

Research on the synergies between low-carbon pilot city policy and high-speed railways in improving Chinese urban electricity efficiency

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Abstract

Purpose – Global climate change is a serious threat to the survival and development of mankind. Reducing carbon emissions and achieving carbon neutrality are the keys to reducing greenhouse gas emissions and promoting sustainable human development. For many countries, taking China as an example, the electric power sector is the main contributor to the country's carbon emissions, as well as a key sector for reducing carbon emissions and achieving carbon neutrality. The low-carbon transition of the power sector is of great significance to the long-term low-carbon development of the economy. Therefore, on the one hand, it is necessary to improve the energy supply structure on the supply side and increase the proportion of new energy in the total power supply. On the other hand, it is necessary to improve energy utilization efficiency on the demand side and control the total primary energy consumption by improving energy efficiency, which is the most direct and effective way to reduce emissions. Improving the utilization efficiency of electric energy and realizing the low-carbon transition of the electric power industry requires synergies between the government and the market. The purpose of this study is to investigate the individual and synergistic effects of China's low-carbon policy and the opening of urban high-speed railways (HSRs) on the urban electricity consumption efficiency, measured as electricity consumption per unit of gross domestic product (GDP).

Design/methodology/approach – This study uses a panel of 289 Chinese prefecture-level cities from the years 1999–2019 as the sample and uses the time-varying difference-in-difference method to test the relationship between HSR, low-carbon pilot cities and urban electricity consumption efficiency. In addition, the instrumental variable method is adopted to make a robustness check.

Findings – Empirical results show that the low-carbon pilot policy and the HSR operation in cities would reduce the energy consumption per unit of GDP, and synergies occur in both HSR operated and low-carbon pilot cities.

Research limitations/implications – This study has limitations that would provide possible starting points for future studies. The first limitation is the choice of the proxy variable of government and market factors. The second limitation is that the existing data is only about whether the high-speed rail is opened or not and whether it is a low-carbon pilot city, and there is no more informative data to combine the two aspects.



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Practical implications – The findings of this study can inform policymakers and regulators about the effects of low-carbon pilot city policies. In addition, the government should consider market-level factors in addition to policy factors. Only by combining various influencing factors can the efficient use of energy be more effectively achieved so as to achieve the goal of carbon neutrality.

Social implications – From the social perspective, the findings indicate that improving energy utilization is dependent on the joint efforts of the government and market.

Originality/value – The study provides quantitative evidence to assess the synergic effect between government and the market in the low-carbon transition of the electric power industry. Particularly, to the best of the authors' knowledge, it is the first to comprehend the role of the city low-carbon pilot policy and the construction of HSR in improving electricity efficiency.

Keywords Carbon neutrality, Electricity efficiency, China, Carbon pilot policy, High-speed rails

Paper type Research paper

Introduction

The continuing and exaggeratedly emitting carbon dioxide (CO₂) to the earth, when used to create productive energy by mankind, has unfortunately accumulated an extensive account of CO₂ in the atmosphere. CO₂ as a heat-trapping greenhouse gas (GHG), has been widely accepted as the primary culprit in anthropogenic climate change, threatening global environmental, economic and social development (Adeyoyin *et al.*, 2020; Cassia *et al.*, 2018). Although the causal relationship between the greenhouse effect and its effect on the global has been understood for more than a century, GHGs and climate have really caught the world's attention, particularly in scientific, policy and business fields in recent decades (Pain and Stephanie, 2009). The arising attentions have induced concerted endeavor by governments (Song and Zhou, 2021), international organizations (Hanif, 2018) and other institutions (Khan *et al.*, 2021) to force or otherwise create conditions to for an economy low-carbon transition with most of the effort being implemented in the early of 21st century.

The transition of the economy involves numerous aspects of society, and among those important issues, the energy transition plays a key role. An energy transition is defined as a process whereby the composition of energy produced and used to meet human demands fundamentally changes over time (Murray and Niver, 2020). In human history, the energy transition has happened several times, for example, from human muscle power to animal power, further to mechanic power or the shift from biomass to fossil fuels. The assumption of fuels such as coal, oil and natural gas has made great advances for human beings, whereas it also has produced the exaggerated number of carbon which has exceeded the tolerance of the earth (Smil, 2010). Currently, the energy transition has been accepted as the transition from fuels to alternative sources such as renewable resources, for example, wind, solar and other clean ones. Unlike previous energy transitions, which characteristically arose from spontaneous technological, market and demographic forces, the contemporary transition is forcefully or intentionally and driven noticeably by a large range of powers, particularly the governing institutions (Balta-Ozkan *et al.*, 2021; Kim *et al.*, 2020).

