation of key technologies can be used at each value chain stage (generation, transmission, distribution, and end-use) to improve electrical energy efficiency (ASSAf 2018) gradually. Furthermore, Abdallah and El-Shennawy (2019) also emphasized that energy-saving technology innovation is particularly crucial in the process of improving electrical energy efficiency through the design of new projects and the revamp of old pieces of equipment. Hence, this study proposes the first hypothesis:

Hypothesis 1a: The coal consumption constraint policy will improve the energy efficiency of the electric power industry.

The other academic perspective is based on the "Following Costs" hypothesis. The prominent argument of this view is that environmental regulations such as environmental taxes and emission standards increase companies' operating costs and inhibit the improvement of energy efficiency (Jaffe & Palmer, 1997; Gray & Shadbegian 2003; Dirckinck-Holmfeld, 2015). Technological innovation requires a significant investment of innovation resources. Only when the expected benefits of innovation exceed its costs will market subjects engage in technological innovation (Parry et al., 2003). As a kind of green technology innovation, the "double externalities"[3] of technological knowledge and environmental benefits of energy-saving technology innovation mean that market subjects cannot obtain the full benefits of technological innovation (Rennings, 2000). Suppose command-and-control environmental regulation imposes less stringent constraints on pollution emissions. In that case, market subjects tend to increase their investment in pollution control to obtain a higher rate of return in the short term. Some of the funding for pollution control may come from investment

[2] The opportunity costs include environmental tax, loss of access to subsidies for energy conservation and emission reduction and payment of fines for excessive discharge, etc.

[3] One is that the knowledge generated by green technology innovation has a spillover (positive externality), where some or all of the new knowledge become public knowledge; the second is that the environmental benefits of green technology innovation have positive externalities, and the benefits of improving the ecological environment are more public than private.

in energy-saving technology innovation, which reduces the level of investment and expectation of technological innovation due to the crowding-out effect (Gollop & Roberts, 1983; Gray, 1987). In this case, the benefits of technological innovation cannot make up for the costs of pollution control, which will not contribute to improvements in energy efficiency. CCCP is a kind of strict environmental regulation. It may encourage power generation companies to switch from coal consumption to natural gas consumption (Wang et al., 2020). However, due to the higher energy substitution costs, Chinese companies tend to follow the pollution mode of "pollution first and treatment later" and use its environmental investment to treat pollution (Yuan & Geng, 2010). In the face of the increasing electricity demand, high economic and environmental governance costs will not be conducive to improving electrical energy efficiency (Reyna & Chester, 2017). Motivated by the observations and argument above, we propose the second hypothesis:

Hypothesis 1b: The coal consumption constraint policy will reduce the energy efficiency of the electric power industry.

Data and methodology

Data descriptions

The CCCP was launched in 2011. To examine the impact of CCCP on electrical energy efficiency, this paper uses panel data of 30 provinces[4] across the country from 2005 to 2016 as the research sample. Firstly, the data used to calculate the electrical energy efficiency is collected from the China electric power yearbook. Secondly, the data of other variables are collected from the China statistical yearbook and provincial statistical yearbooks, China's environmental yearbook, China statistical yearbook on the environment, Almanac of China's water power, and Chinese research data services platform (CNRDS).

Table 2 shows the definition and calculation of all variables concerned. For selecting control variables, Guang (2020) showed that the effect of industrial structure and the level of foreign trade on electrical energy efficiency are positive. In contrast, the effect of urbanization rate is negative. Wang and Yan (2010) found that the degree of economic development positively impacts electrical energy efficiency. Hence, these factors are introduced into the baseline model as control variables. In addition, the proportion of mining workers and environmental pollution control investment are strongly associated with electrical energy intensity (Guo et al., 2020). Changes in these two factors inevitably impact the willingness of the electric power industry to innovate, which further affects electrical energy efficiency. Based on this, we selected these two factors as control variables as well. Table 3 presents the descriptive statistics of variables. To exclude extreme outliers, this study winsorizes the continuous variables at the 1 and 99 percentiles.

