Energy Policy xxx (xxxx) xxx

Contents lists available at ScienceDirect

Energy Policy

journal homepage: http://www.elsevier.com/locate/enpol

Differentiated effects of diversified technological sources on China's electricity consumption: Evidence from the perspective of rebound effect

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ARTICLE INFO

Keywords:
Rebound effect
Technological progress sources
Electricity industry
Coal-electricity linkage
China

ABSTRACT

Technological progress is an effective way to improve electricity efficiency. Due to the existence of the rebound effect, it is of great significance to optimize the technical power saving policy by examining the rebound effect caused by different technological progress paths.Based on the panel data of electricity industry in 30 provinces of China from 1997 to 2013, this paper systematically examines the rebound effects of electricity consumption under the two sources of technological progress, namely independent innovation and technology import. Then, it discusses the impact of coal-electricity linkage policy. The empirical results are as follows: (1) without considering rebound effect, independent innovation significantly promotes electricity conservation, while the effects of technology import is not obvious; (2) when considering the rebound effect, electricity price declining driven by independent innovation is not conducive to electricity saving, while electricity price declining driven by technology import has an electricity-saving effect; (3)The coal-electricity linkage policy that began in 2004 not only reduced the rebound effect by increasing the flexibility of electricity prices to a certain extent and improved the electricity-saving effect of independent innovation, but also reduced the electricity-saving effect of technology import.

1. Introduction

It is well known that the electricity sector is the largest emitter of CO_2 emissions in China as its high-carbon structure of the power generation (Bi, 2014). In order to promote green and low carbon development of the power system, the Thirteenth Five-Year Plan (2016–2020) requires that the carbon dioxide emission intensity of the power sector should be controlled within 550 gCO_2 / (kW h) by 2020. In 2017, the power sector was the first included in the national carbon emission trading system.[1] Due to the real-time balance characteristics of power production and power consumption, improving the utilization efficiency of power consumption has an important impact on the low carbonization of power production (Zhang et al., 2018; Zhang et al., 2018). It is a consensus that technological progress is the fundamental way to improve the efficiency of electricity utilization and thus promote emission reduction (Sun, 2010). Commonly, technological progress can be achieved through two ways: independent innovation and technology introduction. For the Chinese power industry, independent innovation can make the core technologies autonomous and controllable, and the advanced technologies will have a higher matching degree to China's power system to ensure safety of the power sector. Compared with independent innovation, technology introduction enables China's power industry to acquire advanced technologies and improve energy efficiency more quickly, and effectively alleviated the constraints of power shortage on economic development. But there may be an increase in cost and a decline in technical matching. In practice, the impacts of these two ways on power consumption are subjectively immeasurable, and the issue of "the choice of technological advancement methods for independent innovation and technology introduction" has sparked heated debates in the academic world. Some scholars believe that independent innovation

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[1] According to the initial inclusion threshold – key emitters whose annual emissions reach 26,000 tons of carbon dioxide equivalent (comprehensive energy consumption is about 10,000 tons of standard coal) or above, more than 1700 power generation enterprises will be included in the first batch, with CO_2 emissions exceeding 3 billion tons, accounting for more than 1/3 of the total CO_2 emissions in China.

https://doi.org/10.1016/j.enpol.2019.111084
Received 6 February 2019; Received in revised form 13 September 2019; Accepted 1 November 2019

is the main way to achieve the catch-up of technologies (L. Parente and C. Prescott, 1994). While others believe that technology introduction will effectively promote technological progress, and it is a realistic, feasible, low-cost, and effective strategic choice for the developing countries (Keller, 2004). However, there are few studies discussing the heterogeneous effects of these two ways on "energy saving and emission reduction" in Chinese electricity sector, and this paper aims to make up this deficiency from the perspective of rebound effects.

Although technological progress is believed to be the key way to improving energy efficiency, there is some doubt whether it can effectively reduce energy consumption due to the existence of rebound effect (Zhang and Peng, 2017). Technological progress, while promoting energy efficiency and energy conservation, will also lead to a relative decline in the cost of energy services, stimulate consumers' new demand for energy, and partially or completely offset the saved energy, which is known as "rebound effect" in the literature (Li and Jiang, 2016). In other words, the energy-saving effect of technological progress in promoting energy efficiency depends on the size of the "rebound effect", that is, the size of the rebound effect determines whether technology energy-saving policies can work as expected and whether they can be implemented as energy-saving strategic policies. At present, the existence of the rebound effect has been widely recognized by the academic community(Lin and Liu, 2012; Saunders, 2013; Wen et al., 2018; Yang and Li, 2017). This issue should pay more attention in China's power system as the government has a considerable degree of regulation over electricity prices.

The existing literature mainly focuses on measuring the actual size of the rebound effect. The research perspectives are mainly divided into two categories: one is to construct a macro-econometric model to measure the rebound effect value of the macroeconomic level. Many scholars confirm the existence of the rebound effect and have measured the energy rebound of China. Lin and Liu (2012) used the LMDI method to decompose the contribution of technological progress to China's energy intensity changes, and found the rebound effect of China from 1981 to 2009 to 53.2%. Fan et al. (2016) found that there is a significant heterogeneity in the evolution of China's energy intensity. Due to the rebound effect, technological progress is limited in reducing the intensity of energy. Luo et al. (2016) constructed the energy rebound effect from the perspective of energy relative price changes, and found that the long-term rebound effect caused by China's energy relative price changes is 32.2%, and the regional difference factors have a significant impact on the energy rebound effect. Zhang et al. (2017) found that China's overall industry does have an energy rebound effect, and the energy rebound effect of China's industry and manufacturing industry has shown an overall downward trend with the passage of time. Wen et al. (2018) found significant differences in the risk vulnerabilities of energy rebound effects in different regions of China, with Qinghai being the most vulnerable province. Li and Lin (2018) measured the impact of technological progress on energy productivity in Hicks Neutral and Capital in 30 provinces of China from 1997 to 2012, and found that due to the energy rebound effect, capital reflects the poor performance of technological progress.

