Environmental Science and Pollution Research (2019) 26:17333–17350
https://doi.org/10.1007/s11356-019-05082-5

RESEARCH ARTICLE

Effectiveness-based innovation or efficiency-based innovation? Trade-off and antecedents under the goal of ecological total-factor energy efficiency in China

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Received: 29 January 2019 / Accepted: 3 April 2019 / Published online: 23 April 2019

Abstract

Pursuing innovation effect or efficiency is an important trade-off that Chinese local governments need to face in the process of developing economy and protecting the environment. From the perspective of the policy portfolio, we employ the industrial panel data of 30 provinces in China during 2000–2015 to analyze the impacts of effectiveness-based innovation and efficiency-based innovation on ecological total-factor energy efficiency (ETFEE), and further analyze the effects of command-and-control, market-based and voluntary environmental regulations on innovation. The findings reveal that (1) both effectiveness-based innovation and efficiency-based innovation have significant promoting effects on ETFEE. (2) Three types of environmental regulations have significantly inhibitory effects on effectiveness-based innovation and efficiency-based innovation. (3) The interaction term of command-and-control and market-based regulations plays a significant role in promoting effectiveness-based innovation and efficiency-based innovation, whereas the interaction term of market-based and voluntary regulations merely promotes efficiency-based innovation. The interaction term of three types of regulation only has a synergetic and positive effect on the efficiency-based innovation. Finally, this paper gives specific policy recommendations.

Keywords Effectiveness-based innovation · Efficiency-based innovation · Ecological total factor energy efficiency · Environmental regulation · Policy portfolio

Introduction

Since the twenty-first century, the process of China's industrialization has been accelerated. Industrial energy consumption is also at a relatively high level, the percentage of which over total energy consumption has remained above 70%. According to World Bank statistics,[1] in China, energy consumption per unit of GDP rose from \$1.99/kg oil equivalent in 1990 to \$5.7/kg oil equivalent in 2014, an increase of 186%. CO_2 emissions per capita rose from 2.15 tons in 1990 to 7.54 tons in 2014, an increase of 251%. China's CO_2 emissions and energy consumption reached the top in the world in 2008 and 2010, respectively (British Petroleum (BP), 2014). As the data from the environmental protection agency's continuous monitoring of 118 cities nationwide shows, about 64% of the city's groundwater is heavily polluted and basic clean city's groundwater only accounts for 3%.[2] In the process of China's rapid industrialization and urbanization, the imbalance between supply and demand of energy and environmental pollution has intensified, which encumbers the sustainable development of the industry (Li et al. 2007). Therefore, the improvement of ecological total-factor energy efficiency

Highlights
• Innovation is divided into effectiveness-based and efficiency-based innovation
• Innovation has a significant promoting effect on ecological total-factor energy efficiency
• Environmental regulation is divided into command-and-control, market-based, and voluntary regulations
• Environmental regulations have a synergetic and positive effect on the efficiency-based innovation

Responsible editor: Eyup Dogan

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[1] https://data.worldbank.org.cn/country/china?view=chart
[2] http://news.ifeng.com/mainland/detail_2013_02/17/22182632_0.shtml

(ETFEE) is a pivotal approach to combating the three challenges, i.e., climate change, energy security, and sustainable development of economy (Bukarica and Tomšić 2017).

As one of the largest emerging economies, China is accelerating its transformation to innovation, and its innovation capacity and performance have attracted the attention of scholars and policy makers from all over the world (Dang and Motohashi 2015). In 2017, China's R&D intensity reached 2.12%, ranking second in the world after the USA. However, there has always been a debate between effect and efficiency in the process of transforming R&D input into output (Sheng et al. 2013). Effectiveness-based innovation strategies emphasize the degree of innovation of products or technologies in the market (Sethi et al. 2001). The innovation strategy focusing on efficiency focuses on the speed and cost of product or technology to market, namely, the first-mover advantage and cost advantage ahead of competitors (Griffin 1997). Due to the limited resources, industrial enterprises need to carefully balance the relationship between them.

Institutional theory provides a good foundation to study the selection of regional innovation strategies under the framework of environmental regulations (Pérez-Nordtvedt et al. 2015). This theory emphasizes that the development of enterprises depends on their ability of complying with social norms to obtain legitimacy (Sirmon et al. 2007). From the perspective of institutional theory, industrial enterprises play up to social norms abiding by environmental policies. Therefore, the choice of regional innovation strategy depends on the government's pressure of environmental regulation. So, how do regional weigh the efficiency and effect of innovation under the pressure of environmental regulation? And what impact will this choice have on regional industrial ETFEE? This is a topic well worth studying.

Porter hypothesis argues that well-designed environmental regulation can stimulate enterprises to conduct innovation, and thus enhance their competitiveness (Porter and van der Linde 1995). Confronted with excessive consumption of resources and environmental damage caused by economic development, Chinese government has enacted a range of policies on energy conservation and emission reduction (Ren et al. 2018). Since 2000, laws to protect environment such as *Law on the Prevention and Control of Environmental Pollution by Solid Waste* (2004), *Law on Conserving Energy* (2007), *Circular Economy Promotion Law* (2008), *Atmospheric Pollution Prevention and Control* (2015 Revision), etc. have been issued. Additionally, Ministry of Industry and Information released entry conditions for industries like cement, printing and dyeing, casting, etc. These energy-conservation and emission-reduction policies stipulate the technology standards of production and discharge standards of pollutant in a legal or mandatory manner. Meanwhile, to overcome environmental externalities by taking advantage of such instruments as fines, taxes, subsidies, emissions trading, etc., Chinese Ministry of Environmental Protection issued market-based policies like *Administrative Regulations on Levy and Use of Pollutant Discharge Fee* (2003), *Measures for Environmental Administrative Punishment* (2010), *Notice on the adjustment of the subsidies for energy-efficient vehicles* (2011), *Guiding opinions on further promoting compensable use and pilot tests of emissions trading* (2014), etc. Moreover, this ministry has also released voluntary polices to encourage the enterprises and public to participate in energy conservation and emission reduction, such as *Measures on Open Environmental Information* (*Trial*) (2007), *Administrative Measures for the use of China Environmental Labeling* (2008), *Measures for the Public Participation in Environmental Protection* (2015), etc. Overall, energy-saving and emission-reduction policy system that integrates command-and-control, market-based, and voluntary regulation has basically formed in China. Then can China's environmental regulation promote regional industrial innovation? Can good synergy be formed between environmental policies? These questions have not been thoroughly studied.

Based on the above problems, this paper employs 2000–2015 industrial panel data of 30 provinces in China to test the influence of effectiveness-based innovation and efficiency-based innovation on ETFEE, and further analyzes the impact of command-and-control, market-oriented, and voluntary environmental regulation on innovation. This study effectively responds to and resolves the dispute on innovation efficiency and effect existing in previous studies, and is of great significance to the scientific evaluation of the effectiveness of different environmental policies, the promotion of industrial innovation of provinces, and the green transformation of Chinese industries.

This paper has made the following contributions to knowledge. First, we discussed the difference effects of environmental regulation on effectiveness-based innovation and efficiency-based innovation, and the influence of two kinds of innovation strategy on regional ETFEE in system within the framework of the institutional theory. Existing literatures mainly discuss the impact of environmental regulation on product innovation, process innovation, and service innovation based on the differences in innovation contents (Kammerer 2009; Ford et al. 2014; Miguel and Pazó 2017). There is little analysis on the difference in innovation strategy choice of industrial enterprises in response to government environmental policies. This paper effectively responds to and resolves the innovation effect and efficiency existing in previous research, and help for the government to make more effective environmental protection policies and innovation policies.

Second, following the versions of Porter hypothesis, we analyze the factors affecting effectiveness-based innovation and efficiency-based innovation of China's provincial industries. Given that the mechanism of different environmental regulation is not same, this paper divides environmental regulation into three types, namely, command-and-control, market-based, and voluntary environmental regulation. We undertake an in-depth analysis of the impacts of different environmental regulation tools on industrial innovation of Chinese provinces.

Third, we further analyze the synergy effect of three environmental regulation tools on effectiveness-based innovation and efficiency-based innovation. The extant literature mainly measures the level of environmental regulation with a single indicator (Mandal 2010; Yuan and Xiang 2018; Wang and Yuan 2018). Even though multiple indicators are used to classify and study environmental regulation, the synergy effect of environmental regulation tools has been overlooked. This paper not only enriches the Porter hypothesis, but also provides evidence for formulating the environmental protection policy portfolio.