Regarding calculating electrical energy efficiency, this paper selects input and output indicators based on Wang and Zhu's (2015) research. The five input indicators are described as follows: (1) installed capacity: an important indicator of the investment scale of the power generation industry and directly related to the level of power production capacity; (2) coal consumption: an important variable input cost to maintain the operation of the electric power industry; (3) hours of the utilization of power generation equipment: an indicator of the degree of utilization of the power generation equipment in the electric power industry; (4) electricity consumption rate of power plants: the ratio of electricity consumption to electricity generation in the power generation industry; (5) industrial SO_2 emissions: the undesired output is regarded as production input in this paper. The output indicator in this paper is power generation, which indicates the output realization ability of the electric power industry.

Methodology

Super-efficiency SBM-DEA model

DEA model is a scientific method for non-parametric efficiency analysis from the perspective of relative comparison of evaluated objects, which can realize the evaluation of multiple inputs and multiple outputs (Charnes et al., 1978). Standard DEA models are divided into the following two categories: one is the

[4] Due to missing data, the data source in this paper does not include Hong Kong, Macao, Taiwan, and Tibet.

Table 2 Variables and data description

	Definition	Variable	Calculation method	Source
Explained variable	Electrical energy efficiency	EEE	Super-efficiency SBM-DEA model	China electric power yearbook
Explanatory variable	Whether it is a CCCP pilot	du	It is equal to 1 if it is CCCP pilot province, and 0 otherwise	
	Whether CCCP has been implemented	dt	It was equal to 1 in 2011–2016 and 0 in 2005–2010	
Control variable	Industrial structure	IS	The proportion of secondary industry in regional GDP (%)	China statistical yearbook and provincial statistical yearbooks
	The level of foreign trade	OPEN	The proportion of the total import and export in regional GDP (%)	China statistical yearbook and provincial statistical yearbooks
	The degree of economic development	ED	Gross regional domestic product is transformed by the application of the natural logarithm transformation	China statistical yearbook and provincial statistical yearbooks
	Urbanization rate	UR	The proportion of the urban population in total population (%)	China statistical yearbook and provincial statistical yearbooks
	Environmental pollution control investment	EGI	The value is transformed by the application of the natural logarithm transformation	China statistical yearbook on environment
	Mining workers	MK	The proportion of mining workers in total employment (%)	China statistical yearbook and provincial statistical yearbooks
Mediating variables	Green technology innovation	GTI	Number of Green Patents and then the value is transformed by the application of the natural logarithm transformation	Chinese research data services platform (CNRDS)

Source: authors' compilation

Table 3 Descriptive statistics

Variable	*N*	Mean	S. D	Min	Max
EEE	360	0.730	0.249	0.310	1.543
IS	360	45.191	8.154	17.300	62.000
OPEN	360	4.847	5.547	0.480	23.000
ED	360	9.221	0.980	6.213	11.316
UR	360	52.317	14.052	26.870	89.780
EGI	360	4.874	1.003	1.667	7.255
MK	360	1.125	1.011	0.002	5.585
GTI	360	6.390	1.581	0.693	9.717

Source: authors' calculation

CCR model based on constant returns to scale (CRS) and the other is the BCC model based on Variable Returns to Scale (VRS), both of which are radially oriented.[5] To overcome the shortcomings of the standard DEA model, Tone (2002) proposed the SE-SBM (super-efficiency slack-based measure) model. Compared to traditional DEA models, the super-efficient SBM-DEA model further ranks the simultaneously efficient DMUs (efficiency values can be greater than 1), thus facilitating comparative analysis. This paper follows Han and Liu's (2011) approach to calculating each province's electrical energy efficiency by using the undesired output as a production

[5] Radial DEA implies that inputs and outputs are scaled up or down in the same proportion. When there is non-zero slack (Slack) in inputs or outputs, radial DEA usually over-estimates the efficiency value of the DMU.

input. The super-efficient SBM-DEA model is represented as follows:

$$\min\rho_{SE} = 1 + \frac{1}{m}\sum_{i=1}^{m} s_i^-/x_{ik}$$
$$\text{s.t.} \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - s_i^-,, X_{ik} \tag{1}$$
$$\sum_{j=1,j\neq k}^{n} y_{rj}\lambda_j ... y_{rk}$$

where $\lambda, s^- ... 0$; i = 1, 2,..., m; r = 1, 2,..., q; j = 1, 2,..., n (j ≠ k)

The DID model specification

Based on the quasi-natural experiment that Chinese government launched CCCP pilot policy in Jing-Jin-ji Region (Beijing, Tianjin, and Hebei), Yangtze River Delta (Shanghai, Zhejiang, and Jiangsu), and Pearl River Delta (Guangdong) in 2011, this paper uses the DID model to construct a counterfactual to identify the impact of China's CCCP on energy efficiency in the electric power industry in the CCCP-covered provinces. During the implementation of CCCP, only the provinces in the treatment group are affected. We can then get the net impact of the CCCP on the electrical energy efficiency in the pilot provinces.