Some scholars have also measured the energy rebound effects of other countries in the world, and found that the energy rebound effect is real and has an impact on energy consumption. Grubb (2000) measured the IEA countries in the 1970s and 1980s and found that the macro-level energy rebound effect is relatively small, and the technological progress as a whole shows an energy-saving trend. Saunders (2013) predicts energy consumption in 30 US departments and finds that ignoring the rebound effect underestimates energy consumption. Liu and Wang (2016) found that the existence of the rebound effect did reduce the effectiveness of energy efficiency policies by studying the differences in energy efficiency and rebound between different types of energy efficiency improvements.

Another type of research is to measure the rebound effect value from the terminal demand level. Some scholars have measured the exact rebound value of the terminal demand level. Ouyang et al. (2010) revealed the rebound effect of Chinese household consumption between 30% and 50%. Druckman et al. (2011) found that the rebound effect of British household consumption was about 34%. A study by Chitnis et al. (2013) pointed out that the rebound effect of household consumption in the UK is 5%–15%, and most of it stems from the indirect rebound effect. Another part of the scholars analyzed the influencing factors of the rebound value, and found that ways to improve the carbon tax can effectively reduce the rebound effect. Brännlund et al. (2007) found that the energy efficiency of Swiss household consumption has a rebound effect on carbon dioxide (CO2), sulfur dioxide (SO2) and nitrogen oxides (NOx) emissions, and raising the carbon tax helps to reduce the rebound effect. Thomas and Azevedo (2013) reveal that there is a general rebound effect in US household consumption, and implementing a pollution tax or pollution auction mechanism can help reduce the rebound effect. Antal and van den Bergh (2014) found that in the 93 sample countries studied, the "re-consumption" rebound effect in the electricity sector reached 18%. Weizsacker (2014) believed that the waste of energy should be suppressed by means of taxation, and tax revenue should be used for carbon emission reduction, thus alleviating the rebound effect.

In contrast, although the electricity sector is China's largest source of CO_2 emissions, there are few studies about the rebound effect of this sector. Wang et al. (2016) found that Beijing residents' electricity consumption showed a partial rebound effect. The long-term direct and indirect rebound effects are 46%–56%, and the short-term direct rebound effect is 24%–37%. Zhang et al. (2017) measured the direct rebound effect (RE) of China's residential electricity consumption by an average of about 72%. Due to the rebound effect, the electricity bill saved by improving the efficiency of household electricity in China was not as much as expected. Deng et al. (2018) calculated the electricity rebound effect based on electricity price decomposition, and found that the rebound effect value of Southwest China and Central China was higher than 100%, and the annual average rebound effects of Northeast China and South China were 60.39% and 81.47%, respectively. The rebound effect in the northwest region is at least 14.96%.

In summary, although the studies about the rebound effect are fruitful, most of them focuses on measuring the energy rebound effect at the macroeconomic level and the terminal demand level, there are few studies about China's electricity industry. Later, the research perspective is relatively limited, and more concentrated on household electricity, and rarely analyzed the entire electricity industry. In addition, technical energy conservation policies are also very important, especially the implementation of energy conservation and emission reduction technologies, such as independent innovation, technology import, etc. Analysis of the impact of different technological progress ways on the rebound effect has great value for designing technology energy conservation paths.

In view of the shortcomings of the existing literature, the work and innovation of this paper are mainly reflected in the following three aspects. Firstly, based on the theoretical expression of the rebound effect, this paper calculates the direct rebound effect of China's electricity consumption by decomposing the electricity price change and using the electricity consumption function. The research conclusion is more scientific and reasonable. Secondly, from the perspective of independent innovation and technology import, the paper analyzes the impact of different technological progress ways on the technical electricity saving effect through the fluctuation of electricity price, and the research conclusions help to determine the optimal path of technological progress. Thirdly, considering that the Chinese government has implemented the coal-electricity linkage policy since 2004, this paper attempts to explore the impact of the government's improved electricity price policy on the electricity rebound effect.

Based on the above analysis, the questions that this paper tries to answer are: Does the rebound effect caused by China's electricity industry due to technological progress affect the electricity saving effect? What is the difference between the rebound effect caused by different technological progress ways and the electricity saving effect? After the implementation of the coal-electricity linkage policy, is the rebound effect of different technological progress ways reduced? Obviously, the answer to these questions is directly related to the realization of China's "energy saving and emission reduction" goal, which not only helps to guide the optimal path selection of China's electricity industry technological progress, but also has important guiding significance for the rational promotion of the "coal-electricity linkage" policy.

The rest of this article is organized as follows: The second part introduces the model and data. The third part explains the empirical results. The fourth part is a summary and policy recommendations.

2. Methods and data definitions

2.1. Theoretical basis

According to Khazzoom's original definition of the rebound effect, this paper defines the rebound effect as a service limited to a single energy, and represents the energy service as a function of the gradually decreasing energy service price, i.e. $S = S(P_S) = S(P_E/\varepsilon)$, where S is defined as energy service, P_S is the price of the energy service (i.e., cost), P_E is the energy price, and ε is energy efficiency. According to the definition of energy efficiency ε, the energy demand is defined as $E = S(P_S)/\varepsilon$, as shown in equation (1).

$$\eta_\varepsilon(E) = \frac{\partial E/E}{\partial \varepsilon/\varepsilon} = \frac{\partial\left(\frac{S}{E}\right)\varepsilon}{\partial \varepsilon\left(\frac{S}{E}\right)} = \left(\frac{\partial S}{\partial \varepsilon}\frac{1}{\varepsilon} - \frac{S}{\varepsilon^2}\right)\frac{\varepsilon^2}{S} = \frac{\partial S}{\partial \varepsilon}\frac{\varepsilon}{S} - 1 = \eta_\varepsilon(S) - 1 \tag{1}$$

