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Does Energy Price Induce China's Green Energy Innovation?

Yue Liu [1], Siming Liu [2,*], Xueying Xu [3] and Pierre Failler [4,*]

1 Institute of Finance, Guangzhou University, Guangzhou 510405, China; liuyue2013@hnu.edu.cn
2 School of Statistics, University of International Business and Economics, Beijing 100029, China
3 School of Economics and Management, Beijing Forestry University, Beijing 100083, China; xuxueying@bjfu.edu.cn
4 Economics and Finance Group, Portsmouth Business School, University of Portsmouth, Portsmouth PO1 3DE, UK
* Correspondence: liusiming@uibe.edu.cn (S.L.); pierre.failler@port.ac.uk (P.F.)

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Abstract: This paper aims to comprehensively analyze the relationship between energy price and green energy innovation in China, and first studies the impact of energy price on China's green energy innovation, then further investigates the moderating role of energy price distortion in the price–innovation relationship, especially in the context of lagging energy marketization level in the process of China's transition from planned economy to the market economy. Based on the data of 30 provinces in China from 2003 to 2017, this paper provides a measurement of green energy innovation capacity through the number of "alternative energy production" and "energy conservation" patents. Our results show that energy price has a significantly positive impact on China's green energy innovation, no matter the number of green energy patent applications or the number of green energy patent grants is used as the proxy of green energy innovation capacity. However, there exists heterogeneity related to the influence of energy price on green energy innovation. Specifically, energy price has a noticeable role in promoting green energy innovation in central and western China, but not in eastern China. Further research results show that energy price distortion significantly reduces the inducing effect of energy price on green energy innovation. Meanwhile, the distortion degrees of energy price in the central and western regions of China are significantly lower than that in the eastern region, which explains to a large extent why the inducing effect of energy price on innovation is more prominent in the central and western regions.

Keywords: energy price; green energy innovation; energy price distortion; patent

1. Introduction

Identifying the impact of energy price on green energy innovation is of great importance for green energy innovation promotion and energy transformation acceleration. At present, the production activity and human life become increasingly dependent upon energy consumption. According to BP statistics (http://www.bp.com.cn/stats2019), except in 2009, global primary energy consumption has maintained a sustained growth momentum in the past 20 years. In 2018, the growth rate reached 2.9%, the highest since 2010. As the world's largest developing country, China's rapid economic growth in recent years has also generated huge energy consumption. In 2018, China's primary energy consumption reached 3273.5 million tons of oil equivalent, accounting for 23.6% of the total global primary energy consumption, making it the world's largest energy consumer. China's fossil fuel energy consumption accounted for 87.67% of the total energy consumption in 2014, 6.76 percentage points higher than the global average (https://data.worldbank.org). In the context of the increasing pressure on energy supply and climate change in the world [1], especially in big developing countries such as China, accelerating green energy technology innovation as an important means to promote energy transformation has reached a broad consensus on a global scale [2–4]. Therefore, it is necessary to analyze the key influencing factors of energy technology innovation. The induced innovation hypothesis proposed by Hicks [5] highlights the important role of energy price in spurring innovation, and energy price is supposed to play a leading role in the improvement of green energy innovation capacity.

A growing number of studies have conducted empirical research on the impact of energy price on green energy innovation, and most of them have verified the positive inducing effect of energy price. At the macro level, Ley et al. [6], based on the data of 18 OECD countries over 30 years, found that energy price had a significant promoting effect on green innovation from the perspective of either the number of green innovations or the ratio of green innovations to nongreen innovations. Nicolli and Vona [7] detected that electricity prices had a positive impact on the innovation of solar energy technology and biofuels, through research on the influencing factors of renewable energy innovation in EU countries from 1980 to 2007. Using the data of 10 most innovative countries in the world from 2000 to 2018, Nunes and Catalaolopes [8] found that oil prices had a significant positive impact on the number of patent applications of alternative energy. Also, scholars like Lanzi et al. [9], Verdolini and Galeotti [10], Cheon and Urbelainen [2] have also verified the positive innovation-induced effect of energy price. At the micro-level, Noailly and Smeets [11] used company-level data on renewable energy and fossil fuel technology patents submitted by 5261 European companies between 1978 and 2006 to explore how energy price, market size and knowledge stock affect corporate technological innovation, showing a positive and significant impact of energy price on technological innovation. However, based on the data of 26 OECD countries from 1979 to 2009, Kruse and Wetzel [12] found that energy prices had a positive effect on innovation for some but not all green energy technologies.

However, existing studies mainly focus on developed countries, and the literature with developing countries as the research focus is still rare. According to the authors' knowledge, at present, only Lin and Chen [3] have examined the impact of electricity prices on China's renewable energy technological innovation. However, electricity price is only one kind of energy price, which cannot reflect the comprehensive level of energy price. Meanwhile, in addition to renewable energy technologies, green energy technologies should also include energy conservation technologies. Besides, Lin and Chen [3] only carried out a full-sample analysis at the national level and did not investigate the potential heterogeneous effects of energy price on green energy innovation in different regions of China. Finally, different from developed countries with a complete energy market mechanism, China has a relatively serious market distortion in energy prices due to the lagging marketization level of energy factors. Therefore, in the discussion of the relationship between energy price and green energy innovation in China, the issue of energy price distortion needs to be taken into consideration, but there is no relevant literature at present.

To understand in-depth the relationship between energy price and green energy innovation in China, this paper initially analyzes the impact of energy price on China's green energy innovation and further explores the moderating role of energy price distortion in the connection between energy price and energy technology innovation, based on the data of 30 provinces in China from 2003 to 2017. The main contributions are as follows. On the one hand, different from most studies which focus on the impact of energy price on green energy innovation in the context of developed countries, this paper not only investigates the influence of energy price on green energy innovation but also tests whether this impact is related to the degree of energy price distortion, combined with the reality of the lagging of energy factor marketization in the process of China's transition from planned economy to market economy, which expands the understanding of the relationship between them from a novel perspective. On the other hand, in terms of the impact of energy price on green energy innovation, this paper not only measures energy price covering four categories of commodities (i.e., coal, oil, natural gas and electricity), but also reflects green energy innovation capacity by the number of "alternative energy production" and "energy conservation" patents. In addition, we analyze the heterogeneous impacts of energy prices on green energy innovation capacity in different regions of China, looking at the influence of energy price on green energy innovation in a comprehensive manner.