Specifically, this paper takes pilot provinces as the treatment group and non-pilot provinces as the control group. The sample period is divided into two stages: before the implementation of CCCP (2005–2010) and after implementing the policy (2011–2016). The difference in electrical energy efficiency between the treatment and control groups before and after the implementation of CCCP is the net impact of China's CCCP on energy efficiency in the electric power industry in the CCCP-covered provinces. The basic DID model is shown as follows:

$$EEE_{it} = \alpha_0 + \alpha_1(du_{it} \times dt_{it}) + \beta\, Controls_{it} + f_i + f_t + \varepsilon_{it} \tag{2}$$

where i and t denote provinces and years; du is a dummy variable for provinces (1 for the pilots of CCCP, and 0 for others); dt is a dummy variable for time taking the value 1 after CCCP was implemented in 2011 and 0 before that; the coefficient α_1 reflects the net impact of changes in the energy efficiency in the electric power industry in the pilot province before and after the launch of CCCP in China; *Controls* means control variables, including *IS*, *OPEN*, *ED*, *UR*, *EGI*, and *MK*; ε_{it} represents the error term; f_i and f_t indicate the province-fixed and year-fixed effects, respectively.

Dynamic regression model

In order to investigate the dynamic impact of the implementation of the CCCP, the overall sample interaction term of difference in Eq. (2) is replaced by six interaction terms of 2011–2016 annual dummy variables multiplied by Pilot, as shown in Eq. (3).

$$EEE_{it} = \beta_0 + \sum_{t=2011}^{2016} \beta_t T_t \times Pilot_i + \theta Controls_{it} + f_i + f_t + \varepsilon_{it} \tag{3}$$

Mechanism analysis and heterogeneity analysis

In order to further explore the impact mechanism and difference of China's CCCP on electrical energy efficiency in the CCCP-covered provinces, this paper employs the mediating effects model to explore the specific mechanism. It uses Eq. (2) to investigate further the heterogeneity of law enforcement, hydropower investment, and region with the method of grouping regression of sample data in the process of overall impact assessment.

Empirical results

Baseline results

Table 4 reports the results of the DID estimation of the impact of the CCCP on electrical energy efficiency. The first column presents the results of the fixed effects model without the inclusion of control variables. The second column shows the results of the fixed effects model with the inclusion of control variables. After controlling for province and time fixed effects, the results of both models indicate that the implementation of the CCCP reduces the electrical energy efficiency in the CCCP-covered provinces. Consequently, hypothesis 1b is verified. Only the degree of economic development and the proportion of mining workers are significant at the 5% significance level for control variables. The direction of the coefficient of the degree of economic development is

Table 4 Results of the DID model and the dynamic analysis

	Average treatment effect (FE) EEE	Average treatment effect (FE) EEE	Dynamic effect EEE
$du \times dt$	−0.1281* (−2.0085)	−0.1047* (−1.7792)	
$du \times T_{2011}$			−0.0612 (−0.7253)
$du \times T_{2012}$			−0.1450** (−2.1706)
$du \times T_{2013}$			−0.1121* (−1.7054)
$du \times T_{2014}$			−0.1347* (−1.9817)
$du \times T_{2015}$			−0.0941 (−1.3501)
$du \times T_{2016}$			−0.0663 (−0.7007)
Constant	0.7808*** (31.0519)	−3.1903* (−1.7352)	−3.1385* (−1.6994)
IS		0.0022 (0.4357)	0.0021 (0.4017)
OPEN		−0.0153 (−1.0424)	−0.0140 (−0.9772)
ED		0.4910** (2.1282)	0.4837** (2.0715)
UR		0.0019 (0.2339)	0.0020 (0.2357)
EGI		−0.0224 (−0.6699)	−0.0214 (−0.6084)
MK		−0.1671*** (−2.8888)	−0.1685*** (−2.8912)
Province-fixed effect	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes
N	360	360	360

Robust *t*-statistics are in parentheses, and *, **, and *** indicate the significance at the 10%, 5%, and 1% levels, respectively. $du \times T_{2011\text{-}2016}$ are six interaction terms of 2011–2016 annual dummy variables multiplied by Pilot. Source: authors' calculation

consistent with existing literature results (e.g., Wang & Yan, 2010). In addition, it is only logical that a higher rate of mining workers would lead to a reduction in electrical energy efficiency.