In the above formula (1), $\eta_\varepsilon(E)$ represents the efficiency elasticity of the energy demand, and $\eta_\varepsilon(S)$ represents the efficiency elasticity of the energy service. According to Berkhout et al. (2000), the rebound effect can be expressed as:

$$\begin{aligned} RE_D &= \frac{(\Delta\varepsilon/\varepsilon)E - (E - E^{'})}{\Delta\varepsilon/\varepsilon E} = \frac{\delta E + \Delta E}{\delta E} = 1 + \frac{\Delta E}{(\Delta\varepsilon/\varepsilon)E} = 1 + \frac{\Delta E}{\Delta \varepsilon}\frac{\varepsilon}{E} \\ &= 1 + \eta_\varepsilon(E) = \eta_\varepsilon(S) \end{aligned} \tag{2}$$

It can be seen that the direct rebound effect is the efficiency elasticity of energy services. Where $\frac{\Delta\varepsilon}{\varepsilon}$ represents the ratio of change in energy efficiency. That is:

Since energy prices are mainly influenced by energy demand rather than energy efficiency, we can assume that the efficiency elasticity of energy prices is zero, that is, from equations (2) and (3), another definition of direct rebound effect can be obtained:

$$RE_D = \eta_\varepsilon(S) = -\eta_{P_S}(S) \tag{4}$$

If the price is inelastic to efficiency, the rebound effect can be expressed as the negative price elasticity of the energy service (exogenous hypothesis). The decline or rise in the price of energy services will not affect energy efficiency, but consumers will equate the decline in energy service prices with energy efficiency, and in the same way reduce prices and improve efficiency. On the other hand, they believe that technological progress is precisely due to price increases (symmetry assumptions). The definition of formula (4) is entirely due to these two assumptions.

Similarly, the price elasticity of energy demand can be translated into:

$$\begin{aligned} \eta_{P_E}(E) &= \frac{\partial \ln E}{\partial \ln P_E} = \frac{\partial \ln E}{\partial \ln P_S}\frac{\partial \ln P_S}{\partial \ln P_E} = \frac{\partial \ln (S/\varepsilon)}{\partial \ln P_S}\frac{\partial \ln (P_E/\varepsilon)}{\partial \ln P_E} \\ &= \left(\frac{\partial \ln S}{\partial \ln P_S} - \frac{\partial \ln \varepsilon}{\partial \ln P_S}\right)\left(\frac{\partial \ln P_E}{\partial \ln P_E} - \frac{\partial \ln \varepsilon}{\partial \ln P_E}\right) \\ &= [\eta_{P_S}(S) - \eta_{P_S}(\varepsilon)][1 - \eta_{P_E}(\varepsilon)] \end{aligned} \tag{5}$$

Based on equation (5), if the energy efficiency is exogenous, this means that efficiency is inelastic to the price, i.e. $\eta_{P_S}(\varepsilon) = 0$ and $\eta_{P_E}(\varepsilon) = 0$ Based on the symmetry assumption, the definition of the rebound effect can be expressed as a negative price elastic energy demand:

$$RE_D = \eta_\varepsilon(S) = -\eta_{P_E}(E) \tag{6}$$

Equation (6) shows that the rebound effect can be measured by price elasticity. For example, if the energy price elasticity coefficient is −0.3, it means that for every unit of energy price increase, energy consumption drops by 0.3 units. In other words, The increase in unit energy prices has achieved 70% of energy savings, and 30% of theoretical energy savings are considered to be unrealized due to the rebound effect. In essence, the resulting rebound effect is the spontaneous response of the market to energy efficiency improvements caused by technological progress. This paper takes China's electricity industry as the research object and believes that the electricity rebound effect means that technological progress will reduce the actual price of electricity while increasing the electricity efficiency, thus causing changes in electricity demand. Therefore, we use Eq. (6), that is, the price elasticity of electricity prices to measure the rebound effect of electricity consumption. It is worth noting that the self-price elasticity of direct use of electricity prices may be misleading. The rebound effect derived from the definition of microeconomic analysis framework is that the increase in energy efficiency reduces the effective price of energy consumption, which leads to an increase in energy demand (Barker et al., 2007; Binswanger, 2001; Deng et al., 2018). However, we observe that the price of electricity is fluctuating, and what is related to the rebound effect is the decline in electricity prices. In this regard, we use the method of Gately (1993) to break down the electricity price into three parts: the historical highest price P^{MAX}, the price drop P^{CUT} and the price increase P^{REC}. The relationship between electricity prices and the three of them is as follows:

$$P_{E_{it}} = P_{E_{it}}^{max} \times P_{E_{it}}^{cut} \times P_{E_{it}}^{rec} \tag{7}$$

$$P_{E_{it}}^{max} = \max\{P_{E_{i1}}, P_{E_{i2}}, \ldots, P_{E_{iT}}\} \tag{7a}$$

$$P_{E_{it}}^{cut} = \prod\nolimits_{m=0}^{t} min\left\{1, \left(\left(P_{E_{i,m-1}}^{max} \middle/ P_{E_{i,m-1}}\right) \middle/ \left(P_{E_{im}}^{max} \middle/ P_{E_{im}}\right)\right)\right\} \tag{7b}$$

$$P_{E_{it}}^{rec} = \prod\nolimits_{m=0}^{t} max\left\{1, \left(\left(P_{E_{i,m-1}}^{max} \middle/ P_{E_{i,m-1}}\right) \middle/ \left(P_{E_{im}}^{max} \middle/ P_{E_{im}}\right)\right)\right\} \tag{7c}$$

The decomposed electricity price chart is shown in Fig. 1.