The results show that energy price has a significant and positive impact on China's green energy innovation in general. However, the inducing effect of energy price on green energy innovation is significant in central and western China, but insignificant in eastern China. Further research in this paper shows that energy price distortion significantly reduces the inducing effect of energy price on China's green energy innovation. Meanwhile, this paper also finds that the degree of energy price distortion in central and western China is noticeably lower than that in eastern China, which to a large extent explains why the inducing effect of energy price is more prominent in central and western China.

The remaining part of this paper is arranged as follows: section two puts forward the research hypothesis of this paper; the third section introduces the model setting, relevant data and variables in related to the influence of energy price on green energy innovation, and then presents and discusses the results of empirical analysis; the fourth section further tests empirically whether the impact of energy price on China's green energy innovation is related to the degree of energy price distortion; the last section summarizes the research conclusions.

2. Research Hypotheses

Focusing on the impact of energy price on green energy innovation and the moderating role of energy price distortion in the relationship between energy price and green energy innovation, this paper puts forward the following three research hypotheses.

In theory, energy price plays a leading role in green energy technological innovation. Hicks [5] first proposed the induced innovation hypothesis, that is, energy price drives technological innovation. He pointed out that "a change in the relative prices of the factors of production is itself a spur to the invention, and to the invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive". In the research framework of Hicks, through the studies of Ahmad [13], Kamien and Schwartz [14] and Binswanger [15], a relatively complete theoretical system of the relationship between factor price and innovation process has been gradually established. Generally speaking, the price rise of a certain factor will directly lead to a rise in production cost. To save production costs, enterprises usually take two measures. One way is to improve the use efficiency of this factor through technological innovation, thus reducing the use of relatively expensive factors by enterprises. The other way is to seek corresponding alternative factors. In the energy sector, the rise in energy price will not only promote enterprises to improve the use efficiency of traditional energy factors by increasing energy-saving technology innovation but also promote enterprises to increase the innovation of new energy technology, to realize the substitution between different types of energy varieties (such as nonrenewable energy and renewable energy) [10]. This is because energy, as a necessary factor of production, cannot be replaced by other factors of production such as capital and labor [16,17]. In this sense, the energy price will have an inducing effect on the innovation of energy conservation and energy substitution technologies, and it will have a more prominent inducing effect on the innovation of green energy technologies.

Extensive empirical research has been conducted on the impact of energy price on green energy innovation, and most of the studies have confirmed the positive inducing effect of energy price. To test the induced innovation hypothesis introduced by Hicks [5], early studies focused on specific industries in a single country, such as the United States, to examine the relationship between energy price and technological innovation. Lichtenberg [18] examined the impact of energy price changes on the R&D investment of US manufacturing enterprises in the early to mid-1970s. The results suggest that higher energy price has contributed significantly to the increase in R&D investment by US manufacturers. Subsequently, Popp [19], Linn [20] and Kong et al. [21] also verified the inducing effect of energy price on technological innovation. In recent years, with the increasing availability of patent data which are widely used to measure technological innovation [22], more and more scholars begin to focus on the field of energy and investigate the impact of energy price on green energy technological innovation. As discussed above, these studies mainly focus on developed countries, and most of them demonstrate the positive impact of energy price on green energy innovation [2,6–11]. More recently, some studies have made empirical findings in developing countries. Lin and Chen [3] focused on the impact of electricity prices on China's renewable energy technology innovation and found that in the long run, the increase of electricity prices can promote renewable energy technology innovation, but its short-term effect is not significant.

Based on the above literature review, we can find that energy price has a positive leading effect on green energy technological innovation from both theoretical analysis and most empirical studies. In this regard, this paper proposes Hypothesis 1:

Hypothesis 1 (H1). *Energy price has a positive impact on China's green energy innovation.*

It should be noted that the above theoretical analysis of the impact of energy price on green energy innovation is based on a sound market mechanism. In empirical research, existing literature focuses on developed countries with a high level of energy factor marketization. However, as will be discussed in detail later, the marketization level of China's energy factors is low in general, and there exists the issue of energy price distortion [23–26], which will weaken the inducing effect of energy price on technological innovation to a large extent. In addition, given that the degree of energy price distortion in different regions of China differs significantly [27,28], the inducing effects of energy price on green energy innovation may be significantly different between various regions, so this paper puts forward Hypothesis 2:

Hypothesis 2 (H2). *Energy price has heterogeneous effects on green energy technology innovation in different regions of China.*

Under the background of the low marketization of energy factors in the process of China's transition from planned economy to market economy, energy price distortion plays a moderating role in the relationship between energy price and green energy technology innovation. For a long time, China's energy price marketization process has been lagging, and the government plays a leading role in the energy price formation mechanism. Energy price has been suppressed in China over the past decades [29]. In recent years, although the Chinese government has accelerated the reform process of the energy market, most of the four largest energy industries of oil, electricity, coal, and natural gas are monopolized by large state-owned enterprises (SOEs), who have the right to formulate a unified energy price, and the government, through administrative power, has suppressed the energy price to a lower level [25]. At the same time, combined with inappropriate subsidy incentive policies [30], China's actual energy price is lower than the market equilibrium price, which leads to the distortion of energy prices [31].

This paper holds that the low energy price in the context of distorted energy prices in China will play a negative moderating role in the inducing effect of energy price on green energy technology innovation. Specifically, the low price of coal, oil and other traditional energy commodities caused by energy price distortion cannot correctly reflect the scarcity of energy factors and environmental costs [32], and the reduction of energy use cost will make enterprises tend to increase the consumption of low-cost energy factors in the production process, which will lead to the lack of power for enterprises to pursue energy-saving technology innovation and reduce the consumption of traditional energy factors through independent research and development or international knowledge spillover and other channels, which will undoubtedly weaken the development and utilization of new energy technologies. Therefore, the higher the distortion level of energy price is, the higher the degree of resource mismatch is, and it can be expected that the effect of energy price on green energy technology innovation in this region will be smaller. In this regard, this paper proposes the third research hypothesis:

Hypothesis 3 (H3). *Energy price distortion plays a negative moderating role in the relationship between energy price and green energy technology innovation in China.*

3. Analysis of the Effect of Energy Price on Green Energy Innovation

3.1. Model Specification

In the analysis of factors affecting national and regional technological innovation capacity, the framework of ideas production function proposed by Romer [33] and Jones [34] has been widely used [35,36]. The framework emphasizes the effect of knowledge stock and R&D labor input on the new ideas' production of a country or region. The specific expression is as follows:

$$\dot{A}_t = \delta H_{A_t}^{\lambda} {A_t}^{\phi} \tag{1}$$

where $\dot{A}_t$ represents the flow of new ideas at year t and also reflects the technological innovation capacity of a country or region in the corresponding year; H_{A_t} is the quality of human capital devoted to the idea-producing sector, which is measured by the level of R&D labor input; A_t represents the stock of knowledge discovered in the past; λ refers to the productivity of R&D labor; ϕ is the parameter which reflects the effects of intertemporal spillover effects on new ideas (Romer [33] assumes that $\phi = 1$, while Jones [34] believes that $\phi < 1$).