The dynamic regression model results

According to Eq. (3), this paper obtains the dynamic impact of the implementation of China's CCCP on electrical energy efficiency in the CCCP-covered provinces, and the results are shown in Table 4 (third column). The electric power construction in China is a rigid state monopoly demand. With the growth of China's economy and accelerated urbanization in recent years, the electricity demand has been growing steadily. Unless there is a major reform of the electricity market, it won't be easy to further improve electrical energy efficiency significantly in a short time (Feng et al., 2018). Therefore, the directions of the coefficients in Table 4 are all negative, which is consistent with reality. In addition, the coefficients of the interaction term become significant 1 year after the implementation of the policy and the effect of the policy is most pronounced in 2012. This negative impact lasted only 3 years (2012–2014). It can also be noted that the interaction term coefficients show the trend of the first decrease and then increase during these 3 years. The main reason for this is that the thermal power sector has become the main target for the second phase of the CCCP implementation. In conclusion, CCCP only has a short-term disincentive effect on energy efficiency in the electric power industry in the CCCP-covered provinces.

Robustness tests

The parallel trend test results

The important premise of using the DID model is that the treatment group and control group should meet the assumption of parallel trends (Beck et al., 2010). In our case, the energy efficiency in the electric power industry should maintain relatively stable trends before the implementation of the CCCP. Based on the parallel trend test conducted by Kudamatsu (2012) and Alder et al. (2016), this paper constructs six new annual dummy variables T_{2009}–T_{2014} and six interactive terms $(T_{2009}$–$T_{2014}) \times$Pilot. Subsequently, this

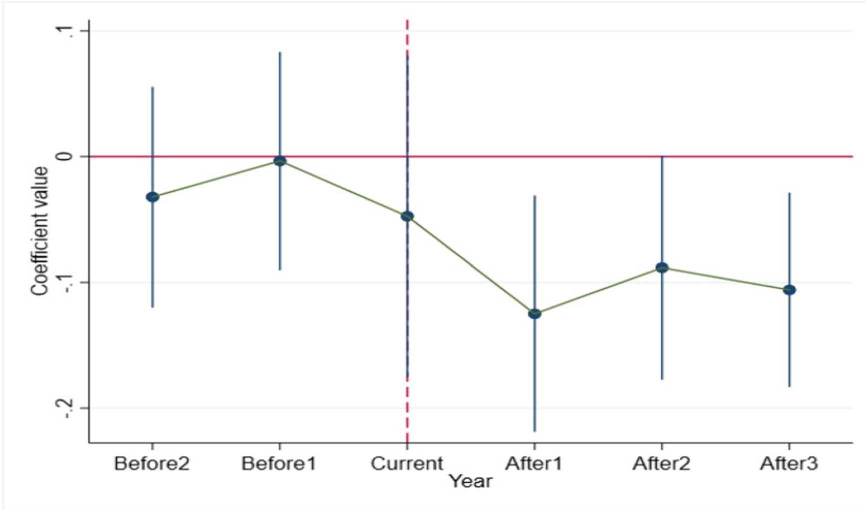

Fig. 3 The coefficient of T×Pilot from 2009 to 2014. Source: authors' calculation

paper uses Eq. (4) to test whether there are significant differences in the energy efficiency between the pilot and non-pilot provinces before the implementation of the CCCP.

$$EEE_{it} = \beta_0 + \sum_{t=2009}^{2014} \beta_t T_t \times Pilot_i + \theta Controls_{it} + f_i + f_t + \varepsilon_{it} \tag{4}$$

The results of the parallel trend test indicate that the coefficients of the first two interaction items T_{2009}×Pilot and T_{2010}×Pilot are not statistically significant.[6] This suggests that the changes in the energy efficiency of the electric power industry in the treatment and control groups tend to be consistent in the 3 years before the implementation of the CCCP in China, which conforms to the parallel trend hypothesis for the DID model. Therefore, the treatment group and control group can be compared in this paper. As reflected inFig. 3,[7] it can be found that the coefficients have an upward trend before the implementation of the CCCP, which may reach 0 and become insignificant. After the implementation of the CCCP, the coefficient becomes smaller despite some fluctuations. As a result, these results prove that the central research results above in this paper are relatively robust.