The low-carbon transition of the electric power industry is the leading edge of the current energy transition in most countries. The possible reason is that most countries have been heavily relying on coal-powered. Globally, among the major pollutants contributing to climate change, carbon dioxide emissions account for more than 75% of GHG emissions, with about 80% of them generated by the energy industry (Akpan and Akpan, 2012). The low-carbon transition of the electric power industry is thus to generate power by relying on renewables, such as wind and solar, on the supply side to reduce carbon emission and simultaneously improve energy usage efficiency. Knowing the transition direction does not mean that this transition would take place automatically. Previous studies indicate that this

transition has been forged by a mix of macroeconomic factors, technological factors, clean energy policies, environmental and social factors (Acar *et al.*, 2021; Chai *et al.*, 2020; Chen and Kim, 2019). In each country, factors that steer the transition are unique. Murray and Niver (2020) document that the distinct American institutional and market factors that determined the successful US electric power industry transition toward a low-carbon one to largely reduce carbon emissions.

The low-carbon transition of the electric power industry in different countries, mostly at different periods, has its' different patterns. This article, thus, focuses on the Chinese experience with the current energy transition. As the world well knows that China is the largest emitter of carbon dioxide gas in the globe, for example, with 10.06 billion metric tons in 2018. The primary source of CO₂ emissions in China is fossil fuels, notably coal burning to generate electricity. In 2019 about 58% of the total energy derived in China is generated by coal. Thus, China is facing a big challenge to reduce its carbon emissions. However, China's announcement of its "carbon peak and neutrality" target has become the largest climate commitment in the world so far to reducing global warming expectations. Following this ambitious target, China has made great efforts in reducing carbon emissions. Thus, observing and examining factors that are driving China toward the low-carbon course in the electricity industry is worthy because it might provide insightful knowledge and profound implications for academic cycles and policymaking communities.

As mentioned before that the low-carbon transition of the electricity industry involves a wide range of activities and factors. In general, efforts should be put into two aspects: the supply side and the demand side. On the supply side, it needs to increase the composition of new energy in the total power supply. Similarly, on the demand side, it needs to improve the energy usage efficiency to control the total primary energy consumption by improving energy efficiency. In other words, the improvement of energy usage is the most direct and effective means to reduce emissions. In the present study, we, hence, focus on the demand side to investigate factors driving the increased energy consumption efficiency. Among numerous factors (Murray and Niver, 2020; Owen *et al.*, 2018), we follow previous studies to investigate the government and market factors; more importantly, in contrast to these studies, we intend to examine the synergic effect of government and market factors steering low-carbon transition of the Chinese electricity industry. At this point, the initiative of a low-carbon city pilot policy by the government is chosen as the governing factor. Meanwhile, in the market perspective, a city's operation of a high-speed railway (HSR) is chosen as the market channel by which market power is elicited to steer the low-carbon transition of the electricity industry on the demand side. In the theoretical discussion and empirical work, cities are chosen as the analysis unit because cities typically have the primary government power to execute low-carbon policies. In addition, the choice of the city as the sample might provide an appropriate research setting by offering sufficient observations to capture the heterogeneity of institutions in a single country.

Using a sample of 5,475 city-year observations from 289 Chinese prefecture-level cities between the years 1999 and 2019 and the timing-varying difference-in-difference (DID) regression method, we find that:

- low carbon pilot cities have a higher electricity consumption efficiency, measured as a lower energy consumption per unit of gross domestic product (GDP);
- HSR-operated cities have a higher electricity consumption efficiency, measured as a lower energy consumption per unit of GDP; and

- cities simultaneously with a low carbon policy and with HSR operations have a higher electricity consumption efficiency, measured as a lower energy consumption per unit of GDP.

This study makes several contributions to extant literature. First, our work is one of the first efforts to examine the synergies of government and the market in steering the low-carbon transition of the electric power industry. Although different authors present different factors representing their government factors and market factors in their research setting (Chapman and Itaoka, 2018; Murray and Niver, 2020; Seck *et al.*, 2020), less work is invested in examining the interaction between these two types of factors. Our work thus could provide important implications to explore the synergies or conflict role of different factors. Second, government policies or initiatives to reduce carbon emissions in electric power industries or in general economic activities vary in countries. A comprehensive initiative in China in the past decade is the low-carbon pilot city policy. Until now, the effect of this important policy initiative has been widely investigated in existing literature (Khanna *et al.*, 2014; Peng and Deng, 2021; Song *et al.*, 2021; Wang *et al.*, 2015), whereas little work has been put into the cause of low-carbon transition of Chinese electric power industry. Third, the construction of HSRs (with an average speed exceeding 300 km/h) has become an important priority for many countries. China entered an era with high investments in and rapid expansion of HSR transport infrastructure a decade ago. So far, China has owned the largest mileage of HSR in the world. Previous studies have thus widely examined the effect of HSRs on various economic and social aspects (Chen, 2017; Gao and Zheng, 2020), including carbon emissions (Chen *et al.*, 2021a, 2021b; Kaewunruen *et al.*, 2020). In view of the carbon emission, scholars mostly examined the direct effect of HSR construction and operations. Beyond these direct roles in carbon emissions, HSR might also provide an indirect way to influence carbon emission, i.e. the reduction mechanism in the present study in improving the electricity consumption efficiency, and thus, facilitating the low-carbon transition of the Chinese electric power industry. Our study thus extends the inquiry of HSRs' effect beyond transportation and particularly strengthens our objective understanding of the role of HSR in economic low-carbon transition course.