Similarly, in the analysis of the effect of energy price on the green energy innovation capacity for province i in year t in China, according to the ideas production function, this paper first constructs the extended form of the ideas production function in Formula (2):

$$Y_{it} = \delta (EP_{it})^{\alpha} {L_{it}}^{\lambda} {S_{it}}^{\phi} \tag{2}$$

where Y represents the innovation capacity of green energy technology; EP is energy price; L and S represent the R&D labor input in the field of green energy and green energy knowledge stock, respectively. The logarithm of both sides of Formula (2) can be further obtained as follows:

$$\ln Y_{it} = \ln \delta + \alpha \ln EP_{it} + \lambda \ln L_{it} + \phi \ln S_{it} + \varepsilon_{it} \tag{3}$$

Considering that in the context of an open economy, developing countries with relatively backward technology such as China can not only accumulate their ideas and invest in R&D, but also gain international idea spillovers by introducing foreign direct investment (FDI), to improve their technological innovation capacity. In this paper, FDI is incorporated into the econometrical model specification as a control variable. Also, since the outbreak of the 2008–2009 global financial crisis and the Copenhagen Climate Conference 2009 [37], China has attached more importance to the innovation of green energy technology, this paper further adds the time dummy variable of the year 2009 as the control variable. Finally, this paper further constructs the benchmark empirical model as shown in Equation (4).Because FDI is in the form of proportion, this paper does not deal with it logarithmically in line with most empirical studies [21,38,39]:

$$\ln Y_{it} = \ln \delta + \alpha \ln EP_{it} + \lambda \ln L_{it} + \phi \ln S_{it} + \beta FDI_{it} + \gamma Dum2009 + u_i + \varepsilon_{it} \tag{4}$$

where *FDI* stands for foreign direct investment, *Dum2009* represents the time dummy variable of the year 2009, and u_i is used to control the individual effect of the province.

As discussed below, to ensure the robustness of the empirical results, this paper will use both the number of green energy patent applications and the number of green energy patent grants in each province to measure China's provincial green energy innovation capacity. Considering that energy price, R&D input and other independent variables have a certain time lag effect on the innovation output of green energy technology, and to reduce the estimation result bias caused by potential endogenous problems in the model estimation, as in Ley et al. [6], this paper, similarly, uses the one-year lagged value of the independent variables in the empirical model with the green energy patent applications as the dependent variable. The specific model is shown in Formula (5):

$$\ln PA_{it} = \ln \delta + \alpha \ln EP_{it-1} + \lambda \ln L_{it-1} + \phi \ln S_{it-1} + \beta FDI_{it-1} + \gamma Dum2009 + u_i + \varepsilon_{it} \quad (5)$$

where PA is the number of green energy patent applications; EP_{it-1} represents energy price of region i in year $t-1$, that is the one-year lagged value of energy price; L_{t-1}, S_{t-1} and FDI_{t-1} are the one-year lagged values of corresponding variables.

Considering that it takes about two years for Chinese patents from application to grant, in the empirical model with the number of green energy patent grants as the dependent variable, the independent variable uses the three-years lagged value. The specific model is shown in Equation (6):

$$\ln PG_{it} = \ln \delta + \alpha \ln EP_{it-3} + \lambda \ln L_{it-3} + \phi \ln S_{it-3} + \beta FDI_{it-3} + \gamma Dum2009 + u_i + \varepsilon_{it} \quad (6)$$

where PG is the number of green energy patent grants; EP_{it-3}, L_{t-3}, S_{t-3}, FDI_{t-3} are three-years lagged values in region i of corresponding variables.

3.2. Variables and Data

3.2.1. Variable Measurement

In the empirical analysis, the measurement of the dependent variable green energy innovation capacity, core explanatory variable energy price and control variable are as follows.

Green energy innovation capability. The number of patents reflects the output level of new knowledge [40], which can reflect the connotation of innovation and thus be widely used to measure the innovation capacity or innovation performance of a country or region [3,22,35,36,41]. In this regard, like Cheon and Urpelainen [2], Ley et al. [6] and Lin and Chen [3], this paper measures the green energy innovation capacity in China's provinces through the number of green energy patents. In addition, the number of patents includes the number of patent applications and the number of patent grants. Compared with patent grants, the data of patent applications are not easily affected by human factors. Meanwhile, due to the time required from the application to the grant of a patent, the number of patent applications can better reflect the current innovation level of a region. Therefore, many scholars believe that the number of patent applications is a better indicator to reflect the level of innovation output [42,43]. However, compared with the relatively low technical threshold for patent applications, the patents authorized in China are those that are granted after rigorous examination of the accepted patents from the three aspects of novelty, creativity and practicality, which can better reflect the invention with potential commercial value. Therefore, a lot of literature takes the number of patent grants as an indicator to measure the innovation ability of a country (region) [35,36]. In this regard, to ensure the robustness of the empirical results, this paper uses both the number of green energy patent applications and the number of green energy patent grants to measure the technological innovation capacity of green energy in China's provinces. In the quantitative analysis of green patents or green energy patents, many studies refer to the International Patent Classification (IPC) of Green Inventory issued by the World Intellectual Property Organization (WIPO) to define green patents or green energy patents. IPC Green Inventory made seven classes, which contain a series of subclasses (For more information about the IPC Green Inventory, please visit the website: https://www.wipo.int/classifications/ipc/en/green_inventory/index.html). According to the research objective, following Ardito et al. [44], this paper classifies green energy patents into "alternative energy production" and "energy conservation" patents and obtains all corresponding IPC codes. Based on obtaining the IPC codes to green energy technologies, this paper, according to the Patent Star website of the State Intellectual Property Office of China (Website address: http://cprs.patentstar.com.cn/), first identifies green energy patents, then retrieves the number of applications and grants of green energy patents in each province of China over the years.

