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Does electricity price matter for innovation in renewable energy technologies in China?

Boqiang Lin *, Yufang Chen

School of Management, China Institute for Studies in Energy Policy, Collaborative Innovation Center for Energy Economics and Energy Policy, Xiamen University, Fujian 361005, PR China

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ABSTRACT

Though the development of renewable energy is rapid, innovation in renewable energy technologies is relatively weak due to the late commencement of renewable energy in China. In addition, renewable energy is mainly introduced into the supply mix of electricity generation, which increases the costs of electricity generation. Higher electricity price will make renewable energy more competitive and call forth renewable energy technological innovation. Based on FMOLS and DOLS models, as well as PMG model, this paper investigates the induced long and short run effects of electricity price, funding support, and economic growth on innovation in renewable energy technologies at the provincial level in China during the period 2006–2016. The Conclusions drawn were: (1) R&D expenditure and economic growth have positive impacts on innovation in renewable energy technologies in the long and short run; (2) Electricity price only has a long run effect on patenting in renewable energy technologies; (3) In the long run, a 1% increase in electricity price can lead to a 0.7825%–1.0952% increase in the patent counts of renewable energy technologies; (4) Electricity pricing system in China does not play any role in driving renewable energy technological innovation in the short run.

1. Introduction

The role of renewable energy in global climate change mitigation and energy supply security has been widely recognized. In recent years, the renewable energy industry in China has developed rapidly. This is reflected in two aspects: (1) The scale of renewable energy market has rapidly expanded, as the newly installed capacity of wind energy and solar photovoltaic energy in China ranked first globally in 2017, and renewable power generation is expected to rank first in the world; (2) China's renewable energy investment in 2017 reached 126.6 billion dollar, and accounted for 45% of global green energy investment.

Broadly defined, renewable energy includes wind energy, solar energy, biomass and waste energy, geothermal energy, ocean energy, and hydro energy. Due to the matured development stage of hydroelectricity, the growth rate of hydroelectricity will not be very significant in the future (Lin and Chen, 2018). In China, the scale of development of wind energy, solar energy, biomass and waste energy, geothermal energy and ocean energy will still be expanded to realize the target of emission reduction and increase the share of renewable energy in total energy use. Moreover, the cost of hydroelectricity is closed to that of thermal power, while wind energy, solar energy, biomass and waste energy, geothermal energy and ocean energy need a very large significant amount of renewable energy subsidies from the government due to their higher costs. Therefore, renewable energy in this paper includes only wind energy, solar energy, biomass and waste energy, geothermal energy and ocean energy.

Though the development of renewable energy is rapid, innovation in renewable energy technologies is relatively weak due to the late commencement of renewable energy in China. However, renewable energy technology innovation is the key to the development of renewable energy. Patent counts and patent stock are generally used to measure the outcome of technological development process, which provides a valuable source of information on the nature of the invention and reflects the innovative performance (Griliches, 1990; Archibugi and Pianta, 1996; Lindman and Söderholm, 2016; Li and Lin, 2016; Lam et al., 2017; Schleicha et al., 2017; Böhringer et al., 2017; Hu et al., 2018; He et al., 2018; Lach, 1995; Park and Park, 2006; Grafström and Lindman, 2017; Kim et al., 2018). Hence, patent counts are the most important indicator of technological innovation and are widely used to proxy technological innovation in many studies. Compared with inputs of technological innovation, patent counts as an outcome are more direct, and are strongly correlated with R&D spending (Griliches, 1990). Though not all invention is patented, there are very few

* Corresponding author.
E-mail address: bqlin@xmu.edu.cn (B. Lin).

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significant inventions without patenting (Johnstone et al., 2010), which also indicates that patent counts can better reflect the technological innovation performance. There are also two advantages of adopting patent counts and patent stock to proxy innovation in renewable energy technologies. One is that patent counts and patent stock are related to invention and also can be disaggregated into specific technological areas, and the other is that the data on the number of patent counts are available and patent stock is easily calculated from patent counts (Lindman and Söderholm, 2016; Park and Park, 2006; Cohen et al., 2017). In summary, patent counts and patent stock are good proxies for innovative activities. In general, the patent counts in renewable energy technologies are collected according to the International Patent Classification (IPC) codes of each kind of renewable energy technologies, following the studies of Popp et al. (2011), Johnstone et al. (2010) and Noailly and Shestalova (2017). Therefore, based on this definition, the IPC codes of each kind of renewable energy technologies are shown in Appendix A, Table A. Before the renewable energy industry entered the stage of large-scale commercialization, patent counts of renewable energy were at a low level mainly because renewable energy in China started late and lacked the core technologies. In 2005, the National Development and Reform Committee (NDRC) issued the *Guiding Catalogue on Renewable Energy Development*, which, to a certain extent, increased the patent counts of renewable energy technologies.