The remainder of the paper is structured as follows. The "Literature review" section is a literature review. In the "Methods and materials" section, we describe the methods and materials. Results are presented in the "Results" section. The "Discussion" section is the discussion. Conclusions are presented in the "Conclusions" section.

Literature review

Ecological total-factor energy efficiency

The research on total factor energy efficiency (TFEE) mainly includes two aspects. First, the expected output is the only indicator of output, regardless of the environmental impact of energy consumption. For example, at the regional level, Zhang et al. (2011) investigated 23 developing countries and found that the total factor energy efficiency in developing countries is relatively low during the period of 1980–2005. Özkara and Atak (2015) studied total factor energy efficiency scores of the manufacturing industry in 26 regions of Turkey and proposed that Istanbul region is the best performer. Zhang et al. (2018) indicated that the total factor energy efficiency and carbon emission performance of CDM host countries appear much lower than those of investment countries. Chang and Hu (2010) and Heshmati and Kumbhakar (2011) found that China's regional total factor energy efficiency increases progressively, but at a relatively low level. At the industry level, the total factor energy efficiency of the thermal power industry, the industry, the agriculture, and the iron and steel industry in China experiences an increasing trend, but at a relatively low level (Bi et al. 2014; Zhao et al. 2014; He et al. 2018; Chen et al. 2008; Sheng and Song 2013).

Second, considering the environmental impact of energy consumption, undesirable outputs like CO_2 are subsumed into the outputs. The general conclusion is that ETFEE is lower than TFEE, and there exist distinct region heterogeneity and industry heterogeneity. At the nation level, Camioto et al. (2016) found that ETFEE in the G7 countries is higher than that in the BRICS countries. At the region level, although China's regional ETFEE is increasing during the sample period, it is still weakly effective as a whole, and the ETFEE in the eastern region is higher than the central and western regions (Li and Hu 2012; Zhang et al. 2015; Li et al. 2007; Feng et al. 2018; Zhang and Ye 2015; Yue et al. 2017; Tao et al. 2016).

At the industry level, Lin and Tan (2016) and Guo et al. (2018) asserted that the ETFEE in China's energy-intensive industries is relatively low. Mandal (2010), Chen and Golley (2014), Tian and Lin (2017), Li and Lin (2018), Yang et al. (2017), Li et al. (2018a), Shao et al. (2016), Wang et al. (2017), Zhang and Wei (2015), Li and Lin (2016), Lin and Zhang (2018), and Zhu et al. (2018) studied the cement industry, industry, non-ferrous metal industry, transportation industry, manufacturing industry, service industry, and mining industry respectively and found that ETFEE is relatively low when considering the environmental impact. Moreover, Zhang et al. (2017) compared Chinese and American airlines and revealed that the ETFEE of Chinese airlines lags far behind that of American airlines, and the gap of ETFEE between those two countries' airlines is enlarging. In general, the fact that China's industrial ETFEE is relatively low is indisputable. Therefore, further exploration of how to improve industrial ETFEE through environmental regulation and innovation is an urgent task for current and future research.

Innovation type and innovation performance

The existing literature is mainly based on different content of innovation and focuses on product innovation, process innovation, organizational innovation, etc. For instance, Choi et al. (2016) demonstrated that in the long term, investments in product innovation are more influential in increasing a firm's profit than investments in process innovation. Rajapathirana and Hui (2018) found that organizational innovation, process innovation, product innovation, and marketing innovation are capable of promoting a firm's innovation. Geldes et al. (2017) chose Chile as an emerging market context and their results show that only product innovation affects innovation performance. Lee et al. (2017) revealed that both product and process innovation can propel firm performance. Fu et al. (2018) analyzed the manufacturing firms in Ghana and found that technological innovation positively impacts the labor productivity of firms more than managerial innovation. Liao (2018) contended that eco-organization innovation, eco-process innovation, and eco-product innovation can build up firm's reputation.

However, innovation can also effectively promote regional or industrial green development and improve environmental quality. For instance, Balsalobre et al. (2015) suggested that energy innovations help reduce CO_2 emission and mitigate the negative impact of energy intensity on environmental quality. Álvarez-Herránz et al. (2017a, 2017b) found that energy innovation measures have a positive effect that enables countries to enhance their environmental quality. Wakeford et al. (2017) studied Ethiopia's cement, leather, and textile sectors and found that product and process innovation are important drivers of green industrialization. Li et al. (2018b) considered that technological innovation is the major factor in promoting China's industrial total factor carbon productivity.

Environmental regulation and innovation

There are three strands of the literature on the relationship between environmental regulation and innovation (the "weak" Porter hypothesis). First, based on the different content of innovation, most of studies mainly examine the effects of environmental regulation on product innovation, process innovation, service innovation, environmental innovation, eco-innovation, etc. For example, Kammerer (2009), Ford et al. (2014), and Miguel and Pazó (2017) found that environmental regulation has significantly positive effects on product innovation, service innovation, and process innovation. Yabar et al. (2013) concluded that environmental regulation can significantly promote environmental innovation by studying the case of household appliances recycling industry in Japan. Chen et al. (2017), and Aloise and Macke (2017) discovered that environmental regulation has a significant and positive impact on regional eco-innovation.

Second, in terms of innovation intensity, several studies use R&D investment as a proxy of innovation intensity and analyze the impact of environmental regulation on innovation. For instance, Kneller and Manderson (2012) found that environmental regulation can increase environmental R&D investment, but it can not increase total R&D investment. Environmental R&D has a crowding-out effect on non-environmental R&D. Using the industrial panel data of Taiwan, Yang et al. (2012) detected that environmental regulation can augment R&D expenditures. Sen (2015) proved that environmental taxes can increase R&D investment of enterprises.

Third, from the perspective of environmental regulation, voluminous literature is based on the classification of environmental regulation tools. For example, Kemp and Pontoglio (2011) found that market-based regulation tools such as environmental taxes and emissions trading play a limited role in promoting innovation. Bergek et al. (2014) studied the case of the energy and automobile industries in Sweden and found that such regulatory tools as economic incentives and environmental standards can stimulate innovation. Zhao et al. (2015) found that market-based environmental regulation has a limited effect on firm's innovation. Cheng et al. (2017) discovered that command-and-control regulation has an insignificant impact on technological progress but it can reduce carbon emissions. Moreover, market-based regulation can facilitate technological progress but its effectiveness of emissions reduction is weak. Liao (2018) revealed that market-based instrument and information-based instrument can propel firm's environmental innovation while command-and-control instrument merely promotes eco-organization innovation.

Methods and materials

Econometric regression model

We construct the econometric regression models as below.

Equation (1) is used to test the effects of effectiveness-based innovation and efficiency-based innovation on provincial industry ETFEE.

$$\ln etfee_{i,t} = \alpha_0 + \alpha_1 \ln effe\_inno_{i,t} + \alpha_2 \ln effi\_inno_{i,t} + \alpha_3 control_{i,t} + \upsilon_{i,t} \quad (1)$$

Equation (2) examines the influence of different types of environmental regulations on effectiveness-based innovation and efficiency-based innovation.

$$\begin{cases} \ln effe\_inno_{i,t} = \beta_0 + \beta_1 \ln cer_{i,t} + \beta_2 \ln mer_{i,t} + \beta_3 \ln ver_{i,t} + \beta_4 \ln(cer_{it} \times mer_{i,t}) + \beta_5 \ln(cer_{i,t} \times ver_{i,t}) + \\ \quad \beta_6 \ln(mer_{i,t} \times ver_{i,t}) + \beta_7 \ln(cer_{i,t} \times mer_{i,t} \times ver_{i,t}) + \beta_8 control_{i,t} + \varepsilon_{i,t} \\ \ln effi\_inno_{i,t} = \beta_0 + \beta_1 \ln cer_{i,t} + \beta_2 \ln mer_{i,t} + \beta_3 \ln ver_{i,t} + \beta_4 \ln(cer_{it} \times mer_{i,t}) + \beta_5 \ln(cer_{i,t} \times ver_{i,t}) + \\ \quad \beta_6 \ln(mer_{i,t} \times ver_{i,t}) + \beta_7 \ln(cer_{i,t} \times mer_{i,t} \times ver_{i,t}) + \beta_8 control_{i,t} + \varepsilon_{i,t} \end{cases} \quad (2)$$

In Eqs. (1) and (2), effectiveness-based innovation (*effe_inno*) and efficiency-based innovation (*effi_inno*) denote effectiveness-based innovation and efficiency-based innovation respectively. *etfee* represent ecological total-factor energy efficiency. *cer*, *mer*, and *ver* indicate command-and-control, market-based and voluntary regulation, respectively. The interaction term stands for the synergy effect of environmental regulation policies. *control* means the control variable group. υ and ε denote residual terms. i is the province. t is the year.