The PSM-DID model

The DID method is prone to selectivity bias. It cannot ensure that the treatment and control groups have the same individual characteristics before policy implementation. In this paper, the sample covers 30 provinces, and the geographical and economic differences between the samples are great, which presents the large individual differences. Therefore, there may be sample selection bias. To solve this problem, the PSM method is an effective way to handle this (Rosenbaum & Rubin, 1983).

This paper uses "1 to 1 nearest neighbor matching within caliper" method for matching propensity scores. Meanwhile, the balancing test is then conducted to check the matching results to ensure the

Table 5 Results of the balancing test

	Mean treated	Mean control	t	$P>t$
IS	47.939	49.732	−1.65	0.107
OPEN	5.1377	5.0364	0.12	0.905
ED	9.8343	9.7803	0.26	0.796
UR	55.227	53.01	0.63	0.530
EGI	5.5299	5.5366	−0.03	0.976
MK	1.4837	1.6994	−0.68	0.498

Source: authors' calculation

[6] The p-values of T_{2009}×Pilot and T_{2010}×Pilot are 0.726 and 0.766, respectively.

[7] Before1 and Before2 denote 2009 and 2010, respectively; current indicates the year (2011) in which the policy was implemented; After1, After2, and After3 denote 2012, 2013, and 2014 respectively.

Table 6 Robustness test results of the PSM-DID method and the placebo test

	PSM-DID	The placebo test		
	EEE	EEE (2009)	EEE (2010)	EEE (2012)
du × dt	−0.1218*** (−3.6018)	−0.1014 (−1.4122)	−0.0869 (−1.6061)	−0.1071* (−1.8348)
Constant	−13.1135*** (−5.7277)	−3.3914* (−1.8111)	−3.3378* (−1.8186)	−3.1734* (−1.7262)
Control	Yes	Yes	Yes	Yes
Province-fixed effect	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes
N	100	360	360	360

Robust *t*-statistics are in parentheses, and *, **, and *** indicate the significance at the 10%, 5%, and 1% levels, respectively. Source: authors' calculation

robustness of the propensity score matching (Zhao et al., 2020). According to Table 5, the results of all *t*-tests do not reject the original hypothesis of no systematic difference in the characteristics of the treatment and control provinces, presenting a good pairwise effect. Subsequently, the DID method was adopted to further address the research question, which can effectively reduce the bias of policy evaluation (Heckman et al., 1997). As is shown in Table 6, the coefficient of the interaction term in the second column is −0.1218, which is statistically significant at the 1% level. Consequently, this suggests that the baseline results obtained in this paper are still robust.

The placebo test

This paper also adopts the counterfactual method to verify a common trend between the treatment and control groups. The basic principle and procedure are to assume that the time of the CCCP pilot is advanced to 2009 and 2010, and construct the corresponding dummy variables for the DID regression. Suppose the coefficients of the policy and time interaction terms are not significant in the dummy policy setting. In that case, it indicates a common trend between the treatment group and the control group, and the change in the energy efficiency of the electric power industry is caused by the CCCP rather than other factors. Otherwise, it indicates that the conclusion is not robust. According to the results of the third and fourth columns in Table 6, it can be seen that the coefficients of the interaction terms are not significant under the assumption of dummy policies at either time points. In addition, this paper also postpones the implementation of the policy to 2012 for further testing. The coefficient of the interaction term in the fifth column is significant. Therefore, the above results indicate that the CCCP causes changes in the electrical energy efficiency in the CCCP-covered provinces.