The key to the study of electricity rebound effects is to assess the reduction in the price of electricity caused by the electricity-specific technological progress source (i.e., the drop in the price after the decomposition of the electricity price), resulting in additional electricity consumption. At the same time, this paper considers two main ways of technological progress, namely, independent innovation and technology import.

2.2. Empirical strategy

It can be seen from the above analysis that, first of all, what really affects the electricity rebound effect is the decline in electricity price. Therefore, this paper breaks down the electricity price into three parts according to the above method, and measures the rebound effect by the part of the electricity price drop; compared with the direct use of electricity price elasticity, this method improves the reliability and accuracy of the rebound effect value.

Second, the electricity-saving effects of different technological progress sources are not the same. Accordingly, different technological progress sources have different effects on the electricity rebound effect (Deng et al., 2018). Independent innovation and technology import are the two main sources of technological progress. This paper examines the impact of these two technological progress ways on the electricity rebound effect.

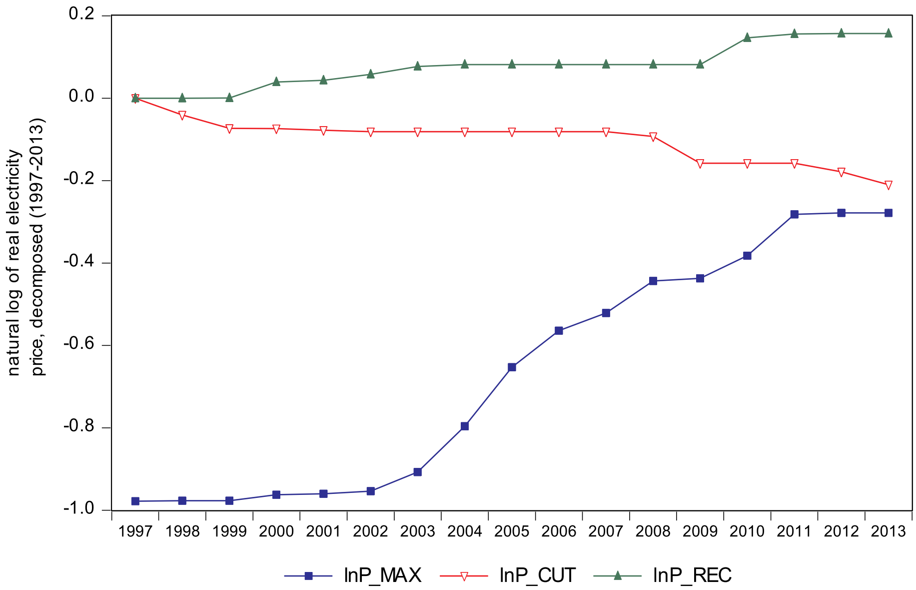

Fig. 1. Decomposition of the logrithm of electricity price in 1997–2013. *Data Source:* This paper uses the average selling price of electricity published by the former State Electricity Commission and converts it to the constant price of the year 2000 according to the purchasing price index of fuel and power for which a unit CNY/kilowatt-hour. Data originate from each year's *Supervision Report on Electricity Transaction and market order in China, Supervision Report on Executive Condition of electricity Price, Annual Report on Electricity Supervision and Notification on Electric Charge Settlement.*

The Chinese government has certain differences in the support policies for the two different technological progress ways. The impacts of these two ways are fundamentally different (Li, 2018). Therefore, there is reason to believe that there are significant differences in the impact of the two technological progress ways on electricity consumption. Based on this, this paper first directly investigates the impact of electricity price changes on electricity consumption. The basic model is as follows:

$$\ln ele_{it} = \alpha + \beta_1 \ln PE\_Cut_{it} + \beta_2 \ln TP\_inn_{it} + \beta_3 \ln TP\_imp_{it} + \beta_4 \ln T_{it} + X_{it} + \varepsilon_{it} \quad (8)$$

In the above formula, ele_{it} represents the level of electricity consumption, measured by the total annual electricity consumption of each province; PE_cut_{it} represents the part of the electricity price decline; TP_inn_{it} is the independent innovation characterized by the energy independent research and development of knowledge stock; TP_imp_{it} is introduced by technology introduction of technology; X_{it} is the set of control variables; T is the time trend term; ε_{it} is the random disturbance term; i and t represent the provinces and years of the Chinese mainland respectively; *ln* is the logarithmic operator.

From the perspective of the influencing factors of electricity consumption, on the one hand, although the decline in electricity price has the largest contribution rate to the electricity rebound effect, the historical high price of electricity and the increase in electricity price will also affect electricity consumption, and the three components of electricity price are related. On the other hand, electricity consumption is affected by economic development factors such as GDP, industrial development level, and urbanization level. Generally speaking, the higher level of GDP, industrial development and urbanization will bring about a higher level of electricity consumption. Based on this, this paper mainly focuses on GDP ($\ln GDP_{it}$), the historical highest price of electricity ($\ln PE\_max_{it}$), the rising part of electricity ($\ln PE\_rec_{it}$), and the proportion of tertiary industry in the secondary industry from two perspectives of electricity price change and economic development level. The level of industrialization ($\ln IND_{it}$), the level of urbanization (URB) measured by the proportion of urban population to total population, are included in the set of control variables.

The aforementioned theoretical analysis shows that technological progress will lead to a decline in the actual cost of electricity use, thereby affecting the self-price elasticity of electricity consumption. In order to investigate whether the decline in electricity prices caused by different technological progress ways contributes to electricity saving, we include interaction terms of technological advancement (independent innovation, technology import) and electricity price decline in model (8), namely $\ln TP\_inn * \ln PE\_Cut_{it}$, and $\ln TP\_imp * \ln PE\_Cut_{it}$. On the one hand, this improvement examines the transmission mechanism of the rebound effect more clearly.The impact of technological progress on electricity consumption depends on price changes, and there are other factors. Therefore, increasing the number of interactive projects can directly test the impact of different technological progress on electricity consumption and electricity consumption. On the other hand, the impacts on electricity consumption depend on the interaction between technological progress and electricity price. Therefore, adding interaction items can describe it.