The article continues in the next section with hypothesis development. We then introduce the data and analytical method used. The fourth section provides the empirical results and discusses the implications of the results. The final section concludes this paper by providing the main findings and limitations.

Theoretical framework and hypotheses development

Low-carbon pilot city project and electricity efficiency

It is widely acknowledged in the extant literature and policymaking cycles that electricity consumption, a major part of intermediate and final consumption of all sectors of a city, plays a key role in carbon emission (Akpan and Akpan, 2012; Zhang *et al.*, 2019). Hence, the efficient exploitation and development of a city's energy resources are of great importance to the advance and well-being of the consuming public and the overall growth of the urban economy. A literature review shows that higher energy consumption has become the key contributor to the main culprit for carbon emission in both advanced and less advanced regions (Belaid and Zrelli, 2019; Waheed *et al.*, 2019). Thus, to find conditions and design appropriate initiatives for government to replace the nonrenewable energy sources (i.e. fuels) to generate electricity, run industrial operations, and for transportation purposes and further improving the electricity consumption efficiency becomes increasingly important for both central and local governments.

In line with this important argument, the central government initiated its policies to transit the national economy into a low-carbon one (Song *et al.*, 2021; Zhang *et al.*, 2014). Among these initiatives, the low-carbon pilot city policy becomes evident because this is a great innovation policy to comprehensively change cities' economic and social development patterns to a low-carbon dominated one. Thus, the pilot project of low-carbon cities is an important endeavor to align China's national aims for climate change governance with local governments' low-carbon efforts. In this study, we thus use this policy as the government's efforts to achieve the low-carbon transition of the electric power industry, owing to its uniqueness mostly in contrast to policies in other countries.

The design and implementation of low-carbon city pilot projects are the careful thought of Chinese characteristics and carbon reduction situations. It is well known that in 2007 China exceeded the USA, becoming the largest country in GHG emissions (Lewis, 2010). This becomes an important event for the Chinese central government to adopt actions to control carbon emissions and to build up a national-level climate management system and working mechanism (Song *et al.*, 2020). Given China's huge territory and different resource endowment and economic development stages, regions vary in the working base and the low-carbon development level and incentives in handling carbon issues (Khanna *et al.*, 2014). Thus, to reflect the regional differences in Chinese paths and models for low-carbon development and mostly to stimulate local governments' efforts to control for carbon emissions, the central government, thus, initiated a policy to allow local governments to explore new strategies based on their different conditions. This consists of the background of the birth of China's low-carbon city pilot projects. In 2010, 2012 and 2017, China's Climate division of the National Development and Reform Commission has carried out three batches of low-carbon pilot cities. Currently, there are 87 cities were chosen to explore for the principle and direct of low-carbon development strategies and tools (Song *et al.*, 2020). The low-carbon pilot project is a key measure for the Chinese central government to deal with climate change at the local level. There is no mandatory target or specific implementation tool at the national level. In other words, the central government hope these pilot cities would innovate and create efficient policy tools and measures to control carbon emissions and finally successfully obtain efficient ways to transit cities' economies to low-carbon ones (Lo, Li and Chen). In short, the low-carbon pilot cities were encouraged by the central government to develop low-carbon cities, low-carbon industries and advocating low-carbon lifestyles to promote the executive of China's carbon emission control aim. However, the specific means of achieving these targets are left up to the local governments. Low-carbon urban planning and implementations, learning and communications and participation in national and international cooperation were widely used by these piloted cities as basic paths toward low-carbon cities.

Although different pilot cities might have different tools to construct a low-carbon city, there are many similarities among those cities (Cheng *et al.*, 2019). In general, the exploration of low-carbon city construction emerged changes in developmental trajectories of cities and consequently impacts production and manufacturing patterns and the local people's daily life. Through scholars' observations, the pilot policies executed in cities included traditional policies such as encouraging the developing renewable energy and improving energy efficiency and innovative policies such as using voluntary, mandatory and market-based tools (Wang *et al.*, 2015; Zhan and de Jong, 2018). These tools, in particular, in public transportation and energy-saving technologies, thus, might lead to a significant improvement carbon emission reduction and further the energy consumption efficiency (Cheng *et al.*, 2019). For example, according to work by Liu and Qin (2016) and Shi *et al.* (2018) that carbon emissions and energy-intensive activities were largely reduced in pilot cities like Xiamen, Shenzhen and Hangzhou by more than 200,000 tons annually, attributing to the usage of low-carbon transportation and

construction projects. In addition, according to [Song et al. \(2015\)](#) work, the carbon emissions per unit of GDP of Wuhan, Urumqi, Zunyi and Jiangdezheng were lower than that of the whole provinces by 19%, 19%, 20% and 25%, respectively. Moreover, land transfer in energy-intensive industries fell by an average of 26%–29% ([Tang et al., 2018](#)). In short, the low-carbon pilot policy is changing the industry production pattern toward energy-saving activities, and relatedly government would spend more on innovative schemes of energy efficiency on their own. This led to the following hypothesis:

- H1.* Owing the low-carbon pilot policy, the energy efficiency would be higher relative to cities without this policy.