Further discussion

Mechanism analysis

The literature review in this paper points out that there are two paths for CCCPs to impact the energy efficiency of the electric power industry. The one is that the innovation effect path has a positive impact, and the other is that the cost-effective path has a negative impact. However, the direction of the impact of environmental regulation on energy efficiency may not be determined by a single effect. The findings of several studies have supported the view of the combination effect. When the benefits of innovation compensation exceed the costs of environmental regulation, reasonable environmental regulation can effectively stimulate the production technology innovation of the regulated companies, which leads to increased energy efficiency (Porter & van der Linde, 1995; Curtis and Lee, 2019). In addition, Popp et al. (2010) found that environmental regulation compresses companies' profit margins in the short run and does not provide incentives for companies to carry out research and development. However, in the long run, this negative impact will improve with increasing investment in technology development. Therefore, this study envisages that the direction of the net effect of CCCP on electrical energy efficiency may depend on the superposition of these two effects. Due to the unavailability

Table 7 Results of the impact mechanism analysis

	EEE	GTI	EEE
du × dt	−0.1047* (−1.7792)	0.2441** (2.4919)	−0.1411** (−2.6690)
GTI			0.1491** (2.6875)
Constant	−3.1903*		
(−1.7352)	−6.0830*		
(−1.7500)	−2.2833		
(−1.3846)			
Control	Yes	Yes	Yes
Province-fixed effect	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes
N	360	360	360

Robust *t*-statistics are in parentheses, and *, **, and *** indicate the significance at the 10%, 5%, and 1% levels, respectively. Source: authors' calculation

of data on cost changes due to CCCP, the path of cost effects cannot be tested directly. Therefore, this paper uses a mediating effects model to complete the direct identification of the innovation effect and the indirect identification of the cost effect. Regarding the selection of mediating variables, the number of green patents is used to measure green technology innovation (GTI). The basic mediating effects model is specified as follows:

$$\begin{cases} EEE_{it} = c(du_{it} \times dt_{it}) + \theta Controls_{it} + \mu_{it} \\ GTI_{it} = a(du_{it} \times dt_{it}) + \theta Controls_{it} + \varepsilon_{it} \\ EEE_{it} = c^{'}(du_{it} \times dt_{it}) + bGTI_{it} + \theta Controls_{it} + v_{it} \end{cases} \tag{5}$$

where coefficient c captures the net effect of CCCP on electrical energy efficiency; coefficient a captures the effect of CCCP on the green technology innovation; coefficient b separates the effect of green technology innovation on electrical energy efficiency. The product of coefficients a and b is called the mediating effect, which identifies the innovation effect of the CCCP on electrical energy efficiency. The coefficient c' is the residual effect of CCCP on electrical energy efficiency after excluding the innovation effect, which is used to identify the cost effect. Regarding the impact mechanism analysis, Kang et al. (2018) provided the following identification strategies: (1) the coefficient $c > 0$ means that the net effect is positive; the coefficients $a > 0$, $b > 0$, and $ab > 0$ mean that the innovation effect is positive; the coefficient $c' < 0$ means that the cost effect is negative and the innovation effect exceeds the cost effect. (2) The coefficient $c < 0$ indicates that the net effect is negative; similarly, the coefficients $a > 0$, $b > 0$, and $ab > 0$ indicate the innovation effect is positive; the coefficient $c' < 0$ and $|c'| > |c|$ indicate not only that the cost effect is negative, but also that the cost effect exceeds the innovation effect.

According to Table 7, the net effect of the CCCP on the electrical energy efficiency is negative (the coefficient c is -0.1047, significant at the 10% level). However, it still captures a positive contribution to the green technology innovation of pilot provinces (the coefficient a is 0.2441, significant at the 5% level). It has a positive transmission of effect on its electrical energy efficiency through green technology innovation (the coefficient b is 0.1491, significant at the 5% level). After excluding the innovation promotion effect, the cost effect is -0.1411, which is significant at the 5% level. Apparently, the cost effect's negative effect is greater than the net effect ($|-0.1411| > |-0.1047|$). Although the implementation of the CCCP can spur the electric power industry in the pilot provinces to accelerate innovation of green technologies in a short time, it cannot completely offset the negative effects caused by cost effects, which has led to a reduction in electrical energy efficiency.