However, identifying the impact of electricity prices on electricity consumption may be plagued by endogenous problems. First, it can be seen that cities with higher GDP may bring about corresponding changes in electricity consumption, and change in electricity consumption will further affect its GDP. The same is true for the relationship between electricity prices and electricity consumption. In short, there is a two-way causal relationship between GDP and electricity consumption. There is also a two-way causal relationship between price and consumption. Secondly, since the three parts of the electricity price adopted in this paper are obtained by decomposition, they cannot be directly observed. There may be measurement errors to some extent. In order to solve the endogenous problem that may exist, this paper uses the two-stage least squares (2SLS) to re-estimate the model by using the first-order lag term of GDP, electricity price, electricity consumption as the instrumental variables (IVs). We believe that these IVs are suitable. Specifically, the reasons are as follows: First, GDP, electricity consumption are time-oriented, and electricity prices are sticky, so they and their own lags are strongly relevant. Secondly, the residuals related to power consumption in the current period will not be affected by the lag period variables.

In addition, for a long time, China's coal market has a dual-track system of planned coal (mainly coal for electricity plants) and market coal. The planned coal is guided to produce and sell according to the national plan. The coal supply, demand and transportation are signed together by the three parties. The price is subject to the government. The prices for market coal forms according to coal supply and demand. This dual-track system has caused many years of coal-electricity conflicts, as well as various transactional chaos. For coal enterprises, the "dual track system" is neither reasonable nor fair. Low-cost contract coal is a heavy burden for coal companies, but these losses are not fairly evenly shared by all coal companies. Increasingly severe coal conflicts have affected electricity supply, social harmony, and sustainability of the electricity industry. At the end of 2004, China issued coal electricity linkage policy. The coal-electricity linkage policy has improved the cost pressure on the power industry from rising coal prices and reduced unnecessary social impact, but this policy has affected the market-oriented changes in electricity prices to a certain extent. Therefore, coal-electricity linkage may have an impact on the electricity rebound effect. In order to investigate the impact of coal-electricity linkage on the electricity rebound effect, we introduce the dummy variable *colin* in model (8), which was set to 0 in 1997–2004 and 1 in 2005–2013.

2.3. Data description and variables

This paper takes 30 provinces, municipalities and autonomous regions in mainland China except Tibet as the research object. The sample period is from 1997 to 2013.

The explanatory variable is the electricity consumption (*ele*) of each place. The data comes from the "China Energy Statistics Yearbook" over the years, and the unit is 100 million kWh. The core explanatory variable is the electricity price. The average selling price[2] is used as a measure of electricity price and it comes from the former China Electricity Regulatory Commission. According to the price index of fuel and electricity purchases in various regions over the years, it is converted into the constant price in 2000, in units of yuan/kWh. In addition, the electricity price variable in model (8) is decomposed into three components according to equation (7): historical highest price P^{MAX}, price drop P^{CUT} and price increase P^{REC}.

For independent innovation, it is measured by the energy independent R&D knowledge stock, and it is widely adopted by many scholars, which can be estimated by the following formula:

$$\text{TP\_inn}_{it} = \sum_{s=0}^{\infty} e^{-\beta_1 s}\left[1 - e^{-\beta_2(s+1)}\right] PAT_{is} \tag{9}$$

In the above formula, β_1 and β_2 respectively represent the stale rate and diffusion rate of knowledge. According to Fang (2013)_ENREF_9, this paper set 36% and 3% respectively; PAT represents the number of energy patent licenses, and the data comes from Li and Lin (2016); *s* indicates the time from the base period to the current year.

The technology introduction is measured by the foreign technology import stock. Due to the lack of patent technology import data for various provinces, this paper uses foreign technology import expenditures of large and medium-sized industrial enterprises in various provinces to calculate the foreign technology import stock. Furthermore, the perpetual inventory method is used to estimate it. From the perspective of statistics, the foreign technology import expenditures can reflect the ability of technology introduction. In this sense, it is appropriate to use technology introduction expenditure to reflect the introduction of technology. It can be estimated as follows:

$$TP\_imp_{it} = E_{it} + (1-\delta)TP\_imp_{i,t-1} \tag{10}$$

Among them, E indicates the foreign technology import expenditure (calculated in 2000 constant price), and δ is the depreciation rate, which is set at 15% (see Table 1).

Table 1
Shows the descriptive statistics of the variables in this paper.

Variable	Obs	Mean	Std. Dev.	Min	Max
ele	510	929.4056	861.0725	34.6	4956.6
gdp	510	6841.619	7137.818	205.6817	46509.53
ind	510	0.3886506	0.0823913	0.1265931	0.5480025
ep	510	0.5366489	0.201177	0.2443052	1.343093
urb	510	0.4468218	0.1624801	0.140392	0.8960663
inn	510	602.6605	1352.641	2.378246	15697.35
imp	510	44.95915	56.41237	0.0013859	298.2236

3. Empirical results and discussions

3.1. 1Estimation results

This part uses equation (8) as the basic regression equation to estimate the impact of two technological progress ways on electricity consumption and rebound effects. The results are shown in Table 2.