Energy price. At present, the Chinese government has not publicly released the indicator data of the comprehensive level of energy prices. Due to the variety of energy commodities, it is difficult to obtain the price data of all kinds of energy commodities. In this regard, this paper refers to the practice of most literature [25,45,46], and constructs the energy price level of each province in China by integrating the prices of four major energy consumption categories, namely, coal, oil, natural gas and electricity. In terms of the construction idea of the energy price level, this paper weighted the price of four types of energy commodities through the proportion of four types of energy consumption in the total energy consumption of the region in each province. For details, please refer to Tao et al. [47] and Ouyang et al. [25]. At the same time, to make the data comparable, the energy prices of each province are adjusted to the real prices with the price in 1999 at a constant price.

R&D labor input in the field of green energy. Because it is impossible to obtain the data of the R&D labor in the green energy sector in China from the public channels, and the full-time equivalent of R&D personnel is a better indicator to measure R&D labor input than the number of R&D personnel, this paper estimates the full-time equivalent of R&D personnel in the field of green energy of each province. This paper assumes the patent applications per full-time equivalent of R&D personnel in a province's green energy sector is equal to that in the nongreen energy sector of the province. That is, the patent applications per full-time equivalent of R&D personnel in a province's green energy sector is equal to that in all the sectors of this area. As the data of the number of both total patent applications and the total full-time equivalent of R&D personnel in each province are available, the estimation method of the full-time equivalent of R&D personnel in the field of green energy in a region is shown in Equation (7):

$$L_{it} = \frac{PA_{it}}{PAT_{it}} \times LT_{it} \tag{7}$$

where PAT_{it} and LT_{it} represent total patent applications and full-time equivalents of R&D personnel of province i in year t, respectively.

Green energy knowledge stock. As the data of green energy knowledge stock cannot be obtained directly, it needs to be estimated. Referring to the practice of Aghion et al. [48] and Ley et al. [6], this paper estimates the knowledge stock in the field of green energy in China's provinces by perpetual inventory method (PIM). The specific formula is as follows:

$$S_{it} = (1 - \delta)S_{it-1} + PA_{it} \tag{8}$$

where δ is the depreciation rate of R&D. The estimation method of green energy knowledge stock at the beginning of the period is: $S_0 = PA_0/(g + \delta)$. Considering that the time of the base period is set earlier, the initial knowledge stock estimation has less influence on the latter one, this paper sets the base period as 1999. In the setting of R&D depreciation rate, this paper refers to the practice of most literature [6,49], and sets it to 15%. g represents the annual average growth rate of green energy patent applications in each province from 1999 to 2017.

Foreign direct investment. Referring to Shatz and Venables [50], Jungmittag and Welfens [51], Li et al. [39] and Rafique et al. [52], in this paper, the proportion of FDI in the GDP of each province is used to investigate the foreign investment attraction of each province. In the calculation of FDI, since the original data are denominated in US dollars, this paper converts US dollars into RMB based on the exchange rate of each year.

Time dummy variable. The value before 2009 is set to 0 and the value since 2010 is set to 1.

The variables involved in the empirical analysis and their definitions are shown in Table 1.

Table 1. Definitions of variables.

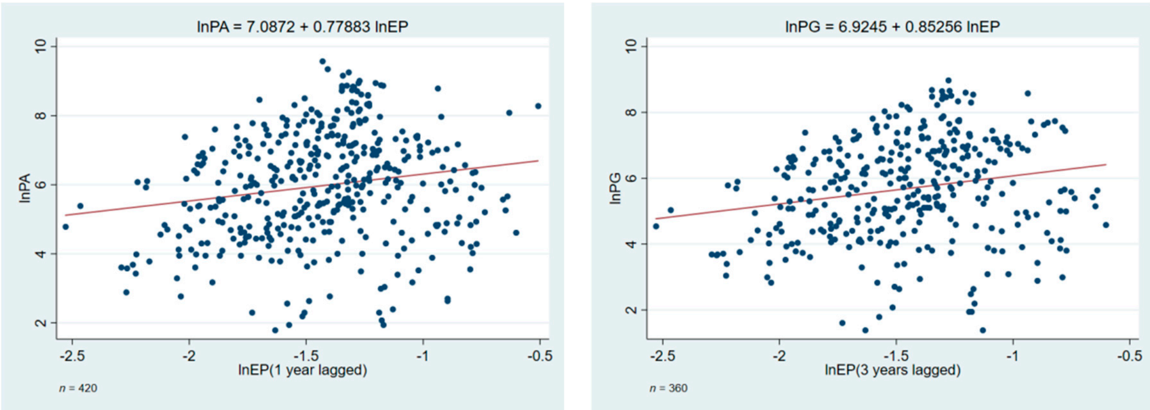
Variable Types	Variable Names	Variable Definitions
Dependent variables	Number of green energy patent applications (*PA*)	The number of patent applications for "Alternative energy production" and "Energy conservation" in WIPO's IPC Green Inventory [44]
	Number of green energy patents grants (*PG*)	The number of patent applications for "alternative energy production" and "energy conservation" in WIPO's IPC Green Inventory [44]
Core independent variables	Energy price (100 million yuan/ton) (*EP*)	Weighted price of coal, oil, natural gas and electric power
Control variables	R&D personnel in the field of green energy (*L*)	Authors' estimation of the number of the full-time equivalent of R&D personnel in the field of green energy
	Green energy knowledge stock (*S*)	Estimated by the perpetual inventory method
	Foreign direct investment (*FDI*)	FDI/GDP
	Time dummy variable (*Dum 2009*)	It is 0 before 2009 and 1 since 2010

3.2.2. Data Sources and Statistical Description

China implemented major market-oriented reforms in coal, electricity and other sectors in 2002, and the marketization of energy prices in China has accelerated since then. In this regard, the research period of this paper is set as 2003–2017. Because of the relatively limited data in Tibet, Hong Kong, Macau and Taiwan, 30 provinces in China are selected as subjects for this study. The original data sources of this paper are from China Statistical Yearbook, China Energy Statistical Yearbook, China Science and Technology Statistical Yearbook, China Price Yearbook, China Urban (town) Life and Price Yearbook, China's Third National Industrial Census in 1995, China Industrial Economic Statistical Yearbook and China Industrial Statistical Yearbook. The data of green energy patent applications and grants in each province are obtained from the Patent Star website of the State Intellectual Property Office of China.

Referring to Nguyen and Bhatti [53], Nguyen et al. [54] and alrahleh et al. [55], we provide statistical information on the mean, standard deviation, minimum, maximum, skewness and kurtosis of the main variables. Descriptive statistical results for the main variables are listed in Table A1, Appendix A.