High-speed railways and electricity efficiency

HSRs typically refer to trains with a speed over 300 km/h. HSRs were first developed in Japan 1960s, then sped to France in 1980s, and later in Spain, the UK, German, the USA, China and other countries. Today, the establishment of HSRs has become a crucial priority for many nations. For example, before entering to the HSR era, China mainly relied on highways and conventional railways with running speeds of less than 120 km/h to transfer goods and passengers. Since HRSs began to operate in China in 2008, the HSRs have been rapidly developed in the latest decades. By 2020, the operation mileage of HSR in China has increased suddenly to 146,000 km.

The unexpected advance of the HSR services and the rapid expansion of HSR network have caught great attention of academic and policymaking areas. For instance, in the energy field, prior studies thus have examined the relationship between HSRs and traction energy consumption as well as carbon emissions ([Chen et al., 2021a, 2021b](#); [Feng, 2011](#)). As [Chen et al. \(2021a, 2021b\)](#) found that the operation of HSR itself would increase the energy consumption and relatively carbon emissions, while when taking into account the substitution effect of ordinary-speed rains, flights, cars, the net energy saving become positive and the carbon emissions become negative, offsetting energy consumption and emissions from HSR infrastructure construction and vehicle manufacturing. However, these studies mostly focused on the HSRs themselves in terms of their energy consumption and time-saving, ignoring their social aspect. Prior studies also documented that the construction of HSR lines and the operation HSRs cannot be considered as simple as transport infrastructure ([Chen et al., 2020](#)). Thus, the effect of HSR on energy efficiency in the HSR-operated cities was not discussed. This study, thus, argues that HSR operations in cities would improve urban energy efficiency.

First of all, the HSRs have achieved a great improvement in accessibility, compressed time and space distance, reduced travel costs and broke the barriers caused by low traffic connectivity, thereby minimizing the impact of geographical distance and administrative power on the flow of elements ([Cascetta et al., 2020](#); [Ma et al., 2021](#); [Zhang et al., 2020](#)). HSRs make the flow and exchange of capital, logistics and information flow more rapid and convenient across regions ([Guo and Wu, 2020](#)). For microentities, the operation of HSRs promotes the temporal and spatial allocation of production factors, especially high-end production factors such as management, technology and knowledge, in a wider range ([Yang et al., 2021](#); [Yun and Qing, 2021](#)). The migration and reorganization of factors on the scale of inter-urban areas have accelerated the re-allocation of resources ([Huang et al., 2019](#)). The opening of HSRs has further improved the utilization and efficiency of resources, thereby reducing the energy required per unit of output value in the process of economic development and increasing electricity consumption efficiency. Second, the operation of HSR provides more convenient conditions for technological innovation and knowledge dissemination. The HSRs increase the possibility of rational distribution of innovation factors

across regions, which is conducive to improving the availability and reserves of innovation resources in different regions (Kobayashi and Okumura, 1997). Due to geographical constraints, the initial distribution of innovation resources, especially human resources, is often unbalanced (Bernstein and Mohnen, 1998). HSRs are conducive to optimizing the spatial distribution of innovation elements, increasing the city's attractiveness to talents, and increasing the reserve of innovation elements required for regional innovation and development (Levinson, 2012; Tierney, 2012). The increase in the flow space of innovative elements and the increase in the flow rate has also promoted the improvement of production technology and output efficiency and the development of production methods in a more effective direction (Duan *et al.*, 2021). Producers can achieve less energy consumption and a higher degree of industrial specialization. At the same time, high-speed rail can promote the communication and exchange of innovative elements, enhance the spillover effect of knowledge, and improve the level of innovation (Yun and Qing, 2021). The rapid flow of population across regions drives knowledge interaction and exchanges between different subjects, thereby accelerating knowledge spillover, which is conducive to the development of low-energy high-tech industries and the emergence of new business formats, thereby reducing energy consumption in economic output. Finally, for cities along the HSR lines, the HSR operation also effectively increases the availability of innovative resources and elements outside the region and promotes the improvement of the level of open innovation in cities and the formation of inter-city innovation networks (Sun, 2015). Therefore, the HSRs promote the flow of innovative elements and promote the improvement of technology. The development of technology further improves the efficiency of resource utilization, thereby reducing the city's energy consumption per unit of GDP. In summary, this article proposes the following hypotheses:

- H2.* The energy efficiency would be higher in HSR operation cities relative to cities without HSR operations.