Variable selection and definition

Ecological total-factor energy efficiency We employ the super-efficiency slack-based measure model (SE-SBM-DEA) with undesirable outputs to evaluate the industrial ETFEE in 30 provinces of China. The model is shown in Appendix. Given the availability of data, the input indicators for measuring ETFEE are overall energy consumption, labor input, and capital input in industrial enterprises of each province. The desirable output indicator is gross industrial output of the region, and undesirable output indicators are industrial waste water, waste gas, solid waste, and CO_2 (Li and Hu 2012; Chen and Golley 2014; Lin and Zhang 2018).

Effectiveness-based innovation and efficiency-based innovation The effectiveness-based innovation strategy emphasizes the innovation degree of the product or technology in the market (Sethi et al. 2001), while the efficiency-based innovation strategy focuses on the speed and cost of the product or technology to the market, that is, the first-mover advantage and cost advantage ahead of competitors (Griffin 1997). According to Li et al. (2007), invention patents are the most high-tech, high-cost, and difficult patents, and they belong to high-level technological innovation projects; however, utility model and design patents are relatively low-tech, low-cost, and less difficult inventions. Hence, we measure the industrial effectiveness-based innovation of each province by the number of invention patent applications, and efficiency-based innovation is measured by the total number of utility model patent and design patent applications.

Environmental regulation According to the Porter hypothesis (Porter and van der Linde 1995), we divide environmental regulation into three types, i.e., command-and-control (*cer*), market-based (*mer*), and voluntary regulation (*ver*) to examine the effects of different environmental regulation tools on industrial innovation and ETFEE of provinces. Command-and-control regulation is measured by industrial construction project "three simultaneous" environmental protection investment of provinces. Market-based regulation is measured by the levy amount of pollutant discharge fees in industrial enterprises of each province. Voluntary regulation is measured by the number of environmental letters and calls of each province (Liao 2018; Xie et al. 2017).

Control variables We select control variables from three dimensions: demand side (market pull), supply side (technology push), and industry characteristics. Market-pull factor is market competition (*mc*) (Kneller and Manderson 2012; Tabacco 2015). Technology-push factor is foreign direct investment (*fdi*) (Zakaria and Bibi 2019; Huang et al. 2019). Industry characteristics include capital intensity (*ci*) (Yuan et al. 2017), profitability (*pr*) (Long et al. 2015), and regional industry concentration (*lq*) (Jang et al. 2017). Moreover, we add R&D intensity (*r&d*), R&D personnel (*rdp*) (Song and Oh 2015), and industry size (*gdp*) (Kneller and Manderson 2012) in Eq. (2). Variables are defined in Table 1.

Data sources and processing

We use the industrial panel data from 30 provinces in China in 2000–2015 as the sample. Due to the lack of data in Tibet, Hong Kong, Macao, and Taiwan, those regions are excluded from the research scope of this paper. To further analyze the regional heterogeneity effects of environmental regulation and innovation on industrial ETFEE of provinces, we categorize 30 provinces into the eastern, central, and western regions (Chang and Hu 2010; Li and Hu 2012).[3]

The number of patents, the number of invention patent applications, R&D investment, and R&D personnel of the industry in each province are from *China Statistical Yearbook on Science and Technology*. The data, energy consumption of the industry in each province, is derived from *China Energy Statistical Yearbook*. The data on industrial waste water discharged, the volume of waste gas emission of the industry, and the industrial solid wastes generated in each province come from *China Statistical Yearbook on Environment*. CO_2 emission is calculated according to the method mentioned in IPCC (Intergovernmental Panel on Climate Change) Guidelines for National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Change (IPCC) 2007). The data, including fixed assets, total assets, labor input, total output value of the industry, FDI, the number of enterprises, and profits of industrial enterprises in each province, is obtained from *China Statistical Yearbook*. To rule out the impact of inflation, we use current price/PPI (Producer's Price Index for Manufactured Products) to transform current year's prices (current data) into constant price of 2000. Investment in fixed assets of each industry is computed with Perpetual Inventory Method (Zhang et al. 2011). Table 2 displays the descriptive statistics of all variables in the econometric models.

Results

Unit root test and cointegration test

We carry out stationary test on the data before the econometric regression analysis. In this paper, the LLC (Levin-Lin-Chu), ADF-Fisher, and PP-Fisher test are used for unit root test. The results show that all variables are stationary sequences (see Table 3).

[3] The eastern region includes Beijing, Tianjin, Liaoning, Shanghai, Jiangsu, Zhejiang, Shandong, Fujian, Guangdong, Hainan and Hebei; the central region covers Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hunan and Hubei; Inner Mongolia, Guangxi, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Xinjiang, Ningxia, and Chongqing are encompassed in the western region.

Table 1 The definitions of variables in the econometric model

Variable name	Definition	Unit
Ecological total-factor energy efficiency (etfee)	Calculated by the SE-SBM-DEA model	–
Effectiveness-based innovation (effe_inno)	The number of invention patent applications of the industry in each province	Piece
Efficiency-based innovation (effi_inno)	The number of non-invention (utility model and design) patent applications of the industry in each province	Piece
Command-and-control environmental regulation (cer)	As measured by construction project “three simultaneous” environmental protection investment of each province	100 million yuan
Market-based environmental regulation (mer)	The levy amount of pollutant discharge fees of each province	10,000 yuan
Voluntary environmental regulation (ver)	The number of environmental letters and calls of each province	Piece
Market competition (mc)	Ratio of the number of enterprises with *i* unit output value in each province to that in the whole nation	–
Foreign direct investment (fdi)	Investments from large- and medium-sized foreign-funded enterprises, or Hong Kong, Macao, and Taiwan of the industry in each province	100 million yuan
Capital intensity (ci)	Fixed assets/total assets of the industry in each province	–
Industry size (gdp)	Total output value of the industry in each province	100 million yuan
Profitability (pr)	Total profits of industrial enterprises in each province	100 million yuan
Industry concentration (lq)	The industrial location entropy of each province (the ratio between the proportion of the industrial output value to GDP in each province and that in the whole nation)	–
R&D intensity (r&d)	Industrial per capita R&D investment in each province	Yuan/Person
R&D personnel (rdp)	Full-time equivalent of R&D personnel in industrial enterprises above designated size of each province	Man-year

Table 2 Descriptive statistics of variables

Variable	Mean	SD	Min	Max
lnetfee	− 0.896	0.505	− 2.364	0.195
lneffe_inno	6.169	2.025	0.693	10.926
lneffi_inno	6.912	1.897	0.000	11.267
lncer	3.247	1.311	− 2.296	7.840
lnmer	10.304	1.074	6.648	12.531
lnver	8.708	1.399	3.912	11.656
lnmc	− 0.165	0.394	− 1.207	0.794
lnfdi	6.090	1.739	0.854	9.836
lnci	− 0.585	0.203	− 1.399	− 0.060
lngdp	7.890	1.233	4.186	10.318
lnpr	5.957	2.461	− 23.026	9.179
lnlq	− 0.091	0.238	− 1.164	0.231
lnr&d	− 4.193	0.643	− 6.387	− 2.715
lnrdp	9.304	1.627	4.277	12.997

Table 3 The results of unit root test

Variable	LLC test	ADF-Fisher test	PP-Fisher test	Conclusion
lnetfee	− 15.729***	197.460***	225.869***	Stationary
lneffe_inno	− 44.334***	381.456***	533.125***	Stationary
lneffi_inno	− 38.941***	340.613***	517.408***	Stationary
lncer	− 19.884***	107.99***	187.600***	Stationary
lnmer	− 4.078***	24.526***	23.468***	Stationary
lnver	− 3.703***	24.689***	87.101***	Stationary
lnmc	− 3.613***	116.169***	179.965***	Stationary
lnfdi	− 34.039***	273.276***	513.487***	Stationary
lnci	− 15.815***	203.810***	338.947***	Stationary
lngdp	− 22.614***	190.341***	500.331***	Stationary
lnpr	− 38.430***	299.440***	443.715***	Stationary
lnlq	− 29.377***	238.108***	299.424***	Stationary
lnr&d	− 5.915***	144.567***	144.334***	Stationary
lnrdp	− 28.639***	354.042***	385.406***	Stationary

***, **, and * indicate significance at the 1, 5, and 10% levels, respectively

To avoid the spurious regression, it is necessary to examine the cointegration relationship between environmental regulation, innovation, and ETFEE prior to estimating the parameters of panel data. We use the Pedroni cointegration test (Pedroni 2004). The results (see Table 4) show that the panel cointegration relationships reside between innovation and ETFEE, environmental regulation, and innovation.