From Fig. 1, all provinces in China have patent counts of renewable energy technologies, and the patent counts concentrate on wind energy and solar energy. However, there are great differences in patent counts among provinces. As shown in Fig. 1, the patent counts are concentrated mostly in coastal developed areas. The advantages of intensive technology and labor in the coastal developed areas, such as Jiangsu, Beijing, Zhejiang, Shandong, Guangdong, and Shanghai, facilitates more patent counts. These coastal developed areas have more energy enterprises, research institutions, colleges and universities and research and development personnel, which also require effective investment in R&D activities to drive innovation (Li and Lin, 2016). In addition, these coastal developed areas with a high level of economic development have the abilities to pay more for renewable energy technologies to improve environmental quality and increase electricity demand. Therefore, a higher level of economic growth has induced effect on innovation.

Though many studies focus on the role of energy price in technological innovation, the impact of electricity price on innovation in renewable energy technologies would be discussed in this paper. Firstly, renewable energy is mainly introduced into the supply mix of electricity generation, which may increase the costs of electricity generation. A relatively effective electricity pricing system should consider the increasing costs and keep a reasonable increase in electricity price. Higher electricity price will make renewable energy more competitive and call forth innovation in renewable energy technologies to reduce costs of electricity generation. Secondly, energy price mainly contains fossil fuel price. However, fossil fuel price can affect the diffusion of renewable energy technologies which has taken place after the innovation (Grafström and Lindman, 2017). Unlike energy price, electricity price has a direct induced effect on innovation in renewable energy technologies. Besides, the development of renewable energy technologies relying on government subsidies is not a long-term and effective measure, and subsidy policies will be eventually canceled. Whether electricity price can accurately reflect the cost of electricity generation and market value would impact the renewable energy technological innovation. Thus, this paper argues that there is induced effect of electricity price on patent counts of renewable energy technologies. Some researchers indicate that an increase in electricity price will drive innovation of renewable energy technologies (Johnstone et al., 2010; Nicolli and Vona, 2016; Schleicha et al., 2017). Others find that lower electricity price enhances renewable energy technologies (He et al., 2018). Is China's electricity pricing system effectively and significantly conducive for innovation in renewable energy technologies? Is there a long run equilibrium relationship between electricity price and renewable energy technological innovation? Although this paper concentrates on the effect of electricity prices on innovation in renewable energy technologies, this paper also seeks to answer the question: What factors influence innovative activity?

Following the above, this paper investigates the long run and short run effects of electricity price, funding support, and economic environment on innovation in renewable energy technologies at the provincial level in China. The remainder of this paper is organized as follows: Section 2 briefly reviews existing research. In Section 3, the data used are described, and the estimation methods are introduced. Section 4 presents the results and discussion. The last section presents the conclusions and some policy suggestions.

2. Literature review

Regarding the relationship between energy price and innovation, there is “induced effect” of increasing energy price on innovation (Popp, 2002). An increase in energy prices (calculated by electricity price, light fuel price, and natural gas price) may stimulate green knowledge stock and establish a clean-tech market (Ley et al., 2013). Increasing oil prices can also reinforce existing innovation systems (Cheon and Urpelainen, 2012). Using the Poisson model, Kruse and Wetzel (2016) found that energy prices had a positive impact on innovation for solar energy and ocean energy technologies. Higher electricity price may also have positive “induced effect” on innovation in renewable energy

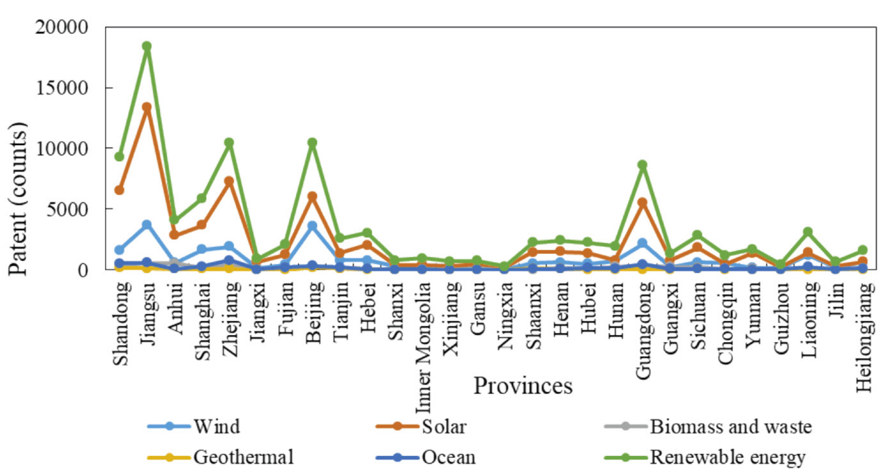

Fig. 1. Cumulative total patent counts of renewable energy technologies across 28 provinces in China during 2006–2017 (excluding Qinghai, Hainan, Tibet, Hong Kong, Macao, and Taiwan).