The synergistic effect of low-carbon pilot policy and high-speed railways on urban electricity efficiency

Low-carbon city pilot projects and the HSR operations have significant synergistic effects on the low-carbon transition of the energy industry and the improvement of energy efficiency in cities. First, low-carbon pilot cities need to optimize their industrial structure to reduce carbon emissions and promote the optimization of energy use structures. The HSR operations promote the flow of factors, accelerate the utilization of various factors, affect the relative prices and input structure of original factors, further affect the marginal productivity of various factors of production and accelerate the spatial flow of factors among different industrial sectors (Tierney, 2012). And the spatial allocation has caused changes and adjustments in the industrial structure, thereby providing a material foundation for optimizing the industrial structure of low-carbon pilot cities and promoting the development of low-energy, high-tech industries. Second, HSR operation might reshape and optimize the location conditions of cities along the HSR lines, bring abundant labor, better technology and more convenient information channels and provide convenience for industrial upgrading and new industrial development in low-carbon pilot cities. Third, the HSRs might promote the economic development of the areas along the HSR lines, and at the same time, it has brought about an increase in rents, income levels and prices, thus, reducing some low-end which are more sensitive to land prices, raw material costs, energy costs and labor costs (Gao and Zheng, 2020). The proportion of manufacturing enterprises is conducive to the development of advanced, low-energy high-tech industries, thereby improving the

efficiency of low-carbon pilot cities. Fourth, HSRs might shorten the transportation time between the stationed area and nearby areas, reduces the cost of cross-regional communication and strengthens the economic connection between low-carbon pilot cities and surrounding areas, which is conducive to attracting business investment and population agglomeration, thereby forming urban economies of scale, reducing reliance on high-energy-consuming industries will also make urban development of rail transit profitable, thereby reducing transportation energy consumption in low-carbon pilot cities. Finally, the economic agglomeration brought about by HSRs is conducive to the improvement of environmental regulation in low-carbon pilot cities. When the degree of economic agglomeration is low, the distribution of enterprises is relatively scattered, which makes supervision difficult and the implementation cost of supervisory measures high. Even with high-standard low-carbon regulatory policies, it is difficult to control enterprises' uneconomic behaviors, such as high energy consumption. Therefore, the agglomeration effect formed by HSRs is conducive to the expansion of the effect of urban low-carbon pilot projects. In summary, we propose the following hypothesis:

H3. There will be a synergic effect in improving the electricity efficiency in low-carbon pilot cities with HSR operations.

Methodology

Data

In this study, the main variables were mainly obtained from three databases. First, we obtained the urban electricity consumption information and prefecture-level city information from the China City Statistical Yearbook for 1999–2019, such as population density, the number of stated firms and so on. Second, we got the HSRs operation information from 2008 to 2019 from the Train Schedule Book, including the operation time, train stations, residence time and so on. Three, we acquired information on low-carbon pilot cities from the National Development and Reform Commission. After merging these three databases, we have got 5,475 prefecture-level city-year samples from 1999 to 2019.

Research model

According to the theoretical analysis and research design, we used [equation \(1\)](#) to examine *H1*, the effect of a low-carbon pilot city project on electricity consumption efficiency:

$$\begin{aligned} Sqrt(Efficiency) = & \partial + \beta_1 Carbon + \beta_2 \ln(population(\%)) \\ & + \beta_3 \ln(Education(\%)) + \beta_4 \ln Size + \beta_5 \ln FDI \\ & + \beta_6 \ln(Internet(\%)) + City + Year + \varepsilon \end{aligned} \quad (1)$$

Where *Sqrt (Efficiency)* is the electricity consumption efficiency, which is the ratio of the city's energy consumption to GDP. A higher value of the ratio indicates low electricity efficiency. To make the independent variable conform to the normal distribution, this study takes the square root of the electricity efficiency. *Carbon* represents the low-carbon pilot policy. In 2010, 2012 and 2017, China's Climate division of the National Development and Reform Commission has carried out three batches of low-carbon pilot cities. Referring the prior studies, this study mainly uses the time-varying DID method to test the relationship between low-carbon pilot policy and electricity efficiency. In the observation period, if the city implements a low-carbon pilot policy, then the *dc* = 1; otherwise, the *dc* = 0. Besides, in the

observation year, if the city has implemented the low-carbon pilot policy or before, the $dt = 1$; otherwise, the $dt = 0$. If the city has implemented two or more low-carbon pilots, this study sets the first time as the policy year. Finally, this study defines the $Carbon = dc*dt$.