The impacts of provincial industrial innovation on ETFEE

Table 5 reports the estimated results on the effects of effectiveness-based innovation and efficiency-based innovation on ETFEE (M1-M4). SYS-GMM is used for regression in the national sample and the fixed effect model or random effect model is adopted to estimate the regional sample.

AR test and Sargan test are required in order to investigate the effectiveness of the SYS-GMM estimated results. AR(1) and AR(2) are used to test the autocorrelation of the residual terms. The null hypothesis is "no autocorrelation in the residual terms." The residuals after difference transformation must have a first-order serial correlation, but if there is no second-order serial correlation, the null hypothesis can be accepted (Arellano and Bond 1991). Fortunately, all the models passed the AR(2) tests and the null hypothesis was accepted, as indicated by p value showing that the serial correlation in the residual terms is not second order.

Then, we conducted over-identifying test (Sargan test) on the models to verify whether the instrumental variables used in the regression process were effective. Sargan test is subject to the chi-square distribution of (n-k) degrees of freedom, n is the rank of the instrumental variables, and k is the number of estimated coefficients. The null hypothesis is "over-identifying restrictions are valid." On the whole, the validity of over-identifying restrictions of instrumental variables used as a necessity for SYS-GMM is confirmed, as indicated by the p-values of the Sargan test. Accordingly, considering all test statistics of these models, we can conclude that the estimated models are adequately specified.

From a national perspective, effectiveness-based innovation and efficiency-based innovation have significant and positive effects on industrial ETFEE ($\alpha = 0.092$, $p < 0.01$; $\alpha = 0.133$, $p < 0.01$), and the elasticity of efficiency-based innovation on ETFEE is 0.041 units higher than that of effectiveness-based innovation, indicating that no matter which innovation strategy industrial enterprises choose, it can promote the growth of ETFEE. Moreover, efficiency-based innovation is the main way to promote ETFEE (Fig. 1).

From a regional perspective, effectiveness-based innovation and efficiency-based innovation in the eastern region can significantly promote ETFEE ($\alpha = 0.092$, $p < 0.1$; $\alpha = 0.260$, $p < 0.01$) (Fig. 2). In the central region, only effectiveness-based innovation can facilitate ETFEE (α =

Table 4 The results of cointegration test

Statistics	Hypothesis	Test type	Results							
			lneffe_inno — lnetfee	lneffi_inno —lnetfee	lncer—lneffe_inno	lnmer—lneffe_inno	lnver—lneffe_inno	lncer—lneffi_inno	lnmer—lneffi_inno	lnver—lneffi_inno
Within groups	H_0: $\rho = 1$ H_1: $\rho < 1$	Panel v-Stat.	0.896	0.745	− 0.844	5.454***	6.213***	− 1.009	5.590***	6.785***
		Panel ρ-Stat.	− 8.780***	− 8.222***	− 63.810***	− 8.655***	− 28.690***	− 62.589***	− 9.043***	− 28.845***
		Panel PP-Stat.	− 4.610***	− 4.470***	− 19.949***	− 4.348***	− 10.327***	− 20.137***	− 4.489***	− 10.332***
		Panel ADF-Stat.	− 6.469***	− 6.652***	− 12.977***	− 4.284***	− 8.021***	− 13.278***	− 4.499***	− 7.898***
Between groups	H_0: $\rho = 1$ H_1: $\rho < 1$	Group ρ-Stat.	− 7.300***	− 6.808***	− 55.785***	− 7.190***	− 24.842***	− 54.709***	− 7.531***	− 24.979***
		Group PP-Stat.	− 4.684***	− 4.532***	− 21.336***	− 4.400***	− 10.890***	− 21.540***	− 4.553***	− 10.895***
		Group ADF-Stat.	− 6.702***	− 6.901***	− 13.768***	− 4.330***	− 8.387***	− 14.095***	− 4.564***	− 8.254***

***, **, and * indicate significance at the 1, 5, and 10% levels, respectively

Table 5 The results on the effects of industrial innovation on ETFEE

Variables	Nation M1 SYS-GMM	Eastern M2 FE	Central M3 FE	Western M4 FE
$\ln etfee_{t-1}$	0.263***(9.96)			
lnmc	− 0.159**(− 2.15)	− 0.451***(− 4.31)	0.046(0.47)	− 0.105(− 1.05)
lnfdi	− 0.232***(− 8.25)	− 0.464***(− 3.61)	− 0.257***(− 4.07)	0.019(0.37)
lnci	− 0.566***(− 20.28)	− 0.678***(− 4.91)	− 0.657***(− 5.72)	− 0.404***(− 2.86)
lnpr	− 0.002*(− 1.79)	− 0.048(− 0.47)	− 0.002(− 0.24)	− 0.001(− 0.13)
lnlq	0.456**(2.04)	0.921***(3.44)	0.688***(3.38)	0.798***(2.86)
lneffe_inno	0.092***(6.46)	0.092*(1.83)	0.150**(2.27)	0.023(0.61)
lneffi_inno	0.133***(12.31)	0.260***(3.79)	0.062(0.88)	0.030(0.69)
_cons	− 1.893***(− 21.51)	− 0.319(− 0.76)	− 0.895***(− 4.15)	− 1.320***(− 6.32)
AR(1)	− 3.21[0.00]			
AR(2)	1.35[0.18]			
Sargan χ^2	27.43[1.00]			
Wald χ^2	5669.26[0.00]			
F-statistic		16.29[0.00]	18.98[0.00]	10.94[0.00]
Hausman statistic		14.19[0.07]	79.51[0.00]	35.14[0.00]
Observations	390	176	128	176

The *t*-statistic and *z*-statistic are in parentheses and the *p* value is in square brackets. ***, **, and * indicate significance at the 1, 5, and 10% levels, respectively

0.150, $p < 0.05$) (Fig. 3). As for the western region, both effectiveness-based innovation and efficiency-based innovation have no significant effects on ETFEE (Fig. 4). The primary reason is that the eastern and central regions are in the leading position in the field of innovation on low-carbon and energy-conservation technologies and energy-saving and environmental invention patents can significantly promote ETFEE. The innovation foundation of the western region is relatively weak, and the pressure of economic development is greater. The local governments in the western region pay more attention to the economic performance of innovation while they overlook the environmental benefits of patent innovation, leading to the fact that the coordinated development of energy and environment has not been achieved.

The impact of environmental regulation on effectiveness-based innovation

Table 6 presents the estimated results on the effects of different types of environmental regulation on effectiveness-based innovation of the provincial industry. From a national perspective, command-and-control, market-based, and voluntary regulations have significantly inhibitory effects on effectiveness-based innovation ($\beta = -0.131, p < 0.01$; $\beta = -0.108, p < 0.1$; $\beta = -0.029$, $p < 0.05$) without considering the synergy of environmental regulation (M1) (Fig. 1). The reason lies in that innovation infrastructure of China's provincial industry is relatively weak. Effectiveness-based innovation requires a large amount of R&D funds and human capital investment.

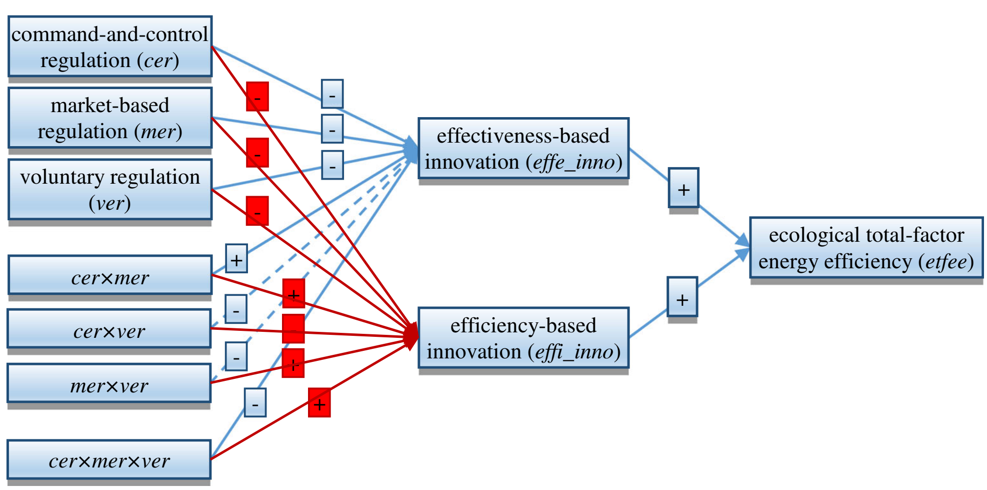

Fig. 1 Causal diagram scheme (Nation). The solid lines indicate that the estimated coefficient is significant at least at the 10% level, and the dotted lines indicate that the estimated coefficient is not significant. *Source*: *prepared by the author*