technologies because renewable energy is generally used to generate power and is simultaneously sold with thermal power. However, the costs of electricity generation from renewable energy are greater than from thermal power (Johnstone et al., 2010). Higher electricity price is conducive for the introduction of renewable energy into the supply mix (Biresselioglu et al., 2016), which reflects more demand for renewable energy and call forth innovation in renewable energy technologies. Therefore, a reasonable increase in electricity price can make renewable energy more competitive and can promote renewable energy technologies (Ouyang and Lin, 2014). In addition, increasing electricity price will signal a higher profit in the future, which will drive innovation of renewable energy technologies (Johnstone et al., 2010; Schleicha et al., 2017). Increasing electricity price has become an important approach to improve electricity generation efficiency (Lin and Liu, 2013), including renewable energy electricity generation efficiency. However, Li and Lin (2016), using panel cointegration and VEC model, proved that energy price was not a significant determinant of energy technology. In other words, China's energy price system impedes innovation in energy technology. Additionally, He et al. (2018) applied the dynamic panel model and found that lower electricity price enhances renewable energy technologies. The above studies reach different conclusions on the impact of electricity price on innovation, and hence, it requires further study. Some researchers use households and industrial end-use price as a proxy for electricity price (Johnstone et al., 2010; Nicolli and Vona, 2016; He et al., 2018), while others use electricity prices for households (Schleicha et al., 2017). In China, the growth of residential electricity is fast in recent years, and the contribution of residential electricity to the electricity consumption of the whole society continues to increase. Additionally, the data on electricity prices for households including surcharges for renewable energy and other governmental projects, which can still capture the induced effect on innovation in renewable energy technologies and reflect investment incentives for renewable energy manufacturers (Schleicha et al., 2017). To some extent, the data on electricity prices for households take account of the renewable energy generation costs. Hence, this paper adopts electricity prices for households (EP) as a proxy for electricity prices.

With respect to the impact of funding support, Popp et al. (2011) and Johnstone et al. (2012) investigated that R&D expenditure is very important for innovation in renewable energy technologies. Johnstone et al. (2010), Nicolli and Vona (2016), Lindman and Söderholm (2016) and Schleicha et al. (2017) used negative binomial fixed effect model and found that R&D investment has an induced effect on innovation in certain renewable energy technologies, especially wind energy and solar energy. However, many studies like Böhringer et al. (2017) and Grafström and Lindman (2017) also illustrated that investment in R&D activities did not have a significant impact on innovation in renewable energy technologies at the matured phase while public R&D spending played a positive role in renewable energy technologies at the early and large-scale development stages. This result suggests that the Chinese government should focus on making efficient use of R&D spending to promote innovation in renewable energy technologies. However, it is hard to obtain data on investment in renewable energy R&D activities at the provincial level in China. Li and Lin (2016) showed that the trend of energy R&D spending was consistent with that of R&D expenditure. The trend of funding for R&D of renewable energy is also consistent with that of investment in R&D activities. Therefore, this paper uses China's investment on R&D activities (RD) as a proxy for funding support because R&D support is the most representative impetus encouraging patenting in renewable energy technologies. The data has been deflated by consumer price index (CPI) (2006 = 1).

Similar to funding support, economic growth plays a positive role in stimulating patenting in renewable energy technologies. Firstly, economic growth shows the willingness to pay for renewable energy technologies, in order to improve environmental quality (Diekmann and Franzen, 1999), and can overcome the higher costs of renewable energy and the costs related with the innovation in renewable energy technologies (Chang et al., 2009). Secondly, economic growth has an important effect on increase in electricity consumption (Narayan and Smyth, 2008; Tang and Tan, 2013; Zhao et al., 2016), which shows that higher demand for electricity will have market size effect (Nicolli and Vona, 2016) and ultimately call forth and trigger innovation (He et al., 2018). Thirdly, the provinces with a higher level of economic development have more research institutions, colleges, and universities, and attract more research and development personnel (Xu and Lin, 2018). Many studies also prove that economic growth is a driving force of innovation (Nicolli and Vona, 2016; Li and Lin, 2016). Therefore, regional Gross Domestic Product (GDP) is used as a proxy for economic growth in this paper. It has been deflated by an indicator of Gross Domestic Product (2006 = 1).

The existing literature has some limitations: Firstly, most studies consider the effects of energy price, R&D funding and economic growth on innovation in renewable energy technologies using negative binomial fixed effect model, Poisson model or dynamic GMM model at the cross-country level. Few studies analyze the long run and short run effects of energy price, R&D expenditure and economic growth on innovation in renewable energy technologies at the provincial level in China. Secondly, most studies pay attention to energy price, but not electricity price. However, renewable energy is mainly introduced into the supply mix of electricity generation. Additionally, energy price mainly contains fossil fuel price. However, fossil fuel price can affect the diffusion of renewable energy technologies which has taken place after the innovation (Grafström and Lindman, 2017). Unlike energy price, electricity price has a direct induced effect on innovation in renewable energy technologies. Besides, the development of renewable energy technologies relying on government subsidies is not a long-term and effective measure, and subsidy policies will be eventually canceled. Whether electricity price can accurately reflect the cost of electricity generation and market value would impact the renewable energy technological innovation. Therefore, whether there is an induced effect of electricity price on patent counts of renewable energy technologies is a very interesting issue. Thirdly, few studies analyze that electricity price plays a role in renewable energy technological innovation from the perspective of long run effect and short run dynamics. There is also a controversy on the positive or negative impact of electricity price on innovation in renewable energy technologies. Thus, this study is of great significance to the literature and policy discussions. This paper can provide targeted policy suggestions according to the conclusions of our study.