Population is the natural logarithm of the population density of the city, which is the number of population per unit of land area. Population growth will lead to an increase in electricity consumption in the region (Auffhammer and Aroonruengsawat, 2011). *Education* is the ratio of a number of students in colleges and universities to the total population of the region. Yen (2021) pointed out that people with higher education have a more positive effect on green energy encouragement. *Size* is the logarithm value of the number of state-owned firms and all nonstate-owned firms with annual sales revenue of more than 5 million, and this indicator represents the firm size of the region. The larger the firm size in a region, the more business activities and the more resource consumption (Acar et al., 2021). *Foreign Direct Investment (FDI)* is the logarithm value of the actual foreign direct investment, which is an important engine of growth in a region and hence helps to improve the regional environment and environmental standards (Zhang and Fu, 2008). *Internet* is the ratio of the number of internet users to the total population in a region. The internet users represent the information transparency in a region, which can bring pressure to the local environment situation (Chen et al., 2021a). Finally, we controlled for the potential impact of indicators, *City* and *Year* dummy variables:

$$\begin{aligned} Sqrt(Efficiency) = & \partial + \chi_1 HSR + \chi_2 \ln(population(\%)) \\ & + \chi_3 \ln(Education(\%)) + \chi_4 \ln Size + \chi_5 \ln FDI \\ & + \chi_6 \ln(Internet(\%)) + City + Year + \varepsilon \end{aligned} \quad (2)$$

Equation (2) was used to test the *H2*. The main difference between equations (1) and (2) is the independent variable. In equation (1), the coefficient of β_1 is the main variable of interest. In equation (2), the main variable of interest is the coefficient of *HSR*, χ_1 . *HSR* represents the operation of HSRs in a city. Due to the operation of HSR is a gradual policy effect; therefore, this study chooses the time-varying DID method to test the relationship between HSR and electricity efficiency. In the observation period 1999–2019, if the city has opened the HSRs, then the $dh = 1$; otherwise, $dh = 0$. In addition, in the observation year or before, if the city has opened the HSR, then the $dt = 1$; otherwise, $dt = 0$. Then $HSR = dh*dt$. Other variables' definitions are the same with equation (1):

$$\begin{aligned} Sqrt(Efficiency) = & \partial + \delta_1 HSR*Carbon + \delta_2 \ln(population(\%)) \\ & + \delta_3 \ln(Education(\%)) + \delta_4 \ln Size + \delta_5 \ln FDI \\ & + \delta_6 \ln(Internet(\%)) + \delta_7 HSR + \delta_8 Carbon + City + Year + \varepsilon \end{aligned} \quad (3)$$

Equation (3) was used to measure the *H3*. This study mainly focuses on the interaction term between *HSR* and *Carbon*, δ_1 . The main purpose of this study is to test the synergies effect of HSRs and low-carbon pilot city policy on electricity efficiency. Other variables' definitions are the same as equation (1).

Results

Descriptive statistics

Table 1 presents descriptive statistics about all indicators and samples. In our sample, electricity Efficiency has a mean value 0.243, with a minimum value of 0.000 and a maximum value of 1.587. Moreover, the mean values of Carbon and HSR are 0.103 and 0.132, respectively. This result reveals that the number of low-carbon pilot cities and cities with HSR operations are smaller. The mean value and standard error of other control variables are in a reasonable range, and then there is no extreme value and abnormal value.

Table 2 examines the pairwise correlation of all indicators in this study. The results show that the independent variables and control variables are correlated with the dependent variable, and the values are in a reasonable range. Therefore, there is no high correlation between indicators. In addition, to judge whether there is a collinearity problem among variables, the variance inflation factor (VIF) test has been adopted. The last column of Table 2 shows the VIF value, and the largest value and mean value are 2.750 and 1.800, respectively, no higher than 10 (Chatterjee and Price, 1991; Zhang *et al.*, 2021). Therefore, the selection of indicators in this study is reasonable.

Parallel trend test. The research in this article mainly involves two policy effects, one is the policy effect of low-carbon pilot cities, and the other is the policy effect of high-speed rail opening. According to previous studies, the DID method is often used for policy effects and the premise of using the DID method is to satisfy the parallel trend test (Chen *et al.*, 2020). The core connotation of the parallel trend test is to divide the sample into a control group and an experimental group. Before the policy is implemented, the samples of the control group and the experimental group have parallel trends. In the first policy effect in this article, the control group is the cities that have not implemented low-carbon pilots and the experimental group is the cities that have implemented low-carbon pilots. In the second

Table 1.
Descriptive statistics

Variable	Observation	Mean	Std. Dev.	Min	Max
Efficiency	5,475	0.243	0.122	0.000	1.587
Carbon	5,475	0.103	0.304	0.000	1.000
HSR	5,475	0.132	0.338	0.000	1.000
Population	4,916	5.726	0.886	1.548	9.356
Education	5,223	4.231	1.217	-0.790	9.126
Size	5,475	3.315	3.244	0.000	10.148
FDI	5,314	9.345	2.259	0.000	15.091
Internet	4,939	3.218	3.846	-3.860	10.575

Table 2.
Pairwise correlation
test

Variables	Efficiency	Carbon	Population	Education	Size	FDI	VIF
Efficiency	1						
Carbon	-0.026*	1					1.240
Population	-0.030**	0.028**	1				1.260
Education	0.120***	0.140***	0.207***	1			1.390
Size	-0.023*	-0.347***	0.093***	-0.033**	1		2.750
FDI	-0.133***	0.145***	0.414***	0.508***	-0.061***	1	1.610
Internet	0.045***	-0.360***	0.040***	-0.046***	0.509***	-0.134***	2.550

Notes: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

policy effect, the control group is the cities without high-speed rail and the experimental group is the cities with HSRs.