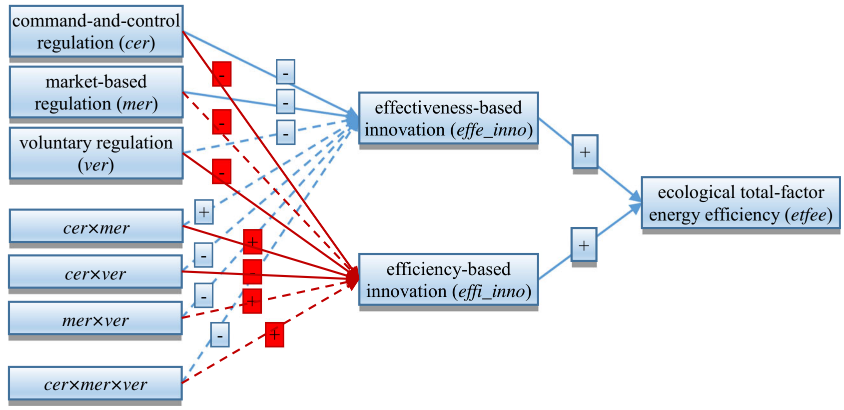

Fig. 2 Causal diagram scheme (Eastern). The solid lines indicate that the estimated coefficient is significant at least at the 10% level, and the dotted lines indicate that the estimated coefficient is not significant. *Source*: *prepared by the author*

However, not only the construction project "three simultaneous" environmental protection investment but also pollutant discharge fees or frequent environmental letters and calls have a strong cost-effect on effectiveness-based innovation, thus crowding out innovation investment.

Furthermore, we investigate the synergy between two types of environmental regulation (M2). The interaction term of command-and-control and market-based regulations plays a significant role in promoting effectiveness-based innovation ($\beta = 0.047$, $p < 0.01$). The main reason is that command-and-control and market-based regulations are complementary. To be more specific, the introduction of market-based regulation enables industrial enterprises to flexibly choose regulatory methods at lower cost, thereby effectively reducing the squeeze on the effectiveness-based innovation investment and stimulating enterprises to undertake innovation. Nonetheless, the effects of the interaction terms of command-and-control and voluntary regulations and market-based and voluntary regulations on effectiveness-based innovation are not significant, which shows that the synergy effect between voluntary regulation and other two types of environmental regulation is not good. It can be attributed to the fact that the system of China's environmental letters and calls is relatively imperfect. Additionally, environmental supervision intensity has been weak for a long time. Thus, it is difficult for voluntary environmental regulation to take effect (Fig. 1).

Finally, the synergistic effect of three types of environmental regulation is examined (M3). The interaction term of command-and-control, market-based, and voluntary regulations has a significantly negative impact on effectiveness-based innovation ($\beta = -0.021$, $p < 0.01$), demonstrating that three types of environmental regulation collectively suppress effectiveness-based innovation (Fig. 1). The primary reason is that Chinese environmental protection authorities have not considered the synergy between policies when formulating environmental protection policies. The incoherence of various environmental protection policies has generated an inhibitory effect on the development and diffusion of environmentally friendly patents and technologies (Costantini and Crespi 2013). As mentioned in the "the General Planning for the Development of Environmental Protection Legislation and Environmental Economic Policies in China during the 12th Five-Year Plan Period," "More than 20 environmental administrative systems are established in China's environmental laws and regulations, but the content of many regulations overlaps or even conflicts. It has not only wasted limited legislative resources and led to the conflicts between laws but also increased the difficulties of amendment work and law enforcement." Lacking a range of environmental protection measures such as systematic end-of-pipe treatment technologies and process innovation results in the partial success of the government's environmental administration (Jänicke 1992).

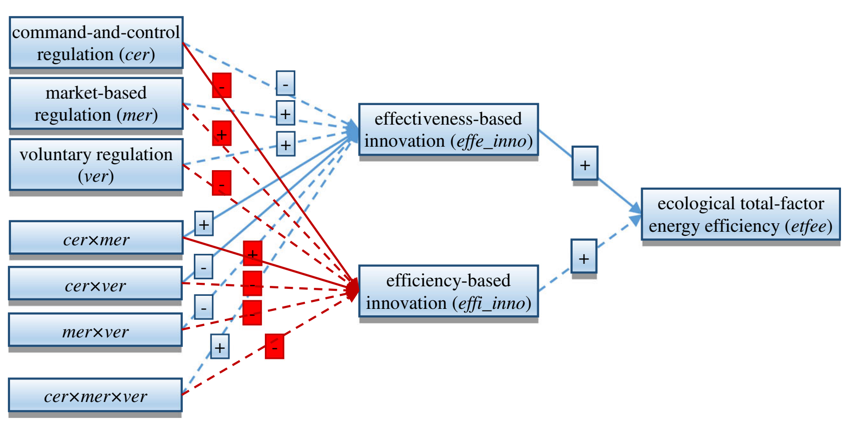

Fig. 3 Causal diagram scheme (Central). The solid lines indicate that the estimated coefficient is significant at least at the 10% level, and the dotted lines indicate that the estimated coefficient is not significant. *Source*: *prepared by the author*

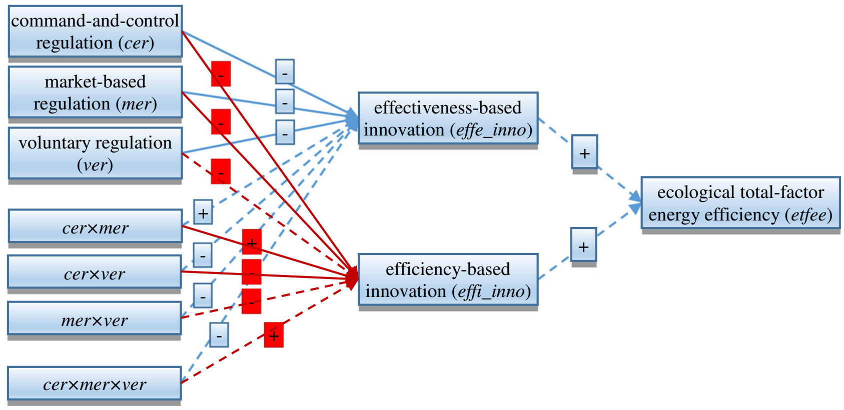

Fig. 4 Causal diagram scheme (Western). The solid lines indicate that the estimated coefficient is significant at least at the 10% level, and the dotted lines indicate that the estimated coefficient is not significant. *Source*: *prepared by the author*

From a regional perspective, in the eastern region, command-and-control and market-based regulations have significantly inhibitory effects on effectiveness-based innovation ($\beta = -0.128$, $p < 0.01$; $\beta = -0.285$, $p < 0.01$) without considering the synergy of environmental regulation (M4). However, the inhibitory effect of voluntary regulation on effectiveness-based innovation is not significant, indicating that environmental policies in the eastern region are unqualified, and the government has not coordinated a single environmental policy with other policies (Fig. 2). Furthermore, we explore the synergy of two types of environmental regulation and that of three types of environmental regulation (M5 and M6). The results show that only the interaction term of command-and-control and market-based regulations has the inclination to promote innovation while other policy portfolio has an insignificantly inhibitory effect. It means that for the eastern region, any type of environmental regulation imposes a significant burden on the innovation of invention patents in provincial industries (Fig. 2).

In the central region, not considering the synergy of environmental regulation (M7), the effects of command-and-control, market-based, and voluntary regulations on effectiveness-based innovation are not significant, whereas market-based and voluntary regulations have the potential to promote effectiveness-based innovation (Fig. 3). Moreover, we explore the synergy of two types of environmental regulation and that of three types of environmental regulation (M8 and M9). The results reveal that the interaction term of command-and-control and market-based regulations has a significant and positive impact on effectiveness-based innovation ($\beta = 0.228$, $p < 0.01$), which manifests that there is good synergy between these two types of environmental regulation. On the contrary, the interaction term of command-and-control and voluntary regulations has a significant and negative impact on effectiveness-based innovation ($\beta = -0.088$, $p < 0.1$), indicating that these two types of environmental regulation are not compatible. Despite of the insignificant impact of the interaction term of market-based and voluntary regulations on effectiveness-based innovation, the impact is positive (Fig. 3). The impact of the interaction term of three types of environmental regulation on effectiveness-based innovation is positive but not significant, which shows that the synergy of environmental regulation has not been fully developed (Fig. 3).