3. Data and methods

3.1. Data sources and description

The data on electricity prices for households are available during the period from 2006 to 2016. Due to the minimal share of patent counts in Qinghai, Hainan, and Tibet, these provinces are excluded from the analysis. The data on electricity prices for households in Hong Kong, Macao and Taiwan are not available. Therefore, the provincial data applied in the study are from 2006 to 2016, which includes only 28 provinces (excluding Qinghai, Hainan, Tibet, Hong Kong, Macao, and Taiwan) in China.

To check the robustness of the estimates, patent counts of renewable energy technologies are substituted with patent counts of wind energy technologies (WPC), solar energy technologies (SPC), and patent stock of renewable energy technologies (NPS). Besides, R&D funding and regional GDP have been further substituted with R&D intensity (RDI) and electricity consumption (EC).

The patent counts of renewable energy technologies, wind energy technologies and solar energy technologies are available in the Chinese Patent Online Databases published by China's State Intellectual Property Office (SIPO). The patent stock of renewable energy technologies is calculated from the patent counts of renewable energy technologies.

Table 1
Introduction of variables.

Category	Variable (Unite)	Content	Data sources
Innovation	NPC (counts)	Patent counts of renewable energy technologies	Chinese Patent Online Databases
	WPC (counts)	Patent counts of wind energy technologies	
	SPC (counts)	Patent counts of solar energy technologies	
Electricity prices	EP (CNY/kWh)	Electricity prices for households	WIND
Funding support	RD (million CNY)	Investment in R&D activities	WIND
	RDI (%)	R&D intensity	WIND
Economic growth	GDP (100 million CNY)	Regional Gross Domestic Product	National Bureau of Statistics (NBS)
	EC (100 million kWh)	Electricity consumption	National Bureau of Statistics (NBS)

The data on investment in R&D activities, R&D intensity and electricity prices for households are obtained from WIND. The data on regional GDP and electricity consumption for the period 2006 to 2016 are collected from the National Bureau of Statistics (NBS). The detailed description of the variables is shown in Table 1.

A panel sample data of 28 provinces in China from 2006 to 2016 was used in this paper. In our estimations, all the variables, except R&D intensity, are in natural logarithm in order to make the data stable. The summary statistics of the variables are shown in Table 2.

3.2. Model specifications

In order to investigate the roles of electricity price in innovation in renewable energy technologies, China's provincial data from 2006 to 2016 are used. The relationships and impacts of funding support and economic growth on patenting in renewable energy technologies are also analyzed. The model constructed for the study is shown below:

$$\ln NPC_{it} = \beta_0 + \beta_1 \ \ln EP_{it} + \beta_2 \ \ln RD_{it} + \beta_3 \ \ln GDP_{it} + \varepsilon_{it} \tag{1}$$

In Eq. (1), NPC represents patent counts of renewable energy technologies. EP is electricity price of households, and RD denotes R&D expenditure as a proxy for funding support. GDP is regional Gross Domestic Product as a proxy for economic growth. In Eq. (1), $i = 1, \cdots\cdots$, 28 indexes the 28 provinces in China, and $t = 2006, \cdots\cdots$, 2016 indexes time. ε_{it} denotes the error term.

Due to the induced effect of electricity price on innovation in renewable energy technologies, a rational increase in electricity price can promote patenting in renewable energy technologies. However, improved renewable energy technologies may reduce power generation cost, which may result in lower electricity price and an increase in electricity consumption. Additionally, R&D funding stimulates innovation. At the same time, development of renewable energy technologies may also attract R&D investment. Therefore, there are biases in estimating the relationships. Moreover, when the variables are cointegrated, the traditional regression models, such as pooled OLS, fixed effect model and dynamic panel model, are biased and produce inconsistent estimates. To estimate long run effects of electricity price, R&D expenditure and regional GDP on innovation in renewable energy technologies, the dynamic OLS (DOLS) and the fully-modified OLS (FMOLS) (Phillips and Hansen, 1990; Saikkonen, 1991; Phillips and Moon, 1999) are applied. DOLS is a parametric method, while FMOLS is a nonparametric method (Lin and Omoju, 2017). However, the FMOLS are more appropriate for the short panel data. Thus, this paper mainly pays attention to the results of the FMOLS model.

Next, the short run coefficients between electricity price and innovation in renewable energy technologies are estimated by panel ECM. Mean-group (MG), dynamic fixed-effect (DFE) and pooled mean-group (PMG) estimators can be used to analyze short run dynamics. DFE allows constant short-run and long-run slope parameters, while MG permits the slope parameters to change in the short run and long run (Salim et al., 2017). PMG assumes the slope parameters to vary in the short run but imposes homogenous slope parameters across all cross-sectional units in the long run (Pesaran et al., 1999). According to the results of joint Hausman test, the PMG estimator is more suitable for our study.

Table 2
Summary statistics of the variables used in the estimations.