Column (1) in Table 2 shows that independent innovation has a significant negative effect on electricity consumption. Specifically, for every 1% increase in independent innovation, electricity consumption is reduced by 0.064%; while the impact of technology import on electricity consumption is positive, but not significant. It can be seen that independent innovation contributes to electricity conservation, and the impact of technology import on electricity consumption is not statistically significant, and economically small (estimated value is small). Independent innovation is to further reduce electricity consumption by improving electricity efficiency, and ultimately achieve the purpose of electricity saving; while technology import is mainly based on material processing and equipment introduction, which may increase electricity consumption. In addition, the insufficient R&D investment, unreasonable structure and weak basic research in the central and western regions of China make the technology import subject to the local technology accumulation and learning ability, so the spillover effect of technology import is not obvious, thereby the impact on electricity consumption may not be significant. The direct rebound effect value of electricity consumption is 37.2% from the price elasticity of price drop component.

Column (2) in Table 2 shows that the self-price elasticity of the price drop component can be expressed as −0.895–0.098*lnTP_inn +0.383*lnTP_imp. This means that the price change driven by independent innovation further increases the self-price elasticity of the falling price of electricity, while the price change driven by technology import reduces the self-price elasticity of the falling price of electricity. Since the self-price elasticity measurability of the price drop component is the direct rebound effect value of electricity consumption, this result

Table 2
Impact of two technological progress sources on electricity rebound.

Variables		(1)	(2)
lnPE_Cut		−0.372*** (0.090)	−0.895*** (0.216)
lnTP_inn		−0.064*** (0.020)	−0.047 (0.033)
lnTP_imp		0.006 (0.004)	0.009 (0.005)
lnTP_inn*lnPE_Cut			−0.098* (0.053)
lnTP_imp*lnPE_Cut			0.383*** (0.054)
lnGDP		0.746*** (0.087)	0.719*** (0.104)
lnPE_Max		0.184*** (0.053)	0.202*** (0.055)
lnPE_Rec		0.325* (0.179)	0.366** (0.154)
lnIND		−0.319*** (0.051)	−0.243*** (0.042)
URB		1.253*** (0.222)	1.415*** (0.272)
lnT		−0.041** (0.016)	−0.043* (0.021)
Consant		0.112 (0.593)	0.209 (0.703)
Adjust R-squared		0.955	0.959
Obs.		510	510
Residual series unit root test	IPS	−2.566***	−2.490***
	PP-Fisher	125.042***	110.370***
	CADF	−2.526*	−2.811***

Notes: Robust standard errors are presented in parentheses under the coefficients.
***p < 0.01, **p < 0.05, *p < 0.10, p < 0.15.

[2] The average sales price refers to the weighted average price of full-caliber sales of power grid enterprises in various provinces, excluding government funds and surcharges.

indicates that the decline in electricity price driven by independent innovation is not conducive to electricity saving due to the amplification of the rebound effect, but is promoted by technology import. The decline in electricity prices has shown an electricity saving effect due to the reduced rebound effect. In other words, the energy efficiency of the power generation is increased by independent innovation, and the power consumption saved is much smaller than the power consumption that increases the effective price of electricity; the impact of technology import on electricity consumption is just the opposite. Although the technology import itself has no significant effect on the decline of electricity consumption, the rebound effect of electricity price decline caused by technology import is less than the electricity consumption saved by energy efficiency improvement. Therefore, the decline in electricity price driven by technology import has an electricity saving effect.

3.2. *The impact of coal-electricity linkage*

The contradiction between coal and electricity prices is one of the main contradictions in China's energy system. This contradiction has already affected electricity supply, social harmony, and sustainable development of the electricity industry. In order to alleviate the cost pressure on the electricity industry caused by the rise of coal, China implemented a coal-electricity linkage policy at the end of 2004. The coal-electricity linkage policy changes the supply-demand relationship by adjusting the price of coal indirectly to affect the price of electricity. It is not less than 6 months as a linkage period. If the average coal price in the cycle changes by 5% or more than the previous period, the electricity price will be adjusted. So that the price of electricity will change with the price of coal, and the price mechanism will be up and down. Through the relatively market-oriented mechanism design, coal-electricity linkage requires that every link in the industrial chain absorbs some of the price increase pressure, and then cooperates with the market-oriented supporting policies such as taxation and subsidies to influence the market and regulate electricity prices, and thus affects the rebound effect. Therefore, we subdivided the sample into coal-electricity linkage implementation (1997–2003) and coal-fired linkage implementation (2004–2013).Since coal-electricity linkage changes the trend of the whole electricity price, this paper takes the three components of electricity price as the variables affected by the policy, and uses the threshold regression model to re-estimate the model (8). The results are shown in Table 3.

Column (1) in Table 3 shows that after coal-electricity linkage, the influence of lnPE_Cut on electricity consumption is significantly negative, and the coefficient rises from −0.611 to −0.344, indicating that after coal-electricity linkage, the increase in electricity consumption due to the decrease in electricity price is reduced. It can be seen that the coal-electricity linkage policy has reduced the rebound effect. Column (2) in Table 3 shows that the influence of lnTP_inn*lnPE_Cut on electricity consumption is significantly negative, and the coefficient rises from −0.618 to −0.123, indicating that after coal-electricity linkage, the increase in electricity consumption due to the decrease in electricity price is reduced, and independent innovation has an electricity-saving effect. The influence of lnTP_imp*lnPE_Cut on electricity consumption is significantly positive, and the coefficient drops from 1.076 to 0.395, which indicates that after coal-electricity linkage, the increase in electricity consumption due to the decrease in electricity price has increased, and the technology import has no electricity-saving effect. From the perspective of the source, coal-electricity linkage has reduced the rebound effect and improved the electricity-saving effect of independent innovation, but at the same time reduced the electricity-saving effect of technology import.

The above regression results show that the coal-electricity linkage policy has generally reduced the rebound effect and effectively saved electricity consumption, but it has not improved the electricity-saving effect of various technological ways, which is determined by the complexity of China's technological innovation background. Independent innovation is closely integrated with localization characteristics and is more adaptable to changes in the Chinese market. However, technology import lacks the ability to change with China's localized market. Therefore, the impact of coal-electricity linkage policy on China's electricity market can effectively improve the electricity-saving effect of independent innovation, and it cannot improve the electricity-saving effect of technology import.