In the western region, without considering the synergy of environmental regulation (M10), command-and-control, market-based, and voluntary regulations have significant and negative effects on effectiveness-based innovation ($\beta = -0.102$, $p < 0.01$; $\beta = -0.276$, $p < 0.01$; $\beta = -0.079$, $p < 0.05$), demonstrating that there is a problem of quality loss in the environmental policy of the western region, that is, the environmental policy itself has quality problems that lead to a sharp decline in policy effectiveness (Fig. 4). Furthermore, we explore the synergy of two types of environmental regulation and that of three types of environmental regulation (M11 and M12). The results turn out that three regulation tools do not breed the synergy, which indicates that there are technical losses between environmental policies and the lack of balance in the design and configuration of environmental policies in the western region, thus incurring policy failures (Fig. 4).

The *t*-statistic and *z*-statistic are in parentheses and the *p* value is in square brackets. ***, **, and * indicate significance at the 1, 5, and 10% levels, respectively

The impact of environmental regulation on efficiency-based innovation

Table 7 reports the estimated results on the effects of different types of environmental regulation on efficiency-based innovation. From a national perspective, not considering the synergy of environmental regulation (M1), command-and-control, market-based, and voluntary regulations have significant and inhibitory effects efficiency-based innovation ($\beta = -0.087$, $p < 0.01$; $\beta = -0.452$, $p < 0.01$; $\beta = -0.078$, $p < 0.01$) because a quality loss problem exists in a single policy (Fig. 1). Another explanation is that China's industry is characterized by high consumption and high pollution so that abundant funds for technological transformation are required, thus affecting innovation investment and non-invention patent outputs.

Table 6 The results on the effect of environmental regulation on effectiveness-based innovation

Variables	Nation			Eastern			Central			Western		
	M1 SYS-GMM	M2 SYS-GMM	M3 SYS-GMM	M4 RE	M5 FE	M6 FE	M7 FE	M8 FE	M9 FE	M10 FE	M11 FE	M12 FE
lneffe_inno$_{t-1}$	0.286*** (7.04)	0.243*** (5.96)	0.233*** (5.04)									
lnr&d	0.419*** (5.47)	0.525*** (4.97)	0.490*** (4.78)	0.715*** (6.02)	0.753*** (4.92)	0.716*** (4.57)	0.230 (1.47)	0.111 (0.73)	0.111 (0.73)	− 0.035 (− 0.27)	− 0.051 (− 0.39)	− 0.055 (− 0.42)
lnrdp	0.253*** (8.82)	0.277*** (7.95)	0.298*** (8.59)	0.088* (1.72)	0.116** (2.22)	0.121** (2.32)	0.165* (1.97)	0.024 (0.27)	0.026 (0.29)	0.126* (1.65)	0.122 (1.59)	0.116 (1.51)
lnmc	0.305** (2.41)	0.108 (0.28)	0.425 (0.68)	− 0.159 (− 1.04)	− 0.075 (− 0.36)	− 0.081 (− 0.39)	0.928*** (4.67)	1.363*** (6.58)	1.354*** (6.48)	0.820*** (4.90)	0.815*** (4.47)	0.835*** (4.53)
lnfdi	− 0.412*** (− 7.85)	− 0.347*** (− 4.26)	− 0.281*** (− 3.08)	0.282** (2.52)	0.270 (1.20)	0.275 (1.23)	− 0.030 (− 0.20)	− 0.062 (− 0.42)	− 0.058 (− 0.39)	− 0.127 (− 1.16)	− 0.229* (− 1.86)	− 0.225* (− 1.82)
lnci	− 0.505*** (− 6.15)	− 0.584*** (− 6.83)	− 0.525*** (− 6.46)	− 0.609** (− 2.54)	− 0.667*** (− 2.96)	− 0.654*** (− 2.90)	− 0.634*** (− 3.17)	− 0.590*** (− 3.13)	− 0.590*** (− 3.12)	− 0.270 (− 1.10)	− 0.256 (− 1.04)	− 0.233 (− 0.94)
lngdp	1.527*** (15.30)	1.422*** (12.79)	1.391*** (12.73)	0.727*** (3.09)	1.220*** (3.19)	1.174*** (3.05)	1.767*** (7.67)	1.871*** (8.08)	1.868*** (8.04)	2.295*** (13.43)	2.373*** (12.10)	2.391*** (12.09)
lnpr	0.001 (0.34)	− 0.002 (− 0.48)	0.001 (0.12)	0.522*** (3.20)	0.132 (0.60)	0.155 (0.70)	− 0.020 (− 1.53)	− 0.015 (− 1.22)	− 0.015 (− 1.27)	− 0.014 (− 0.91)	− 0.015 (− 0.96)	− 0.015 (− 0.96)
lnlq	− 0.799 (− 1.29)	− 0.255 (− 0.33)	− 0.644 (− 0.76)	− 0.536** (− 2.22)	− 1.696*** (− 3.38)	− 1.796*** (− 3.53)	− 0.324 (− 0.66)	− 0.094 (− 0.19)	− 0.095 (− 0.20)	− 2.295*** (− 4.43)	− 2.394*** (− 4.59)	− 2.321*** (− 4.37)
lncer	− 0.131*** (− 6.66)	− 0.107*** (− 5.76)	− 0.099*** (− 5.02)	− 0.128*** (− 2.79)	− 0.129*** (− 2.79)	− 0.109** (− 2.20)	− 0.037 (− 0.78)	0.072 (1.36)	0.074 (1.39)	− 0.102*** (− 2.63)	− 0.088** (− 2.18)	− 0.089** (− 2.20)
lnmer	− 0.108* (− 1.87)	− 0.088* (− 1.84)	− 0.074 (− 1.26)	− 0.285*** (− 2.77)	− 0.114 (− 0.94)	− 0.087 (− 0.71)	0.178 (1.28)	0.277** (2.03)	0.274** (2.00)	− 0.276*** (− 2.99)	− 0.243** (− 2.43)	− 0.257** (− 2.52)
lnver	− 0.029** (− 2.30)	− 0.026* (− 1.66)	− 0.021 (− 1.10)	− 0.049 (− 1.23)	0.019 (0.43)	0.039 (0.80)	0.012 (0.25)	0.053 (1.06)	0.047 (0.91)	− 0.079** (− 2.40)	− 0.061 (− 1.64)	− 0.051 (− 1.27)
lncer×lnmer		0.047*** (3.03)	0.011 (0.59)		0.014 (0.44)	0.001 (0.04)		0.228*** (3.71)	0.232*** (3.73)		0.035 (1.10)	0.015 (0.36)
lncer×lnver		− 0.023 (− 1.59)	− 0.026* (− 1.72)		− 0.006 (− 0.21)	− 0.023 (− 0.72)		− 0.088* (− 1.70)	− 0.092* (− 1.74)		− 0.013 (− 0.48)	− 0.014 (− 0.49)
lnmer×lnver		− 0.003 (− 0.16)	− 0.008 (− 0.38)		− 0.008 (− 0.23)	− 0.006 (− 0.18)		− 0.053 (− 0.96)	− 0.047 (− 0.83)		− 0.068 (− 1.56)	− 0.083* (− 1.73)
lncer×lnmer×lnver			− 0.021*** (− 3.15)			− 0.023 (− 1.09)			0.035 (0.46)			− 0.015 (− 0.75)
_cons	− 4.225*** (− 5.98)	− 3.649*** (− 3.42)	− 4.223*** (− 3.77)	0.646 (0.60)	− 3.444* (− 1.66)	− 3.994* (− 1.87)	− 10.527*** (− 6.13)	− 12.076*** (− 7.16)	− 12.026*** (− 7.09)	− 8.383*** (− 6.55)	− 9.005*** (− 6.67)	− 9.025*** (− 6.76)
AR(1)	− 2.15 [0.03]	− 2.12 [0.03]	− 2.18 [0.03]									

Table 6 (continued)

Variables	Nation			Eastern			Central			Western		
	M1 SYS-GMM	M2 SYS-GMM	M3 SYS-GMM	M4 RE	M5 FE	M6 FE	M7 FE	M8 FE	M9 FE	M10 FE	M11 FE	M12 FE
AR(2)	0.68 [0.50]	0.47 0.64	0.57 [0.57]									
Sargan χ^2	24.69 [1.00]	24.33 [1.00]	25.05 [1.00]									
Wald χ^2	14905.00 [0.00]	10176.94 [0.00]	10299.51 [0.00]	2253.92 [0.00]								
R^2				0.93	0.91	0.91	0.96	0.97	0.97	0.92	0.93	0.93
F-statistic					114.79 [0.00]	107.34 [0.00]	227.11 [0.00]	210.85 [0.00]	195.35 [0.00]	167.69 [0.00]	133.24 [0.00]	124.03 [0.00]
Hausman statistic				3.30 [0.95]	47.32 [0.00]	47.90 [0.00]	55.51 [0.00]	62.97 [0.00]	62.22 [0.00]	78.35 [0.00]	74.80 [0.00]	74.50 [0.00]
Observations	450	450	450	176	176	176	128	128	128	176	176	176