Variable	Obs	Mean	Std. dev.	Min	Max
lnNPC	308	4.8982	1.2665	1.3863	7.8880
lnWPC	308	3.4864	1.3006	0	6.2285
lnSPC	308	4.3780	1.3483	0	7.6324
lnNPS	308	6.0797	1.3048	2.8696	9.1805
lnEP	308	6.2206	0.1129	5.8195	6.4742
lnRD	308	9.5358	1.2014	6.2096	11.9611
RDI	308	1.4908	1.0596	0.2800	6.0800
lnGDP	308	8.9231	0.7234	6.5874	10.3730
lnEC	308	7.1606	0.6304	5.8755	8.6323

4. Empirical results and discussion

4.1. Results of unit root tests and panel cointegration tests

Before estimating the long run effects and short run dynamics, our paper uses panel unit root test to determine the order of integration of the variables. In this paper, the three widely used tests to examine the stationarity of the variables are applied. These tests include the IPS test (Im et al., 2003), Fisher-ADF and Fisher-PP (Choi, 2001). Compared with the IPS test, the Fisher-ADF and Fisher-PP tests can adopt various lag lengths for the individual and are used for unbalanced panel data (Li and Lin, 2016). The results of the unit root test which consider the situation of intercept and trend are reported in Table 3. At level, all the variables except WPC and EP are nonstationary because the statistics of IPS, Fisher-ADF and Fisher-PP are insignificant. At first difference, all the variables are significant at 1%, 5% or 10% level, which shows that all the variables are stationary.

The Pedroni and Kao cointegration tests can examine the existence of long run effects. All variables need to be of the same order before doing cointegration tests (Lin et al., 2012). Due to the stationarity of all variable at first difference as shown in Table 3, this paper further applies the Pedroni and Kao cointegration tests to examine the

Table 3
The results of unit root test.

		IPS	Fisher-ADF	Fisher-PP
Level	lnNPC	1.4001	39.7745	55.1646
	lnWPC	-3.1024^{***}	85.5919^{***}	113.0080^{***}
	lnSPC	0.6596	47.7821	86.8605
	lnNPS	4.1578	18.1611	11.2674
	lnEP	-3.5272^{***}	102.699^{***}	113.259^{***}
	lnRD	6.0693	16.5396	26.9530
	RDI	0.2037	52.0608	50.7771
	lnGDP	5.0895	15.0834	14.3066
	lnEC	4.6104	23.6254	19.2397
First difference	lnNPC	-3.4648^{***}	135.6570^{***}	210.268^{***}
	lnWPC	-5.0587^{***}	153.410^{***}	228.051^{***}
	lnSPC	-4.0301^{***}	147.905^{***}	258.280^{***}
	lnNPS	-1.4429^{*}	89.9270^{***}	119.529^{***}
	lnEP	-6.3383^{***}	175.046^{***}	227.479^{***}
	lnRD	-5.1975^{***}	170.944^{***}	231.415^{***}
	RDI	-5.3568^{***}	167.166^{***}	226.453^{***}
	lnGDP	-2.5410^{***}	107.707^{***}	215.587^{***}
	lnEC	-2.1942^{**}	104.603^{***}	127.172^{***}

Note: ***, ** and * indicate the significance at the 1% level, 5% level and 10% level, respectively.

Table 4
Results of the Pedroni and Kao cointegration tests.

Method		Statistic
Pedroni residual cointegration test	Panel v statistic	−0.2363
	Panel rho-statistic	4.3829
	Panel PP statistic	−7.5481***
	Panel ADF statistic	−5.3375***
	Group rho statistic	6.4737
	Group PP statistic	−15.6688***
	Group ADF statistic	−6.1807***
Kao residual cointegration test	ADF stat	−6.1391***

Note:
*** Indicates the significance at the 1% level.

existence of long run effects of electricity price, R&D funding and regional GDP on innovation in renewable energy technologies. The results of the Pedroni and Kao cointegration tests are presented in Table 4. Due to the significant statistics of the panel PP, panel ADF, group PP, and group ADF, the null hypothesis of no cointegration is rejected. In addition, according to the significant statistics of the ADF, the null hypothesis of no cointegration is also rejected. Hence, the results of the two cointegration tests prove the existence of long run effects.

4.2. Results of long run effect and short run dynamics

This paper uses FMOLS and DOLS models to estimate the long run effects of electricity price, R&D funding and regional GDP on innovation in renewable energy technologies. The results of the FMOLS and DOLS models are shown in Table 5. The time lag in the long run models equals to 1 according to Akaike Information Criterion (AIC), which is in lines with many studies, such as Schleicha et al. (2017) and Böhringer et al. (2017).

First, there is a significant positive correlation between electricity price and innovation in renewable energy technologies in both the FMOLS and DOLS models. Specifically, a 1% increase in electricity price can raise the patent counts of renewable energy technologies by 0.7825% and 1.0952% according to the FMOLS and DOLS models respectively. Moreover, higher electricity price can make renewable energy more competitive, and can introduce renewable energy technologies into the supply mix (He et al., 2018). In addition, an increase in the electricity price will also signal a higher future profit, which can also increase incentives for innovation and secure more profits for renewable energy manufacturers (Johnstone et al., 2010). In China, renewable energy technologies require incentives from electricity price due to relatively higher cost.

Table 5
Results of long run effects.