Table 3
Impact of coal-electricity linkage policy on electricity rebound effect.

Variables		(1)	(2)
lnPE_Cut	Year<2004	−0.611° (0.040)	−0.818*** (0.195)
	Year>2004	−0.344*** (0.076)	
lnTP_inn*lnPE_Cut	Year<2004		−0.618** (0.228)
	Year>2004		−0.123* (0.079)
lnTP_imp*lnPE_Cut	Year<2004		1.076*** (0.283)
	Year>2004		0.395*** (0.063)
lnPE_Max	Year<2004	0.162* (0.087)	0.213** (0.079)
	Year>2004	0.097* (0.057)	0.124** (0.056)
lnPE_Rec	Year<2004	0.033 (0.206)	0.556** (0.231)
	Year>2004	0.424* (0.218)	0.417** (0.152)
lnTP_inn		−0.056** (0.025)	−0.079** (0.025)
lnTP_imp		0.008* (0.004)	0.022** (0.003)
lnGDP		0.733*** (0.089)	0.780*** (0.099)
lnIND		−0.292*** (0.047)	−0.210*** (0.037)
URB		1.325*** (0.260)	1.508*** (0.291)
lnT		−0.054** (0.023)	−0.087** (0.023)
Consant		0.131 (0.596)	−0.146 (0.690)
Adjust R-squared		0.956	0.960
Obs.		510	510
Residual series unit root test	IPS	−2.609***	−2.788***
	PP-Fisher	139.398***	145.325***
	CADF	−2.501°	−2.854***

Notes: Robust standard errors are presented in parentheses under the coefficients. ***p < 0.01, **p < 0.05, *p < 0.10, ° p < 0.15.

3.3. *Endogenous discussion*

Table 4 shows the results for the 2SLS. Column (1) in Table 4 shows that the impact of independent innovation on electricity consumption is significantly negative, while the impact of technology import on electricity consumption is not significant. Column (2) in Table 4 shows that

Table 4
Endogenous test regression results.

Variables		(1)	(2)
lnPE_Cut		−0.818** (0.346)	−0.783* (0.420)
lnTP_inn		−0.068* (0.035)	−0.015 (0.039)
lnTP_imp		0.011 (0.014)	0.014 (0.015)
lnTP_inn*lnPE_Cut			−0.024 (0.115)
lnTP_imp*lnPE_Cut			0.225* (0.131)
lnGDP		0.798*** (0.093)	0.666*** (0.092)
lnPE_Max		−0.039 (0.081)	0.189*** (0.069)
lnPE_Rec		−0.721* (0.447)	0.576° (0.356)
lnIND		−0.330*** (0.047)	−0.248*** (0.052)
URB		1.537*** (0.214)	1.267*** (0.203)
lnT		0.020 (0.046)	−0.006* (0.043)
Obs.		480	480
Residual series unit root test	IPS	−2.416***	−2.540***
	PP-Fisher	91.846***	99.860***
	CADF	−7.708***	−2.890***

Notes: Robust standard errors are presented in parentheses under the coefficients.
***p < 0.01, **p < 0.05, *p < 0.10, p < 0.15.

the partial effect of independent innovation on electricity consumption is −0.015–0.024*lnPE_Cut, and the partial effect of technology import on electricity consumption is −0.015 + 0.225 *lnPE_Cut. It can be seen that the decline in electricity prices driven by independent innovation is not conducive to electricity conservation, and the decline in electricity prices driven by technology import has an electricity saving effect. The partial elasticity of electricity price decline is −0.783–0.024 *lnTP_inn+0.225*lnTP_imp. It can be seen that independent innovation increases the rebound effect, while technology import reduces the rebound effect. The above conclusions are consistent with the results of Table 2.

3.4. Robustness analysis

In order to test the robustness of the above results, this part replaces independent innovation with energy technology patent ownership by thousand people, and replaces the technology with the proportion of fixed assets investment in the whole society. The regression results are shown in Table 5. As shown in column (1) of Table 5, the development of energy patents helps to save electricity, but the introduction of FDI increases electricity consumption. Column (2) shows that although coal-electricity linkage has reduced the rebound effect, the development of energy patents still helps to save electricity, but the introduction of FDI has increased electricity consumption. Column (3) shows that the partial effect of energy patents on electricity consumption is −0.019–0.035 *lnPE_Cut, and the partial effect of FDI introduction on electricity consumption is 0.716 + 6.108 *lnPE_Cut. As the decline in electricity prices means that the negative value of lnPE_Cut is getting larger and larger, the decline in electricity prices driven by energy patents is not conducive to electricity savings, and the decline in electricity prices driven by the introduction of FDI has an electricity saving effect. In addition, from the perspective of the rebound effect, the partial elasticity of the price decline is −0.751–0.035 *patent + patent *fdi, it can be seen that the energy patent has increased the rebound effect, and the introduction of FDI has reduced the rebound effect. Column (4) shows that coal-electricity linkage improves the energy-saving performance of energy patents, but at the same time reduces the electricity-saving effect of FDI introduction. These results also support the benchmark conclusions of this paper, indicating that the estimation results in this paper are robust.