Figure 1 shows the parallel trend test between low-carbon pilot cities and electricity consumption efficiency. The result depicts that before the low-carbon pilot policy, the coefficient of electricity consumption is fluctuated from zero. While after the low-carbon pilot policy, there is a clear downward trend in the coefficient of electricity consumption. Therefore, there is a parallel trend between low-carbon pilot policy and electricity consumption, and DID method is suitable for testing the relationship.

Figure 2 illustrates the relationship between HSR operation and electricity consumption. The result shows that before the operation of HSRs, there is no obvious trend between HSR and electricity consumption, whereas, after the operation of HSR, there is an obvious downward trend between HSR and electricity consumption. Therefore, the operation of HSR

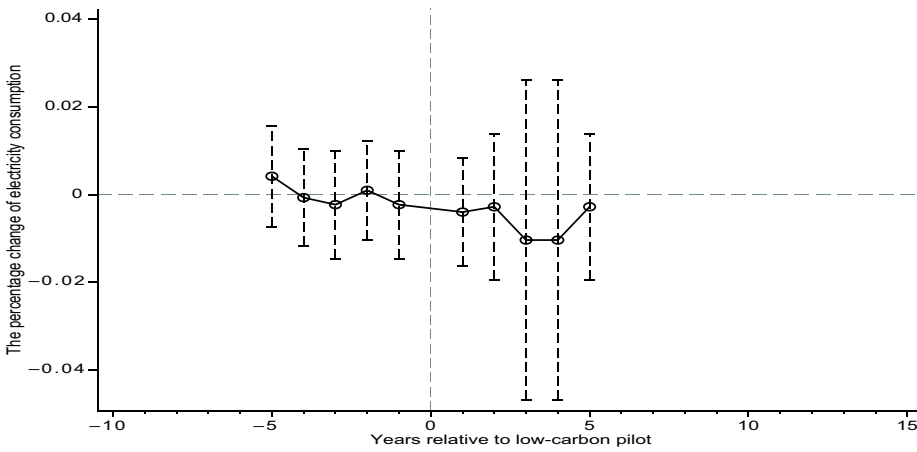


Figure 1.
The parallel trend between low-carbon pilot and electricity consumption

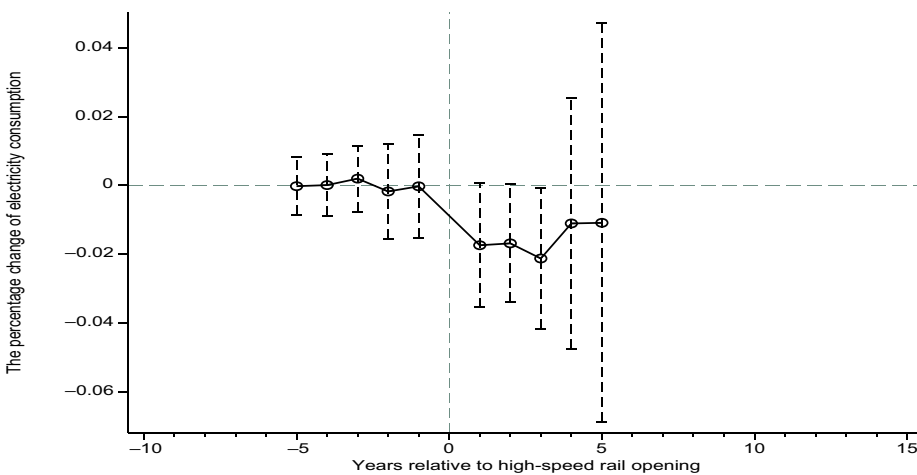


Figure 2.
The parallel trend between HSR operation and electricity consumption

and electricity consumption satisfy the parallel trend, and the DID method is suitable for this test.

Main findings

Table 3, Model 1, presents the regression results for the relationship between low-carbon pilot city policy and electricity consumption efficiency. In line with *H1*, the coefficient of carbon is negative and significant (coefficient = -0.009, $P < 0.01$), suggesting that after the implementing of the low-carbon pilot policy, the electricity consumption efficiency has been improved. In addition, from the control variables (coefficient = -0.01, $P < 0.01$), the results show that there is a negative relationship between education and electricity consumption, which means that in those areas with higher education, the environmental problem obtains more attention and the electricity consumption efficiency is higher. FDI investment has a negative effect on electricity consumption (coefficient = -0.006, $P < 0.01$), which means that FDI investment can promote the electricity consumption efficiency for the advanced technology and management.