Long run	lnNPC	lnNPC
	FMOLS model	DOLS model
lnEP	0.7825***	1.0952***
	(0.0213)	(0.3779)
lnRD	1.0093***	1.1813***
	(0.0101)	(0.0859)
lnGDP	2.1611***	0.5713*
	(0.0228)	(0.3203)

Short run	LnNPC
ecm	−0.6412***(0.0799)
d.lnEP	0.2553(0.5853)
d.lnRD	1.3167***(0.4947)
d.lnGDP	2.3229***(0.4521)
Intercept	−0.3819***(0.0936)

Note: ***, ** and * indicate the significance at the 1% level, 5% level and 10% level, respectively. The standard error is reported in the parentheses.

Regarding funding support, the coefficients for R&D expenditure are positive and significant at 1% level in both models. Specifically, a 1% increase in R&D expenditure leads to 1.0093%–1.1813% increase in patent counts in renewable energy technologies. These results are in line with Li and Lin (2016) and Sung (2015). R&D funding plays an important role in promoting innovation in renewable energy technologies (Costantini et al., 2015; Nicolli and Vona, 2016; Schleicha et al., 2017). Though government's R&D support is most effective in the short and medium term (Guan and Yam, 2015; Wang et al., 2012), renewable energy technologies have long run development cycles with learning disadvantage (Plank and Doblinger, 2018; Bointner, 2014; Kahouli-Brahmi, 2009), which requires more investment in R&D activities from government and enterprises to innovation in renewable energy technologies in the long run.

Regional GDP has a significant and positive impact on patenting in renewable energy technologies in both models. Specifically, a 1% increase in regional GDP can raise the innovation in renewable energy technologies by 2.1611% and 0.5713% respectively according to the FMOLS and DOLS models. The results are similar to the results of Li and Lin (2016) and Sung (2015). This implies that higher economic growth will expand the electricity market size and consumption (Lewis and Wiser, 2007; Sawhney and Kahn, 2012), and sustaining economic growth will stimulate renewable energy technologies.

Next, this paper estimates the short run dynamics via PMG model presented in Table 5. There is no time lag in the short-term model, which is consistent with Li and Lin (2016) and Salim et al. (2017). The coefficient of ecm (−0.6412) is negative and significant at 1% level, which indicates that there is panel cointegration relationship in the short run. It implies that the deviation from the cointegration system of renewable energy technologies patent counts will change about −64.12% in the next term. Electricity price has an insignificant relationship with patent counts of renewable energy technologies in the short run, indicating that electricity pricing system does not play a role in driving the innovation in renewable energy technologies. Due to substantial electricity subsidies, electricity prices for households in China are controlled at a low level by the government (Wang and Lin, 2017). Artificially lowering the electricity prices for households cannot truly reflect the market value, which will hinder the competitiveness of renewable energy technologies, especially for solar energy technologies. Under the current electricity pricing system, high-income groups do not have to increase their expenditure significantly for their excessive consumption (Du et al., 2015b). However, high-income groups are generally willing to pay more for renewable energy technologies. Therefore, the increasing costs of electricity generation due to the renewable energy introduced are not well taken into account at the low level of electricity prices and are not reasonably apportioned to residents of different income levels. Additionally, the reform process of electricity pricing system in China is too slow to effectively deal with above problems, which indicates that electricity pricing system in China does not have any effect on renewable energy technologies innovation in the short run. Nonetheless, the coefficients of R&D expenditure and economic growth are significantly positive at 1% level, which shows that R&D expenditure and economic growth drive the innovation in renewable energy technologies in the short run.

In summary, these conclusions imply that R&D expenditure and economic growth have long run effects and short run dynamics on innovation in renewable energy technologies. Electricity price only has a long run effect on patenting in renewable energy technologies. Though government would consider generation costs when setting and adjusting electricity price, the electricity price cannot play any role in promoting renewable energy technological innovation in the short run due to the unreasonable cross-subsidies, slow electricity pricing reform and artificially regulation bringing the distortion of market value. However, the long-run adjustment of electricity price has a positive effect on patent counts of renewable energy technologies. In other words, there are positively induced effects of electricity price, R&D funding and economic growth on innovation in the long run.

4.3. Robustness checks

To check the robustness of the results in Section 4.2, this paper tests a series of different classifications of variables. First, patent stock of renewable energy technologies, patent counts of wind energy technologies and solar energy technologies are used as explained variables rather than patent counts of renewable energy technologies. Wind energy and solar energy technologies are two main kinds of renewable energy technologies, and their installed capacities in China ranked first globally. Moreover, Schleicha et al. (2017) illustrated that patent stock might further adequately reflect sector-specific effect such as technology suppliers' learning-by-inventing. Hence, this section discusses the induced effects of electricity price, R&D funding and economic growth on patent stock of renewable energy technologies, patent counts of wind energy technologies and solar energy technologies. This paper refers to the formula of Kim et al. (2018) to calculate patent stock of renewable energy technologies as shown below:

$$PS = PS_t + (1-\delta)PS_{t-1} \tag{2}$$

The patent data at the provincial level in China is reported from 1985. Thus, the initial value of patent stock is determined by the value of patent count in 1985. The depreciation rate (δ) is 15%.