Furthermore, the synergy effect of two types of environmental regulation is examined (M2). The interaction term of command-and-control and market-based regulations can significantly promote efficiency-based innovation ($\beta = 0.030$, $p < 0.01$), showing that these two types of environmental regulation can synergistically propel efficiency-based innovation. The reason is that command-and-control and market-based regulations are complementary, and industrial enterprises can flexibly choose regulatory methods at lower cost, thus effectively reducing the squeeze on the investment of efficiency-based innovation. However, the interaction term of command-and-control and voluntary regulations has a significantly inhibitory impact on efficiency-based innovation ($\beta = -0.049$, $p < 0.01$). Conversely, the interaction term of market-based and voluntary regulations has a significantly positive impact on efficiency-based innovation ($\beta = 0.029$, $p < 0.05$). The major reason is that environmental letters and calls can complement administrative supervision and management, making the levy of pollution discharge fees and environmental letters and calls coordinated. The more environmental letters and calls, the more the pollution discharge fees paid by the industrial enterprises. Under this forcing mechanism, enterprises are encouraged to strengthen efficiency-based innovation (Fig. 1).

Finally, we study the synergy effect of three types of environmental regulation (M3). The interaction term of command-and-control, market-based, and voluntary regulations has a significant and positive impact on efficiency-based innovation ($\beta = 0.013$, $p < 0.1$). The reason lies in that the difficulty and cost of efficiency-based innovation such as utility model patents and design patents are relatively low. When three types of environmental regulation jointly constrain corporate behaviors, even if there is a policy conflict, through efficiency-based innovation, industrial enterprises can not only mitigate regulatory pressure but also prevent themselves from slashing capital investment in the production and operation process (Fig. 1).

From a regional perspective, in the eastern region, not considering the synergy of environmental regulation (M4), both command-and-control and voluntary regulations have significantly inhibitory impacts on efficiency-based innovation ($\beta = -0.057$, $p < 0.1$; $\beta = -0.108$, $p < 0.01$) while the inhibitory effect of market-based regulation on efficiency-based innovation is not significant (Fig. 2). Furthermore, the synergy of two types of environmental regulation is examined (M5). The results show that the interaction term of command-and-control and market-based regulations plays a significant role in promoting efficiency-based innovation ($\beta = 0.039$, $p < 0.1$). In contrast, the interaction term of command-and-control and voluntary regulations has a significant and negative impact on efficiency-based innovation ($\beta = -0.058$, $p < 0.01$). Besides, the interaction term of market-based and voluntary regulations is not significant (Fig. 2). Finally, the synergy of three types of environmental regulation is examined (M6) and the results turn out that the interaction term of three types of

Table 7 The results on the effect of environmental regulation on efficiency-based innovation

Variables	Nation			Eastern			Central			Western		
	M1 SYS-GMM	M2 SYS-GMM	M3 SYS-GMM	M4 FE	M5 FE	M6 FE	M7 FE	M8 FE	M9 FE	M10 FE	M11 FE	M12 FE
$\ln effi\_inno_{t-1}$	0.107*** (2.83)	0.079* (1.86)	0.097** (2.22)									
lnr&d	0.457*** (4.91)	0.480*** (4.74)	0.485*** (4.84)	− 0.050 (− 0.43)	− 0.030 (− 0.26)	− 0.026 (− 0.22)	0.379** (2.46)	0.216 (1.51)	0.215 (1.51)	0.209 (1.44)	0.119 (0.83)	0.125 (0.87)
lnrdp	0.129*** (7.68)	0.152*** (6.51)	0.143*** (6.47)	0.130*** (3.58)	0.125*** (3.41)	0.124*** (3.37)	0.254*** (3.06)	0.035 (0.42)	0.030 (0.35)	− 0.053 (− 0.62)	− 0.020 (− 0.24)	− 0.011 (− 0.13)
lnmc	− 0.237 (− 0.46)	− 0.162 (− 0.32)	− 0.197 (− 0.41)	0.032 (0.23)	− 0.116 (− 0.80)	− 0.115 (− 0.79)	0.677*** (3.47)	1.199*** (6.15)	1.225*** (6.28)	− 0.071 (− 0.38)	− 0.291 (− 1.46)	− 0.322 (− 1.60)
lnfdi	− 0.072 (− 1.53)	− 0.157 (− 1.08)	− 0.161 (− 1.07)	0.432*** (2.63)	0.450*** (2.80)	0.449*** (2.79)	0.094 (0.62)	0.113 (0.82)	0.101 (0.74)	0.059 (0.48)	0.019 (0.14)	0.014 (0.10)
lnci	− 0.485*** (− 5.77)	− 0.501*** (− 4.38)	− 0.474*** (− 4.10)	− 0.457*** (− 2.79)	− 0.470*** (− 2.93)	− 0.471*** (− 2.93)	− 0.471** (− 2.40)	− 0.503*** (− 2.84)	− 0.504*** (− 2.86)	− 0.602** (− 2.19)	− 0.664** (− 2.48)	− 0.699** (− 2.60)
lngdp	1.474*** (10.89)	1.448*** (8.91)	1.448*** (8.19)	1.233*** (4.52)	1.250*** (4.66)	1.255*** (4.63)	1.298*** (5.73)	1.428*** (6.56)	1.435*** (6.62)	1.950*** (10.16)	1.790*** (8.37)	1.761*** (8.17)
lnpr	− 0.008* (− 1.90)	− 0.007 (− 1.51)	− 0.008* (− 1.86)	− 0.051 (− 0.33)	− 0.099 (− 0.64)	− 0.101 (− 0.65)	− 0.021* (− 1.67)	− 0.019 (− 1.64)	− 0.016 (− 1.43)	− 0.030* (− 1.73)	− 0.230* (− 1.74)	− 0.029* (− 1.74)
lnlq	0.541** (2.25)	0.637* (1.79)	0.668* (1.76)	− 0.658* (− 1.88)	− 0.483 (− 1.37)	− 0.473 (− 1.32)	0.614 (1.27)	0.882* (1.94)	0.886* (1.96)	− 3.139*** (− 5.40)	− 3.115*** (− 5.47)	− 3.229*** (− 5.58)
lncer	− 0.087*** (− 5.81)	− 0.072*** (− 4.18)	− 0.071*** (− 4.30)	− 0.057* (− 1.87)	− 0.025 (− 0.78)	− 0.027 (− 0.078)	− 0.184*** (− 3.92)	− 0.029 (− 0.59)	− 0.035 (− 0.70)	− 0.119*** (− 2.72)	− 0.076* (− 1.72)	− 0.074* (− 1.68)
lnmer	− 0.452*** (− 3.71)	− 0.342*** (− 3.79)	− 0.385*** (− 4.17)	− 0.132 (− 1.53)	− 0.119 (− 1.41)	− 0.122 (− 1.41)	0.074 (0.54)	0.186 (1.45)	0.193 (1.51)	− 0.510*** (− 4.94)	− 0.372*** (− 3.41)	− 0.350*** (− 3.15)
lnver	− 0.078*** (− 12.57)	− 0.073*** (− 5.18)	− 0.080*** (− 4.65)	− 0.108*** (− 3.31)	− 0.109*** (− 3.41)	− 0.111*** (− 3.32)	− 0.031 (− 0.69)	0.018 (0.39)	0.034 (0.70)	− 0.041 (− 1.13)	− 0.057 (− 1.41)	− 0.074* (− 1.69)
lncer×lnmer		0.030*** (2.96)	0.047*** (3.26)		0.039* (1.70)	0.040 (1.65)		0.325*** (5.61)	0.315*** (5.43)		0.117*** (3.38)	0.148*** (3.27)
lncer×lnver		− 0.049*** (− 5.68)	− 0.047*** (− 4.54)		− 0.058*** (− 2.96)	− 0.057** (− 2.49)		− 0.014 (− 0.30)	− 0.005 (− 0.11)		− 0.064** (− 2.11)	− 0.063** (− 2.08)
lnmer×lnver		0.029** (2.38)	0.031** (2.25)		0.011 (0.52)	0.012 (0.51)		− 0.025 (− 0.48)	− 0.041 (− 0.78)		− 0.017 (− 0.36)	0.006 (0.12)
lncer×lnmer×lnver			0.013* (1.65)			0.002 (0.16)			− 0.097 (− 1.38)			0.023 (1.06)
_cons	1.115 (0.94)	0.654 (0.70)	1.209 (1.28)	− 4.711*** (− 3.13)	− 4.789*** (− 3.22)	− 4.733*** (− 3.09)	− 4.890*** (− 2.90)	− 6.780*** (− 4.27)	− 6.921*** (− 4.37)	− 1.765 (− 1.23)	− 2.635* (− 1.81)	− 2.605* (− 1.79)
AR(1)	− 1.69 [0.09]	− 1.71 [0.08]	− 1.74 [0.08]									