4. Conclusions and policy implications

From the above analysis, we can safely draw some conclusions as follows:

First, from the impact of technological progress on electricity consumption, independent innovation contributes to electricity conservation, and the impact of technology import on electricity saving is not obvious. The possible reason is that the conditional matching of independent innovation is higher. For the power industry, independent innovation is an innovation for the actual situation of the local power industry, and can better match the actual situation of the local power industry, so it can improve energy efficiency more effectively, thus helping to save energy. While technology introduction can directly obtain more mature new technologies in the world, purchasing new technologies will bring huge upfront investment, and it will take a long period to absorb new technologies. At the same time, the matching degree between foreign technology and local production conditions will have an impact on the power saving effect. Therefore, the electricity saving effect brought by the technology import is not obvious. Second, from the mechanism of the rebound effect, the decline in electricity prices driven by independent innovation has increased the rebound effect, while the decline in electricity prices driven by technology import has reduced the rebound effect. In other words, independent innovation can help to improve energy efficiency and reduce costs of electricity plants, and thus the reduced electricity price stimulates users' demand for electricity to a certain extent, and thus increases rebound effect. However, the decline in electricity prices brought about by technology import is less than independent innovation, so the energy saved by technology import is greater than the increase in electricity price, thus the rebound effect is reduced. Third, the coal-electricity linkage policy adjusts the electricity price by monitoring the change of coal price within a certain period. Under the background of high energy efficiency, the rebound effect is reduced, and the electricity-saving effect of independent innovation is improved, but the electricity-saving of technology import is also reduced.

Unlike previous studies, such as L. Parente and C. Prescott (1994), Deng and Li (2018), this paper analyzes the impact of technological advances on power consumption from two paths of independent innovation and technology introduction, and explores the rebound effect of power consumption through innovation, and more accurately calculates

Table 5
Robustness test regression results.

Variables		(1)	(2)	(3)	(4)
lnPE_Cut	Year<2004	−0.343*** (0.094)	−0.615· (0.378)	−0.751*** (0.143)	−0.811*** (0.138)
	Year>2004		−0.341*** (0.097)		
patent		−0.010*** (0.002)	−0.010*** (0.002)	−0.019*** (0.006)	−0.014** (0.006)
fdi		0.348** (0.164)	0.352** (0.150)	0.716*** (0.113)	0.712*** (0.112)
patent*lnPE_Cut	Year<2004			−0.035* (0.019)	−0.255*** (0.087)
	Year>2004				−0.025 (0.019)
fdi*lnPE_Cut	Year<2004			6.108*** (0.967)	5.863*** (1.459)
	Year>2004				5.665*** (1.052)
lnGDP		0.682*** (0.075)	0.682*** (0.064)	0.656*** (0.081)	0.647*** (0.074)
lnPE_Max	Year<2004	0.169*** (0.041)	0.149** (0.065)	0.165*** (0.047)	0.158*** (0.050)
	Year>2004		0.077* (0.042)		0.095** (0.044)
lnPE_Rec	Year<2004	0.381* (0.211)	0.107 (0.225)	0.245 (0.221)	0.170 (0.282)
	Year>2004		0.471* (0.256)		0.250 (0.201)
lnIND		−0.291*** (0.045)	−0.260*** (0.038)	−0.266*** (0.041)	−0.242*** (0.036)
URB		1.147*** (0.224)	1.245*** (0.269)	1.215*** (0.227)	1.275*** (0.232)
lnT		−0.023 (0.017)	−0.039* (0.022)	0.001 (0.022)	−0.014 (0.019)
Consant		0.310 (0.549)	0.266 (0.460)	0.434 (0.602)	0.488 (0.549)
within R-squared		0.956	0.957	0.959	0.960
Obs		510	510	510	510
Residual series unit root test	IPS	−2.326***	−2.477***	−2.378***	−2.463
	PP-Fisher	87.833**	117.484***	96.549***	107.427
	CADF	−2.787***	−2.707**	−2.483°	−2.467

Notes: Robust standard errors are presented in parentheses under the coefficients.
***p < 0.01, **p < 0.05, *p < 0.10, p < 0.15.

the difference in technological progress due to the rebound effect. The approach has a power-saving effect on power consumption, making up for the gaps in previous research.

In recent years, the two technological progress paths of independent innovation and technology introduction around the goal of "energy saving and emission reduction" have been implemented in large and small power plants. At present, this kind of energy-saving ideas led by technological progress and energy efficiency is effective, but it does not maximize the energy-saving potential. Due to the rapid growth of China's economy at this stage, the excessive consumption of energy makes China's rebound effect higher than that of major developed countries. How to optimize the path of technological progress to decrease the rebound effect is an urgent problem to be solved. First, the Chinese government should encourage independent innovation and technology import, and introduce relevant laws and regulations, such as protection and support for energy patents, appropriate encouragement of FDI, subsidies for technological progress of electricity plants, etc., thereby promoting the further development of independent innovation, and thus is expected to further improve electricity efficiency and reduce electricity consumption. Second, the consumer's additional electricity consumption due to the decline in the price of electricity services is appropriately limited, that is, the consumer's spontaneous additional demand is effectively limited, and the amount of rebound is controlled within a scientific and reasonable range. Finally, we should adhere to the coal-electricity linkage policy in the short term and establish a long-term price mechanism. China's coal-electricity linkage mechanism can not only solve the problem of fuel cost of electricity companies, but should focus more on alleviating the financial difficulties of electricity companies and solving the contradiction between short-term coal-fired electricity.

Effectively promoting coal-electricity linkage requires transparent rules and the government strictly follows the rules. In the long run, the fundamental solution is the market-oriented price mechanism reform. In the process of China's economic transformation, due to the lack of market-oriented reforms, it is impossible to carry out a one-time, holistic reform of electricity price marketization. We can first take the coal-electricity operation as the main line of reform, gradually improve the linkage mechanism, and gradually improve the electricity price system, and do a corresponding supporting work for market-oriented reform.

Acknowledgment

We acknowledge the financial support from the National Natural Science Foundation of China (Nos. 71773028, 71603079,71703120, 71974054), the Hunan Natural Science Foundation (No. 2019JJ40039), the Education Department Project of Hunan Province (No.17A142), the International Clean Energy Talent Program (No. LIUJINFA[2017]5047-201702660011), and Beijing Finance Project (PXM2019-178216-000004-00341472-FCG-Innovative project-preresearch).

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