Heterogeneity analysis

Heterogeneity analysis of law enforcement

The effect of environmental regulation depends on the strictness of law enforcement (Bao et al., 2013). Therefore, based on the proportion of sewage charges in the regional GDP, provinces with strong law

Table 8 Results of the heterogeneity analysis

	Law enforcement		Hydropower investment		Region	
	Strong	Weak	Large	Small	North	South
du×dt	−0.0651 (−1.1007)	−0.1951** (−2.1511)	−0.0895 (−0.9975)	−0.1807** (−2.9074)	−0.1531** (−2.6776)	−0.1503 (−1.4135)
Constant	2.7937** (−2.1490)	0.2692 (0.0471)	1.2539 (0.4034)	−3.0471 (−1.1820)	−2.2805 (−0.8401)	3.0167 (1.1565)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Province-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
Year-fixed effect	Yes	Yes	Yes	Yes	Yes	Yes
N	180	180	180	180	180	180

Robust *t*-statistics are in parentheses, and *, **, and *** indicate the significance at the 10%, 5%, and 1% levels, respectively. Source: authors' calculation

enforcement are defined when their proportion is above the median. In contrast, provinces with weak law enforcement are defined when their proportion is below the median. Then, this paper uses this division to explore further the heterogeneous impact of CCCP on the electrical energy efficiency in strong and weak law enforcement.

As reflected in Table 8, the negative impact of CCCP on electrical energy efficiency in provinces with strong law enforcement is not statistically significant. In contrast, the negative impact on electrical energy efficiency in provinces with weak law enforcement is significant at the 5% significance level. In provinces where law enforcement is strong, the electric power industry would comply with CCCP and take the initiative in developing and applying various energy-saving technologies to mitigate the disadvantages caused by the CCCP. However, for provinces with weak law enforcement, these industries will continue to use coal to generate electricity to save energy replacement costs. Therefore, the electrical energy efficiency in these provinces displayed a downward trend under the influence of CCCP.

Heterogeneity analysis of hydropower investment

Hydropower is a clean, renewable energy with a large development scale and high electricity contribution, which has been the preferred investment objective for global green energy development (Strazzabosco et al., 2020). As a result, based on the amount of hydropower investment in each province, provinces with large investments in hydropower are defined when their value is above the median, while provinces with small investments in hydropower are defined when their value is below the median. After that, this paper uses this division to further explore the heterogeneous impact of CCCP on the electrical energy efficiency in large hydropower investment and small hydropower investment.

According to Table 8, the negative impact of CCCP on electrical energy efficiency in provinces with large investments in hydropower is not statistically significant. In contrast, the negative impact on electrical energy efficiency in provinces with small investments in hydropower is significant at the 5% significance level. Compared to provinces with large hydropower investments, provinces with small hydropower investments may bear more operating costs throughout the energy substitution process. To obtain short-term gains, power generation companies will slow down the process of clean energy substitution and maintain thermal power generation behavior, which leads to a reduction in electrical energy efficiency.

Heterogeneity analysis of region

For the analysis of regional heterogeneity, as the pilot areas are all concentrated in eastern China, this paper carries out the heterogeneity analysis from a North–South perspective. Currently, the political and cultural development gap between China's northern and southern provinces is decreasing, but the economic development gap tends to widen gradually (Guo & Fan, 2019). Therefore, this paper divides

China's provinces into southern provinces and northern provinces using the Qinling-Huaihe line as the boundary and further explores CCCP's heterogeneous impact on the electrical energy efficiency in the northern and southern provinces of China.

As shown in Table 8, the negative impact of CCCP on electrical energy efficiency in northern provinces is significant at the 5% significance level. In addition, the CCCP has no impact on the electrical energy efficiency in southern provinces. The main reason for the decline in the electrical energy efficiency of northern provinces may lie in the heating problem. The northern provinces are rich in coal resources. Heating from the thermal power plant is one of the main types of heat supply, which consumes large amounts of coal. Under the constraints of CCCP, the use of other energy sources for electricity generation entails more technical and investment costs than the use of coal for electricity generation (Shi & Li, 2018). Therefore, it is challenging to improve electrical energy efficiency in a short time. These provinces are rich in the variety of energy sources used to generate electricity regarding the southern provinces. Besides, there is a high degree of substitutability between energy sources. Thus, the changes in electrical energy efficiency in the southern provinces were not affected by the CCCP.

Conclusion and policy implications

Based on the panel data of 30 provinces in China from 2005 to 2016, this paper applies the DID model to evaluate the impact of China's CCCP on electrical energy efficiency in the pilot, and then analyzes annual dynamic impacts and confirms the robustness of the core results in this paper. Furthermore, this paper also points out the specific impact mechanisms and discusses the heterogeneous impact of the CCCP. The main conclusions are drawn as follows: firstly, the implementation of the CCCP reduces electrical energy efficiency in the pilot provinces. After performing the robustness checks, the result is still robust. Moreover, the results of the dynamic analysis present that there is only a short-term effect of CCCP. Secondly, the cost-effectiveness of CCCP is greater than the innovation effect it brings, which is the main reason that the CCCP has a negative impact on electrical energy efficiency in the pilot provinces. Thirdly, compared to provinces with strong law enforcement and large hydropower investment, electrical energy efficiency in provinces with weak law enforcement and small hydropower investment is highly vulnerable to the negative impacts of CCCP. In addition, the impact of the CCCP also has significant regional heterogeneity. The CCCP has a negative impact on electrical energy efficiency in northern provinces, while it has no impact on electrical energy efficiency in southern provinces.