Furthermore, Table 3, Model 2, presents the impact of HSRs operation on the electricity consumption efficiency. The coefficient of HSR is negative and significant (Coefficient = -0.009, $P < 0.01$), indicating that the cities with HSRs have higher electricity consumption efficiency, which is in line with *H2*.

Finally, Table 3, Model 3, presents the regression results of the synergies effect of Carbon and HSR on the electricity consumption efficiency. The interaction term, HSR*Carbon, captures the synergies effect. In line with *H3*, the coefficient of the interaction term is negative and significant (Coefficient = -0.008, $P < 0.01$). This result indicates that in the

Variables	Model 1 Efficiency	Model 2 Efficiency	Model 3 Efficiency
Carbon	-0.009*** (-3.17)		-0.011*** (-3.62)
HSR		-0.009*** (-3.43)	-0.011*** (-3.37)
HSR* Carbon			-0.008* (-1.77)
Population	-0.004 (-1.20)	-0.004 (-1.12)	-0.004 (-1.16)
Education	-0.010*** (-7.26)	-0.010*** (-7.17)	-0.010*** (-7.39)
Size	0.003*** (8.99)	0.003*** (9.59)	0.003*** (9.96)
FDI	-0.006*** (-9.78)	-0.006*** (-9.61)	-0.006*** (-9.69)
Internet	0.001*** (3.67)	0.001*** (3.40)	0.001*** (3.80)
Constant	0.328*** (15.73)	0.325*** (15.57)	0.326*** (15.61)
City	Control	Control	Control
Year	Control	Control	Control
N	4,147	4,147	4,147
Wald Chi ²	1,223.49***	1,227.23***	1,213.34***

Table 3.
The regression
results of main
findings

Notes: z-statistics in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

low-carbon pilot city with the operation of HSRs, the electricity consumption efficiency is higher.

Conclusion

In this study, we have investigated the influence of the Chinese low-carbon pilot policy and the HSR operation on the city's electricity efficiency separately and jointly. Using the insights from both the literature examining the effect of low-carbon pilot policy and that examining a wider effect of the HSRs, we have extended the prior literature on the joint role of government and market power in helping transit the electricity power industry into a low-carbon system. Moreover, we contribute to previous literature on the effect of low-carbon pilot projects by providing the first sight in terms of its effect on electricity efficiency, an important aspect of the low-carbon transition of the electricity power industry. Meanwhile, from the line of literature investigating a broader effect of HSRs, our study also extends this line of study by focusing on the HSR role in transiting the city electricity power industry into a low-carbon one.

Our main findings illustrate that there is a synergetic effect between government and the market in help the electricity power industry to transit to a low-carbon sector. Government effects and market factors are represented by government low-carbon pilot initiatives and market mechanisms provided by the construction of HSR lines, respectively. Our empirical results suggest that there is a positive relationship between the low-carbon pilot city policy and urban electricity efficiency, measured by a lower electricity consumption per unit of GDP. In the study of [Yu and Zhang \(2021\)](#), the low-carbon city pilot policy can improve carbon emission efficiency by 1.7%, which are both economically and statistically significant, and is consistent with our study. Likewise, there is also a positive correlation between HSR operation and electricity efficiency in HSR-operated cities. The findings are consistent with the study of [Lin and Jia \(2022\)](#) that HSR construction has positive environmental externalities. An important finding of this study is that we found there is a synergetic effect in the low-carbon pilot cities with HSR operations.

According to the findings, this study provides some theoretical and practical implications. From a theoretical view, our study demonstrates that there is a necessity to collectively consider various factors in analyzing the low-carbon transition (e.g. in the electricity power industry). Various factors might have complementary or substitution effects, which further might rely on various conditions. By considering the impact of more factors on energy efficiency, it can broaden the research on low-carbon boundaries.

From a practical perspective, the results of our study would make policymakers and regulators confident in designing and implementing the low-carbon pilot policy as well as the planning of large infrastructure such as HSR projects. More important, policymakers should consider the synergetic effect among different initiatives, even with those "hard factors", because they might elicit market mechanisms.

Our study is not without limitations that might consist of the main directions for future study. The first limitation is related to our choice of government and market factors. Although the present study chose two unique ones in China, whereas to what extent these findings can be generalized to other countries is unclear. The second limitation is related to our data set; although these data sets have been widely used in the extant literature, there is only information about whether a city has HSR operation or not, and we do not have more information about how frequent the HSRs operate in the city, and how many cities the focal city has been connected to the HSR network. Therefore, future research should try to use a rich data set across countries to provide more robust results for our study and make our

study more generalizable. A network perspective and more information should be collected to investigate the role of HSR in the low-carbon transition of the electricity power industry .

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Further reading

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