As can be seen from the scatter diagram in Figure 1, intuitively, there is a positive correlation between China's provincial energy price (log form) and the number of green energy patent applications (log form) and the number of green energy patent grants (log form), reflecting the possible positive effect of energy price on China's green energy innovation. A strict econometric analysis of the relationship between the two is presented below.



(**a**) (**b**)

Figure 1. (**a**) Energy price and green energy patent applications; (**b**) Energy price and green energy patent grants.

3.3. Full Sample Results

In this subsection, panel data of 30 provinces in China from 2003 to 2017 are first used to estimate the parameters of Equations (5) and (6), respectively, taking the number of green energy patent applications and the number of green energy patent grants as dependent variables. In terms of estimation strategy, to effectively control the provincial fixed effect, this paper firstly adopts the fixed effect model (FE) and the random effect model (RE) to estimate the parameters (F test results also show that the province individual fixed effect is significant). In addition, although in the econometric model setting of this paper, the energy price which is taken as the one-year lagged value (when the number of green energy patent applications is taken as the dependent variable) or the three-year lagged value (when the number of green energy patent grants is taken as the dependent variable) can address the potential endogenous issues in the model estimation to a large extent, yet to ensure the robustness of the estimation results, this paper further uses the panel instrumental variable model for parameter estimation [56,57]. As for the choice of instrumental variables, according to the approach proposed by Lewbel [58], the third-order centered moments of the log of energy price is employed as the instrument variable. The Hausman test results shown in Table 2 indicate that the fixed effect model is better than the random effect model whether the number of green energy patent applications or the number of patent grants is taken as the dependent variable. In this paper, the fixed effect instrumental variable (FE-IV) model is used to estimate the parameters of Equations (5) and (6). The results of parameter estimation under different estimation methods above are shown in Table 2.

According to the estimation results in Table 2, it can be seen that energy price has a significant inducing effect on China's green energy innovation. Specifically, the results in Columns 2 and 3 of the table show that regardless of the control variables, energy price has a significant positive impact on the number of green energy patent applications in China at the significance level of 10%, whether based on the fixed-effect model or random-effect model. Similarly, when the number of green energy patent grants is taken as the dependent variable, the estimated results in Columns 7 and 8 in the table show that the effect of energy price on green energy patents is also significantly positive. According to the estimation results of Columns 4–5 and 9–10 in the table, the estimated coefficient *lnEP* of energy price decreases with the addition of control variables, but is still significantly positive under different estimation methods. Among the estimation results of the fixed-effect model, the estimation coefficients of *lnEP* are 0.224 and 0.361 in Columns 4 and 9, respectively. This shows that every 1% increase in energy price will induce the number of green energy patent applications and the number of green energy patent grants in China to increase by 0.224% and 0.361%, respectively. In the estimation of the panel instrumental variable model, although the positive effect of energy price on China's green energy patent applications is not statistically significant, it has a significant positive effect on China's green energy patent grants. To sum up, based on the empirical data analysis of China, this paper finds that energy price has a significant inducing effect on green energy technology innovation, which is consistent with the findings of Noally and Smeets [11] and Nunes and Catalaolopes [8], and Hypothesis 1 is demonstrated.

Table 2. Results of the effect of energy price on green energy innovation in the full sample.

Variables	Dependent Variable: Logarithm of the Number of Green Energy Patent Applications (lnPA)					Dependent Variable: Logarithm of the Number of Green Energy Patent Grants (lnPG)				
	FE	RE	FE	RE	FE-IV	FE	RE	FE	RE	FE-IV
lnEP	2.489 *** (17.84)	2.408 *** (17.13)	0.224 *** (3.62)	0.208 *** (4.41)	0.111 (0.86)	2.498 *** (20.76)	2.439 *** (20.05)	0.361 *** (3.73)	0.475 *** (5.98)	0.760 *** (2.84)
lnL			0.0656 * (1.66)	0.0524 * (1.71)	0.0747 * (1.84)			0.328 *** (5.43)	0.255 *** (4.76)	0.320 *** (5.15)
lnS			0.891 *** (27.48)	0.959 *** (35.00)	0.894 *** (27.33)			0.792 *** (14.20)	0.805 *** (16.48)	0.730 *** (10.60)
FDI			0.728 (1.25)	1.065 ** (2.18)	0.680 (1.16)			6.929 *** (4.39)	4.734 *** (3.87)	6.473 *** (3.94)
Dum2009			−0.0173 (−0.34)	−0.118 *** (−3.09)	0.009 (0.16)			−0.282 *** (−4.27)	−0.276 *** (−4.80)	−0.338 *** (−4.44)
Constant	9.550 *** (46.76)	9.433 *** (31.03)	−0.335 (−1.37)	−0.698 *** (−5.98)	−0.598 * (−1.68)	9.319 *** (52.34)	9.234 *** (31.70)	−1.472 *** (−3.82)	−0.817 *** (−3.54)	−0.387 (−0.49)
Hausman	16.26 ***		301.88 ***			15.01 ***		500.71 ***		
N	420	420	420	420	420	360	360	360	360	360
R^2	0.450	—	0.945	—	0.993	0.567	—	0.892	—	0.967

Note: *t* statistic values are in brackets; ***, ** and * are significant at the significance level of 1%, 5% and 10%, respectively.

In terms of control variables, whether with the number of green energy patent application or the number of patent grants as the dependent variable, the estimated coefficients of *lnL* under different estimation methods are significantly positive, reflecting the increased investment in R&D personnel in the field of green energy is the important channel to promote China's green energy technology innovation, which is consistent with economic theories. In addition, the influence of green energy knowledge stock on green energy technology innovation is also significantly positive under different estimation methods, which is similar to the conclusion of Ley et al. [6], highlighting the important role of idea accumulation in the past in improving the current level of green energy technological innovation. As far as foreign direct investment is concerned, it has a positive but not robust effect on the number of green energy patent applications in China, but it has a robust promoting effect on the green energy patent grants. In general, the technology spillover brought by foreign direct investment has a certain pulling effect on China's green energy technology innovation.

3.4. Results and Analysis of the Regional Differences

Because there exist huge differences in the level of socioeconomic development between China's eastern coastal areas and central and western inland regions, this paper divides 30 provinces into eastern coastal region samples and central and western inland region samples for parameter estimation according to the division standard of the National Bureau of Statistics of China (the eastern region includes 11 provinces: Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan, and the central and western regions include 19 provinces including Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan, Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang), to further explore the possible heterogeneous impact of energy price on China's green energy technological innovation. The regression results of regional differences are shown in Tables 3 and 4, respectively.