As shown in Table 6, the results are similar to those in Table 5. The coefficients of electricity price, R&D funding, and economic growth are all significantly positive in the long run. Specifically, a 1% increase in electricity price leads to a 0.9231%–1.2508% increase in the number of patent counts in wind energy technologies and a 0.8030%–1.2829% increase in the number of patent counts in solar energy technologies, respectively. Similarly, a 1% increase in electricity price can raise the patent stock of renewable energy technologies by 0.6224% according to the FMOLS model. Given that the coefficients of ecm in Table 6 are negative and significant at 1% level, there is a cointegration relationship in the short run. The coefficients of R&D funding and economic growth have a significant positive impact on the patent stock of renewable energy technologies, patent counts of wind energy technologies and solar energy technologies in the short run. However, the coefficients of electricity price are insignificant in the short run. These results prove again that electricity pricing system in China does not play any role in driving the innovation in renewable energy technologies in the short run.

In addition, since R&D intensity is appropriate to reflect different regions with significantly different scientific resources and capacity (He et al., 2018), R&D intensity is substituted for R&D expenditure in this section. Many studies find that economic growth and electricity consumption have the same variation trend (Yuan et al., 2007; Narayan and Smyth, 2008; Tang and Tan, 2013; Zhao et al., 2016). Therefore, this paper also explores the effects of electricity price, R&D intensity and electricity consumption on innovation in renewable energy technologies. Table 7 indicates that electricity price, R&D intensity and electricity consumption have significant positive impacts on patent counts and patent stock of renewable energy technologies in the long run. Besides, a 1% increase in electricity price leads to a 1.9128%–2.3550% increase in the patent counts of renewable energy technologies and a 0.8855%–2.1250% increase in the patent stock of renewable energy technologies, respectively. The coefficients of other variables are positive and statistically significant in the long run, which is in line with the results of Table 5. For the short run dynamics, the coefficients of ecm in Table 7 are negative and significant at 1% level, and the estimated results in the short run are consistent with Table 5. Thus, it implies that the effectiveness of electricity price system on innovation in renewable energy technologies should be improved in the short run.

Therefore, our findings are consistent and robust across a series of different classification of variables.

Table 6
Results of robustness check (under changing explained variable).

Long run	lnWPC		lnSPC		lnNPS	
	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS
lnEP	1.2508***	0.9231***	0.8030***	1.2829***	0.6224***	0.3000
	(0.0213)	(0.2423)	(0.0213)	(0.4967)	(0.0213)	(0.2054)
lnRD	1.2122***	1.3813***	0.7747***	0.8720***	1.3533***	1.2549***
	(0.0102)	(0.0841)	(0.0102)	(0.1149)	(0.0102)	(0.0480)
lnGDP	1.3723***	−0.0804	3.0860***	1.2253***	0.7344***	1.1101***
	(0.0228)	(0.2901)	(0.0228)	(0.4425)	(0.0228)	(0.1935)

Short run	lnWPC	lnSPC	lnNPS
ecm	−0.7570***	−0.6372***	−0.1913***
	(0.0859)	(0.0749)	(0.0446)
d.lnEP	0.3399	−0.3038	0.0040
	(1.2019)	(0.8126)	(0.2545)
d.lnRD	1.4231**	1.5437***	0.7002***
	(0.6758)	(0.4841)	(0.2655)
d.lnGDP	2.6716***	2.3879***	1.1748***
	(0.7922)	(0.5112)	(0.2151)
Intercept	4.2936***	−8.9379***	2.0700***
	(0.6177)	(1.0264)	(0.4703)

Note: ***, ** and * indicate the significance at the 1% level, 5% level and 10% level, respectively. The standard error is reported in the parentheses.

Table 7
Results of robustness check (under changing explanatory variables).

Long run	lnNPC		lnNPS	
	FMOLS	DOLS	FMOLS	DOLS
lnEP	2.3550***	1.9128***	2.1250***	0.8855***
	(0.0231)	(0.2838)	(0.0231)	(0.1179)
RDI	0.6476***	0.5777***	1.1427***	0.8725***
	(0.0288)	(0.0870)	(0.0288)	(0.0386)
lnEC	1.5537***	1.3913***	1.5534***	1.9844***
	(0.0168)	(0.0790)	(0.0168)	(0.0552)

Short run	lnNPC	lnNPS
ecm	−0.4923***	−0.1820***
	(0.0609)	(0.0384)
d.lnEP	−0.1197	0.0358
	(0.7158)	(0.2082)
d.RDI	0.7937*	0.3692**
	(0.4111)	(0.1520)
d.lnEC	1.1549***	0.6440***
	(0.4046)	(0.2082)
Intercept	−5.8549***	0.1290***
	(0.7863)	(0.0383)

Note: ***, ** and * indicate the significance at the 1% level, 5% level and 10% level, respectively. The standard error is reported in the parentheses.