Based on these basic findings above, to improve the CCCP's efficiency in the future, the cap on coal consumption should be reasonably allocated to each province according to its resource endowment, coal usage, and economic development. Concerning power generation, the CCCP has accelerated the replacement process of coal. It should be implemented over the long term and supported by relevant policies to improve electrical energy efficiency. In this situation, we provide the following specific policy recommendations.

First and foremost, China implemented the policy called "Notice on the Publication of the 2014–2015 Special Action Plan for Energy Conservation and Emission Reduction in Science and Technology" and "Green Credit Guidelines" (GCG2012) to incentivize companies to engage in technological innovation. However, the GCG2012 aims to restrict lending to energy-intensive industries and provide financial support for green industries. In the absence of compensatory policies or financial support, it is difficult for the CCCP to motivate electric power generation companies to innovate in technology. Therefore, the Chinese government should further improve the environmental compensation system and clarify the basis and criteria for environmental compensation. Specifically, they should make full use of the market-based mechanism to levy corresponding taxes or ecological compensation fees on coal resources exported from main coal-producing regions. At the same time, the companies that actively develop energy-saving technology should be given certain tax exemptions, subsidies, or preferential credit. Additionally, it is found that there are North–South differences in the impact of CCCP on electrical energy efficiency. In this instance, the relevant policies must be introduced to encourage the northern provinces to use clean and efficient energy to generate electricity for heating. Besides, the government also needs to develop a reasonable electricity pricing method. The price of electricity that heating companies can afford should be no higher than the price of electricity for coal-fired heating.

Second, the results of this study show that provinces with weak law enforcement fail to contribute toward improving electrical energy efficiency. With the rapid development of the Chinese economy, Chinese companies can withstand more stringent environmental regulatory standards. Hence, the Chinese government should increase its efforts to enforce environmental law enforcement on companies, thus driving them to enhance the ability of independent innovation and to improve electrical energy efficiency. Meanwhile, it is necessary to improve the system of environmental administrative law enforcement and strengthen the central role of environmental regulators in the process of energy-saving and emission reduction. In addition, the government should further improve the environmental information disclosure system, establish an open platform for environmental information through multiple channels, and encourage the public to participate in environmental governance such as reporting illegal and polluting companies and incidents.

Finally, in the context of COVID-19 and the global pandemic, the shift from coal power generation to renewable energy power generation has become a new trend in the development of global electricity. This study's conclusions indicate that the electrical energy efficiency of provinces with small investments in hydropower resources is more vulnerable to the adverse effects of CCCP. Therefore, the government should increase investments in renewable energy power generation and promote the adjustment of energy consumption structure. For provinces with relatively homogeneous energy supplies, the traditional electric power generation companies should be encouraged to explore industrial models that combine traditional and new forms of electric power generation. Moreover, to ensure the efficient use of renewable energy sources and promote electrical energy efficiency, the electric power industry in China should deepen international cooperation in energy science and technology in emerging areas such as smart energy and energy storage. In addition, the industry needs to adopt the development model of the integration of investment, construction, and operation.

For the first time, this study quantitatively examines the impact of CCCP in China on electrical energy efficiency. Because of the data availability, the results derived from the provincial panel data were biased, which is the limitation of this study. Therefore, the city-level data can be used to study this research question once accessible, effectively controlling the heterogeneity across different cities. Moreover, in 2016, the CCCP pilot area was further expanded. Liaoning, Shandong, and Henan became the second batch of pilot provinces. Future research can further examine the impact of CCCP on electrical energy efficiency in the new pilot scope. Additionally, with the advent of the post-pandemic era, the impact of CCCP on electrical energy efficiency and its specific mechanisms need to be further explored.

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Declarations

Conflict of interest The authors declare no competing interests.

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