Table 3. Results of the effect of energy price on green energy innovation in the eastern region of China.

Variables	Dependent Variable: Logarithm of the Number of Green Energy Patent Applications (lnPA)			Dependent Variable: Logarithm of the Number of Green Energy Patent Grants (lnPG)		
	FE	**RE**	**FE-IV**	**FE**	**RE**	**FE-IV**
lnEP	−0.0368 (−0.44)	0.122 (1.55)	−0.214 (−1.45)	−0.0025 (−0.02)	0.291 ** (1.98)	0.0692 (0.34)
lnL	0.211 *** (3.47)	0.121 ** (2.44)	0.196 *** (3.12)	0.473 *** (4.76)	0.325 *** (3.76)	0.482 *** (4.78)
lnS	0.778 *** (14.85)	0.878 *** (18.51)	0.800 *** (14.47)	0.727 *** (7.57)	0.724 *** (8.46)	0.710 *** (7.06)
FDI	1.255 (1.65)	1.054 (1.53)	1.356 * (1.75)	6.823 *** (3.45)	2.671 * (1.72)	6.771 *** (3.42)
Dum2009	0.0011 (0.02)	−0.116 ** (−2.25)	0.0366 (0.47)	−0.334 *** (−3.18)	−0.276 *** (−3.35)	−0.342 *** (−3.23)
Constant	−0.934 *** (−2.77)	−0.701 *** (−3.41)	−1.289 *** (−3.08)	−2.745 *** (−4.38)	−0.943 ** (−2.51)	−2.568 *** (−3.67)
Hausman		24.94 ***			28.04 ***	
N	154	132	154	154	132	154
R^2	0.957	—	0.956	0.898	—	0.898

Note: *t* statistic values are in brackets; ***, ** and * are significant at the significance level of 1%, 5% and 10%, respectively.

Table 4. Results of the effect of energy price on green energy innovation in central and western China.

Variables	Dependent Variable: Logarithm of the Number of Green Energy Patent Applications (lnPA)			Dependent Variable: Logarithm of the Number of Green Energy Patent Grants (lnPG)		
	FE	**RE**	**RE-IV**	**FE**	**RE**	**RE-IV**
lnEP	0.415 *** (4.69)	0.307 *** (4.82)	0.375 *** (3.16)	0.567 *** (4.46)	0.577 *** (5.59)	0.850 *** (3.44)
lnL	−0.00701 (−0.13)	0.0445 (1.09)	0.0427 (1.05)	0.237 *** (2.94)	0.203 *** (2.87)	0.191 *** (2.65)
lnS	0.950 *** (23.24)	0.981 *** (26.53)	0.984 *** (26.48)	0.829 *** (12.04)	0.863 *** (13.53)	0.846 *** (12.69)
FDI	−0.122 (−0.15)	−0.146 (−0.19)	−0.104 (−0.14)	5.717 ** (2.01)	5.049 ** (2.06)	4.979 ** (2.01)
Dum2009	−0.0701 (−1.09)	−0.124 ** (−2.24)	−0.154 ** (−2.19)	−0.285 *** (−3.42)	−0.306 *** (−3.96)	−0.389 *** (−3.78)
Constant	0.0308 (0.08)	−0.637 *** (−3.50)	−0.538 ** (−2.28)	−0.720 (−1.34)	−0.662 * (−1.81)	−0.0638 (−0.10)
Hausman	8.83			2.84		
N	266	266	266	228	228	228
R^2	0.945		0.945	0.897		0.894

Note: *t* statistic values are in brackets; ***, ** and * are significant at the significance level of 1%, 5% and 10%, respectively.

According to the estimates in Tables 3 and 4, there are noticeable differences in the impact of energy price on green energy technology innovation between China's eastern coastal areas and the inland central and western regions. Specifically, in eastern China samples, whether based on the fixed-effect model, random effect model or fixed effect panel instrumental variable model (Hausman test results show that fixed effect model is better than random effect model), the effect of energy price on green energy patent applications in eastern China is not significant. If the number of green energy patent grants is taken as the dependent variable, the effect of energy price on the number of green energy patent grants in eastern China is only significantly positive under the condition of random effect (Column 6 in Table 3), while the estimation coefficients of *lnEP* in both the fixed effect model and the fixed effect panel instrumental variable model are not statistically significant. This shows that energy price has no obvious impact on green energy technological innovation in eastern China. In the samples of central and western China, the estimated coefficients of energy price *lnEP* are significantly positive under different estimation methods, no matter the number of green energy patent applications or the number of green energy patent grants is taken as the dependent variable, which shows that energy price has a significant role in promoting green energy innovation in central and western China. As discussed above, the relatively high degree of energy price distortion in eastern provinces of China should be able to explain to a large extent why the inducing effect of energy price on green energy technology innovation is relatively weak in the eastern region. The following part of this paper will examine whether the impact of energy price on green energy technological innovation in China's provinces is related to the level of energy price distortions in a region.

For the control variables, the impact of the full-time equivalent of R&D personnel, knowledge stock in the field of green energy and foreign direct investment on green energy technological innovation in eastern China and central and western China is generally consistent with the full sample. Besides, compared with the central and western regions of China, the positive effects of R&D personnel investment and foreign direct investment in the field of green energy are more robust in the eastern region of China.

4. Does Energy Price Distortion Inhibit the Effect of Energy Price on Green Energy Technology Innovation

4.1. Models and Variables

4.1.1. Model Setting

To investigate whether the impact of energy price on China's green energy technology innovation is related to the degree of energy price distortion in a region, this paper further takes the number of patent applications and patent grants as dependent variables and sets the empirical model shown in Equations (9) and (10), respectively:

$$\begin{aligned}\ln PA_{it} &= \ln\delta + \alpha\ln EP_{it-1} + \rho Dist_{it-1} + \theta\ln EP_{it-1}\times Dist_{it-1} + \lambda\ln L_{it-1}\\ &+\phi\ln S_{it-1} + \beta FDI_{it-1} + \gamma Dum2009 + u_i + \varepsilon_{it}\end{aligned} \tag{9}$$

$$\begin{aligned}\ln PG_{it} &= \ln\delta + \alpha\ln EP_{it-3} + \rho Dist_{it-3} + \theta\ln EP_{it-3}\times Dist_{it-3} + \lambda\ln L_{it-3}\\ &+\phi\ln S_{it-3} + \beta FDI_{it-3} + \gamma Dum2009 + u_i + \varepsilon_{it}\end{aligned} \tag{10}$$

where *Dist* refers to the degree of energy price distortion, as reflected by the energy price distortion index calculated below. It can be found that the elasticity of the impact of energy price on the number of green energy patents is ($\alpha + \theta + Dist$) when the interaction term of energy price logarithm and energy price distortion index ($\ln EP \times Dist$) is added. If θ is significantly negative, it means that the inducing effect of energy price on green energy technological innovation in a region will decrease with the increase of energy price distortion. In other words, the degree of energy price distortion will play a negative moderating role in the relationship between energy price and green energy technological innovation.