5. Conclusion and policy implications

Based on a panel sample in 28 provinces in China from 2006 to 2016, this paper uses FMOLS and DOLS models and PMG model to investigate the long and short-term induced effects of electricity price, funding support and economic growth on innovation in renewable energy technologies. The following conclusions were drawn: (1) R&D expenditure and economic growth have positive impacts on innovation in renewable energy technologies in the long run and short run; (2) Electricity price only has a long run effect on patenting in renewable energy technologies; (3) In the long run, a 1% increase in electricity price can lead to a 0.7825%–1.0952% increase in patent counts of renewable energy technologies; (4) Electricity pricing system in China does not play any role in driving the innovation in renewable energy technologies in the short run.

Though many methods, such as emission trading scheme and carbon tax, can reduce carbon emission (Lin and Jia, 2017; Lin and Jia, 2018), the increase of renewable energy in the supply mix also achieves emission reduction through reducing fossil fuel production. The *Plan on the Revolution Strategies in Energy Production and Consumption* (*2016–2030*) has stated the goal of increasing the ratio of non-fossil energy consumption in China to about 20% in 2030. Therefore, China's renewable energy industry will continue to expand. More so, innovation in renewable energy technologies has an obvious strategic significance and is conducive for generation costs reduction and utilization efficiency of renewable energy. Based on the above analysis, this paper suggests that the Chinese government should focus on the reform of the electricity pricing system. Simultaneously, the government should make more efficient use of funding support (e.g. R&D expenditure) and narrow the gap of economic growth level between developed regions and developing regions to promote innovation in renewable energy technologies in all regions.

Firstly, the efficient electricity pricing system should be the marginal price of electricity equaling the marginal cost of generation and reasonably contain the environmental costs. The costs of electricity generation from renewable energy are greater than that of thermal power. Therefore, a higher electricity price is conducive for introducing renewable energy into the supply mix and improve the competitiveness of renewable energy power. Moreover, when electricity price is determined by the market, the cost gap between traditional thermal power and renewable energy power may be narrowed. At this time, the innovation of renewable energy technologies will be more needed to reduce costs. The development of renewable energy technologies relying on government subsidies is not a long-term and effective measure, and subsidy policies will be eventually canceled. Electricity price should accurately reflect the cost of electricity generation and market value in order to promote renewable energy technology innovation and gain the ability to compete with thermal power in the supply mix. In addition, the efficient electricity pricing system can promote the development and utilization of renewable energy. Energy pricing reform is an effective way to control total energy consumption and also improve energy efficiency (Lin et al., 2017; Du et al., 2018), while electricity pricing reform is also an effective approach to reduce the rebound effect (Lin and Liu, 2013). Hence, electricity pricing reform is important for low-carbon economy and sustainable development (He et al., 2014). Increasing electricity price can enhance the awareness of energy conservation and the willingness to pay for renewable energy technologies (Sun and Lin, 2013), which foster rapid innovation in renewable energy technologies to achieve these targets. Besides, electricity price in China is flat and relatively low, so it does not play any significant role in stimulating innovation in renewable energy technologies in the short term. Due to unreasonable cross-subsidies, electricity prices for households are relatively low. Hence, cross-subsidies need to be reduced step by step and stage by stage until being abolished. Moreover, electricity price is relatively flat, since the reform process of the electricity pricing system in China is relatively slow. The deep-rooted problem with electricity prices in China is that they are not allowed to adjust quickly enough (Liu et al., 2013). The government needs to accelerate the process of electricity price reform, but also needs to be careful not to haste without success. Thus, the government should build time-varying electricity pricing mechanism to timely respond to the renewable energy market. To carry out electricity pricing reform smoothly and to reduce the uncertainties, the establishment of early warning mechanism, the enactment of complementary policies and so on should be also implemented (Du et al., 2015a).

Finally, promoting R&D expenditure is conducive for innovation in renewable energy technologies in the long run and the short run. However, market failure such as insufficient information makes the actual values of R&D spending uncertain and lower than the optimal level. Therefore, the funding in renewable energy technologies should be efficiently used. The cooperation between public and private sector stakeholders is conducive for sharing information and facilitating the technology transfer (Apergis and Payne, 2010). Additionally, the provinces with lower economic growth level should expand exchanges and cooperation with the provinces with higher economic growth level (Xu and Lin, 2018). Moreover, it is important to narrow the gap in economic growth level and maintain a sustainable economic development, which ultimately promotes the innovation in renewable energy technologies in all provinces. These provinces will be more willing to pay for renewable energy technologies.

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Appendix A

Table A
IPC codes of each kind of renewable energy technologies.

Technology	IPC classes
Wind energy	F03D
Solar energy	F03G6; F24J2; F26B3/28; H0127/142; H02N6; H01L31/04-058
Biomass and waste energy	C10L5/42-44; F02B43/08; C10L5/46-48; F23G5/46; F23G7/10; [C10L1 or C10L3 or C10L5] and [B09B1 or B09B3 or F23G5 or F23G7]; [F01K27 or F02G5 or F25B27/02] and [F23G5 or F23G7]
Geothermal energy	F03G4; F24J3/08
Ocean energy	E02B9/08; F03B13/10-26; F03G7/05

Source: Popp et al. (2011) and Noailly and Shestalova (2017).

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2018.11.014.

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