4.1.2. Measurement of Energy Price Distortion

At present, there are mainly three methods to measure the distortion degree of the factor market, namely, the production function method, the frontier analysis and the shadow price calculation method. Among them, the production function method measures the distortion degree of factor price by the ratio of marginal output to the actual price of each input factor. This method can not only analyze the relationship between actual factor price and market equilibrium price, intuitively reflect the connotation of factor price distortion, but also has the advantages of a simple and easy calculation process, so it has been widely used in the calculation of factor price distortion. In this regard, this paper, like Hsieh and Klenow [24], Leng and Du [27] and Tan et al. [26], uses the production function method to measure the degree of energy price distortion in China's provinces over the years.

The key to the production function method is to estimate the production function. The specific form of the production function with the energy input is as follows:

$$y = Ak^{\alpha}l^{\beta}e^{\delta} \tag{11}$$

where output y is measured by the real GDP of each province at the constant price of 1999, and the data are from China Statistical Yearbook; based on the practice of Zhang [59], capital input k is measured by the capital stock estimated by using the perpetual inventory method (PIM), and the data are from China Statistical Yearbook and China Compendium of Statistics 1949–2008; labor input l is measured by the number of employees in each region at the end of the year, and the data come from the China Statistical Yearbook and the Statistical Yearbook of each province; energy input e is the energy consumption of each region, and the data come from the China Energy Statistical Yearbook and the Energy Statistical Yearbook of each province.

For province, i in year t, the logarithm of both sides of Equation (11) is calculated, and u_i is added to control the individual effect of the province. We can further obtain the following equation:

$$\ln y_{it} = \ln A + \alpha \ln k_{it} + \beta \ln l_{it} + \delta \ln e_{it} + u_i + \varepsilon_{it} \tag{12}$$

Parameter estimation of Equation (12) is carried out by using the fixed-effect model (the results of the Hausman test show that the fixed effect model is better than the random effect model). It is estimated that the output elasticity of energy consumption $\delta = 0.622$.

Based on estimating the elasticity coefficient of energy consumption, the marginal output of energy factors can be calculated by further derivation of energy input with Equation (11):

$$MPE_{it} = \frac{\delta y_{it}}{e_{it}} \tag{13}$$

Then, according to the definition of factor price distortion, the energy price distortion index is calculated to measure the degree of energy price distortion:

$$Dist_{it} = \frac{MPE_{it}}{EP_{it}} \tag{14}$$

If the energy price distortion index *Dist* is equal to one, it means that the actual energy price is equal to the marginal production revenue, and there is no energy price distortion. If *Dist* is less than one, it indicates that the actual energy price is higher than the market equilibrium price. That is, the energy price distortion is upward. If *Dist* is greater than one, it indicates that the actual energy price is lower than the market equilibrium price. In this case, the energy price distortion is downward. At the same time, the higher the index is, the more severe the energy price distortion is.

As can be seen from Figure 2, the energy price distortion indexes of each region (i.e., eastern regions and central and western inland regions) and the whole nation are all greater than 1 in every year between 2003 and 2017, reflecting the generally depressed energy prices in China, similar to the conclusions of most studies such as Dai and Cheng [60], Ouyang et al. [25], Li et al. [28]. Meanwhile, the degree of energy price distortion in China is basically in a slow downward trend from 2003 to 2011, but it rises slowly after 2012, which is similar to the findings of Li et al. [28]. This indicates that the process of energy price market-oriented reform in China is slow in general. Finally, it is observed that the degree of energy price distortion in the eastern region is significantly higher than that in the central and western regions, which is consistent with the findings of Leng and Du [27] and Li et al. [28]. The possible reason may be that the level of economic development, as well as the degree of industrialization of eastern China, is much higher than that of central and western regions, and the authority's price intervention in the energy market of eastern regions is relatively strong to maintain the advantage of this area [27].

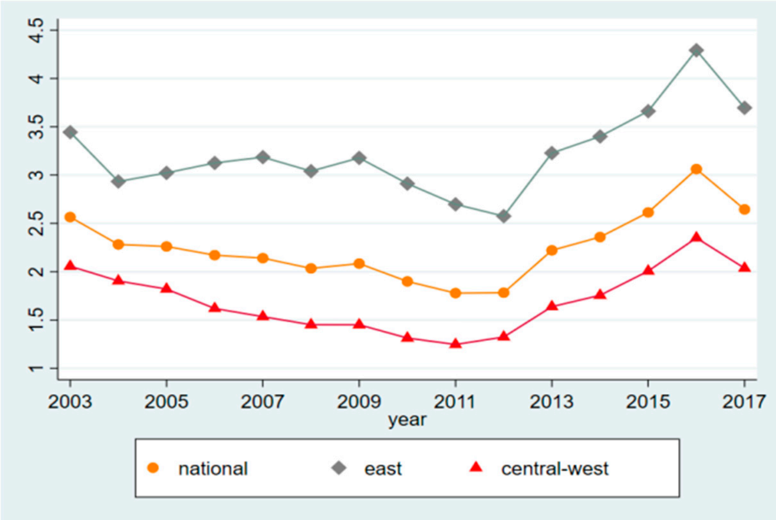


Figure 2. The distortion degree of energy price in eastern, central, western and whole China.

4.2. Empirical Results and Analysis

Based on the panel data of 30 provinces in China from 2003 to 2017, this paper further estimates the parameters of Equations (9) and (10). The results are shown in Table 5. According to the estimation results in Table 5, energy price distortion significantly reduces the inducing effect of energy price on China's green energy technological innovation. To be specific, no matter the number of green energy patent applications or the number of green energy patent grants is taken as the dependent variable, the estimated coefficient of energy price *lnEP* is generally positive under different estimation methods, while the estimated coefficients of the interaction term *lnEP*×*Dist* under FE, RE and FE-IV are significantly negative at the significance level of 10%. This shows that the distortion of energy price significantly inhibits the inducing effect of energy price on China's green energy innovation, which also demonstrates Hypothesis 3. As discussed above, the more distorted the energy price is in the region, the more serious the energy price is depressed, that is, the lower the actual energy price is compared with the marginal output of energy. In this context, the function of energy price as a signal of energy scarcity will be greatly weakened, and enterprises also have sufficient space to use energy factors, which will lead to insufficient incentives of companies for the innovation of "alternative energy production" and "energy conservation" technologies as well as the reduction of green energy innovation output, and the inducing effect of energy price on green energy innovation will not be obvious. As analyzed above, the energy price distortion index in eastern China is significantly higher than that in central and western China, and the mismatch of energy factors is more obvious, which also explains to a large extent why the inducing effect of energy price on green energy innovation is not significant in eastern China.

Table 5. Results of the moderate effect of energy price distortion.

Variables	Dependent Variable: Logarithm of the Number of Green Energy Patent Applications (lnPA)			Dependent Variable: Logarithm of the Number of Green Energy Patent Grants (lnPG)		
	FE	RE	FE-IV	FE	RE	FE-IV
lnEP	0.340 *** (2.80)	0.391 *** (4.43)	−0.120 (−0.41)	0.382 ** (2.11)	0.652 *** (4.42)	0.498 (0.96)
Dist	−0.444 *** (−4.95)	−0.104 * (−1.69)	−0.869 *** (−3.98)	−0.650 *** (−4.02)	−0.308 *** (−2.72)	−0.852 * (−1.90)
lnEP × *Dist*	−0.201 *** (−5.05)	−0.0760 ** (−2.26)	−0.324 *** (−4.33)	−0.258 *** (−4.27)	−0.156 *** (−2.99)	−0.354 *** (−2.85)
lnL	0.0464 (1.20)	0.0550 * (1.75)	0.0277 (0.67)	0.303 *** (5.10)	0.242 *** (4.45)	0.297 *** (4.69)
lnS	0.978 *** (24.67)	0.965 *** (30.94)	1.112 *** (14.68)	0.904 *** (14.01)	0.853 *** (15.31)	0.928 *** (6.74)
FDI	0.842 (1.49)	0.965 * (1.91)	0.711 (1.19)	6.841 *** (4.43)	4.971 *** (3.85)	6.710 *** (4.17)
Dum2009	−0.0312 (−0.64)	−0.136 *** (−3.60)	0.0218 (0.37)	−0.280 *** (−4.27)	−0.291 *** (−5.05)	−0.289 *** (−3.54)
Constant	−0.325 (−1.14)	−0.508 *** (−3.68)	−1.276 ** (−2.17)	−1.488 *** (−3.48)	−0.652 ** (−2.39)	−1.322 (−1.39)
Hausman		363.47 ***			24.55 ***	
N	420	420	420	360	360	360
R^2	0.949		0.943	0.897		0.896

Note: *t* statistic values are in brackets; ***, ** and * are significant at the significance level of 1%, 5% and 10%, respectively.

5. Conclusions

In the context that accelerating green energy technological innovation has become an important focus of promoting energy transformation in the world, it has also become a hot topic for academic circles to investigate the impact of energy price on green energy innovation. At present, the research on the inducing effect of energy price on green energy innovation mainly focuses on the developed countries with a complete energy factor market mechanism. This paper gives full consideration to great differences in economic and social development levels among different regions in China, and puts forward a research hypothesis that energy price innovation leads to overall positive but regionally heterogeneous impact on green energy innovation. Additionally, combined with the background of China's lagging energy marketization in the process of transition from planned economy to market economy, this paper proposes the hypothesis that energy price distortion plays a negative moderating role between energy price and green energy innovation. Last but not the least, based on the data of 30 provinces in China from 2003 to 2017, this paper confirms the three hypotheses. This provides a useful reference for us to fully understand the relationship between energy price and green energy innovation in a large developing country like China, which is in the process of economic transformation. To be specific, the main conclusions can be summarized as follows.

First, energy price has a significantly positive effect on China's green energy innovation. At the same time, whether the number of green energy patent applications or the number of green energy patent grants is used as the proxy variable of green energy technology innovation, or under different estimation methods, the research conclusion is still valid.

Second, the energy price has a heterogeneous effect on green energy technology in different regions of China. Specifically, the effect of energy price on green energy innovation is significant and positive in the central and western regions of China, but insignificant in eastern China.

Finally, energy price distortion has a negative moderating role in the relationship between China's energy price and green energy innovation. Specifically, the inducing effect of energy price on green energy innovation decreases with the increase of energy price distortion. At the same time, the degree of energy price distortion in eastern China is much higher than that in central and western China, which also to a large extent explains why the innovation effect of energy price is not obvious in eastern China.

The conclusions of this paper have obvious policy implications. This study shows that although energy price has a significantly positive effect on China's green energy innovation, energy price distortion will weaken this inducing effect. Therefore, the Chinese government should further accelerate the reform of energy marketization, reduce the low energy price caused by government control, and give full play to the leading role of energy price on green energy innovation through the decisive role of the market mechanism in energy resource allocation. In particular, the eastern region, which has a relatively severe energy price distortion, needs to make great efforts to reverse the situation in which the market level of energy price lags.

There are still some limitations to this study. For example, since the official R&D labor input in the field of green energy has not been released, this paper made an estimation about it, which may affect the final results. In terms of further research issues, we are more interested in whether the research results of this paper are still valid in Russia, Brazil and other developing countries and regions. Besides, in addition to energy price distortion, other factors, which deserve further research, may also explain the heterogeneity of green energy innovation-induced effects of energy prices in different regions of China.

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Appendix A

Table A1. Descriptive statistical results of major variables.

Variables	Obs	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis
lnPA	420	5.966	1.569	1.792	9.576	−0.192	2.632
lnPG	360	5.684	1.523	1.386	8.976	−0.277	2.688
lnEP	420	−1.440	0.352	−2.529	−0.509	−0.130	2.933
lnL	420	7.098	1.231	2.631	9.598	−0.608	3.673
lnS	420	6.892	1.552	3.169	10.485	−0.032	2.565
FDI	420	0.036	0.031	0.001	0.215	1.770	7.686
Dum2009	420	0.500	0.500	0	1		

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