Table 7 (continued)

Variables	Nation			Eastern			Central			Western		
	M1 SYS-GMM	M2 SYS-GMM	M3 SYS-GMM	M4 FE	M5 FE	M6 FE	M7 FE	M8 FE	M9 FE	M10 FE	M11 FE	M12 FE
AR(2)	1.02 [0.31]	0.95 [0.34]	0.95 [0.34]									
Sargan χ^2	24.13 [1.00]	23.57 [1.00]	24.08 [1.00]									
Wald χ^2	9912.05 [0.00]	13181.83 [0.00]	15762.49 [0.00]									
R^2				0.93	0.94	0.94	0.95	0.96	0.96	0.86	0.87	0.87
F-statistic				197.04 [0.00]	163.38 [0.00]	151.49 [0.00]	185.16 [0.00]	189.25 [0.00]	178.28 [0.00]	84.86 [0.00]	72.20 [0.00]	67.52 [0.00]
Hausman statistic				48.15 [0.00]	52.40 [0.00]	51.86 [0.00]	50.08 [0.00]	61.64 [0.00]	61.95 [0.00]	78.23 [0.00]	77.73 [0.00]	77.68 [0.00]
Observations	450	450	450	176	176	176	128	128	128	176	176	176

The *t*-statistic and *z*-statistic are in parentheses and the *p* value is in square brackets. ***, **, and * indicate significance at the 1, 5, and 10% levels, respectively

environmental regulation can not synergistically enhance efficiency-based innovation (Fig. 2).

In the central region, without considering the synergy of environmental regulation (M7), command-and-control regulation has a significant and inhibitory impact on efficiency-based innovation ($\beta = -0.184$, $p < 0.01$), but the effects of market-based and voluntary regulations on efficiency-based innovation are not significant (Fig. 3). Further analysis (M8) finds that the interaction term of command-and-control and market-based regulations has a significant and positive impact on efficiency-based innovation ($\beta = 0.325$, $p < 0.01$), whereas the interaction terms of command-and-control and voluntary regulations as well as market-based and voluntary regulations have insignificant impacts on efficiency-based innovation (Fig. 3). The synergy of three types of environmental regulation does not play a synergistic role in promoting efficiency-based innovation (M9) (Fig. 3).

In the western region, without considering the synergy of environmental regulation (M10), command-and-control and market-based regulations have significant and inhibitory effects on efficiency-based innovation ($\beta = -0.119$, $p < 0.01$; $\beta = -0.510$, $p < 0.01$) while the impact of voluntary regulation on efficiency-based innovation is not significant (Fig. 4). Further analysis of the interaction effect of two types of environmental regulation (M11) uncovers that the interaction term of command-and-control and market-based regulations has a significant and positive impact on efficiency-based innovation ($\beta = 0.117$, $p < 0.01$). On the contrary, the interaction term of command-and-control and voluntary regulations has a significant and negative impact on efficiency-based innovation ($\beta = -0.064$, $p < 0.05$). Moreover, the interaction term of market-based and voluntary regulations is not significant (Fig. 4). Lastly, the interaction term of three types of environmental regulation does not play a synergistic role in promoting efficiency-based innovation (M12) (Fig. 4).

Discussion

Theoretical implication

This paper draws the following theoretical implication:

(1) Whether to pursue efficiency or effect has always been an important trade-off for regional innovation. How to use the limited resources to balance the innovation efficiency and effect effectively determines the regional innovation performance to a great extent. Under the framework of institutional theory, this paper discusses the difference in the impact of effectiveness-based innovation and efficiency-based innovation on ETFEE, as well as the difference environmental regulations on the two innovation strategies and ETFEE, which effectively

responds to and resolves the dispute on innovation efficiency and effect existing in previous studies (Sheng et al. 2013; Sethi et al. 2001; Griffin 1997).

(2) This paper divides environmental policies into three types: command-and-control, market-based, and voluntary. It examines the impact of three different types of environmental regulations on innovation, and reveals the heterogeneity of environmental regulation policies. This is the first extension of the "Porter hypothesis" theory. At the same time, the relevant literature on institutional theory has also been expanded (Pérez-Nordtvedt et al. 2015). And in this paper, we found that command-and-control, market-based, and voluntary environmental regulation have significant inhibitory effect on the effectiveness-based innovation and efficiency-based innovation, and shows that single market-based and voluntary environmental policy is of low quality, which causes the policy failure. Therefore, policymakers should focus on improving the quality of environmental policies.

(3) This paper further tested the synergistic effect of environmental policies, and revealed whether there was synergistic promotion effect between environmental policies, which was not considered by previous studies (Ren et al. 2018; Xie et al. 2017), and it was also the second extension of the "Porter hypothesis" theory. We found that the interaction between command-and-control and market-based regulations can significantly promote innovation, while the interaction between market-based and voluntary regulations only promotes efficiency-based innovation. The interaction terms of command-and-control, market-based, and voluntary regulations can synergistically promote efficiency-based innovation, but have a significant negative impact on effectiveness-based innovation. Therefore, whether the Porter hypothesis can be established in China depends not only on the quality of individual policies, but also on the coordination between policies.

Policy implication

This paper provides policy implications below:

(1) Innovation has become an important driving force for energy efficiency and the coordinated development of energy and environment of China's provincial industries, given that effectiveness-based innovation and efficiency-based innovation have significant and positive impacts on industrial ETFEE. The government should underpin major R&D programs for energy conservation and emission reduction by means of proactive fiscal policies and preferential tax policies to encourage enterprises to continuously increase R&D investment. At the same time, the government should maintain the market competition environment and utilize the market mechanism to guide enterprises to improve energy efficiency via innovation.

(2) The policymakers should improve the quality of the single policy since the single policy has an inhibitory impact on both industrial innovations. When formulating the policies on energy conservation and emission reduction, the investigation and verification of stakeholder appeals ought to be emphasized so that policies and programs are capable of meeting the demands of energy conservation and environmental protection for provincial industrial enterprises. Moreover, environmental regulation tools should be optimized to prompt environmental regulation to be transformed from the cost effect to the compensation effect.

(3) The systematicness of environmental regulation policies is supposed to be optimized. With the establishment of Ministry of Ecology and Environment of China, we should speed up summarizing and analyzing previous environmental polices so as to weed out or amend conflicting regulation policies. In line with the realistic needs of China's provincial industrial enterprises for energy conservation and emission reduction, the intensity and focus of current policies ought to be adjusted as quickly as possible, thus reinforcing the synergy effect of command-and-control, market-based, and voluntary regulations.

(4) Regional heterogeneity should be fully considered when formulating the policies on energy conservation and emission reduction. The eastern, central, and western regions may as well flexibly choose the policy portfolio that combines command-and-control, market-based, and voluntary regulations according to their own economic development level, energy, and environmental carrying capacity and industrial structure characteristics.

Limitations and suggestions for future studies

This paper has limitations worthy of further investigation. First, given the availability of data, we merely use a single indicator to measure each environmental regulation, and we have not taken into account environmental taxes, environmental subsidies, and other policies. With the promotion of China's environmental tax, carbon tax, and other policies, scholars can consider using multiple indicators to measure each environmental regulation tool in the future. Second, the impacts of environmental regulation on industrial innovation may be influenced by external factors such as enforcement of environmental law and regional marketization degree. Future research can consider the institutional boundaries of the impacts of different environmental regulation on industrial innovation and further explore the institutional environment for the effective implementation of environmental regulation.

Conclusions

This paper draws the following conclusions:

(1) Both effectiveness-based innovation and efficiency-based innovation can significantly promote ETFEE of provincial industries. Furthermore, the elasticity of efficiency-based innovation on ETFEE is greater than that of effectiveness-based innovation, indicating that innovation based on process transformation and design is the main driving factor for ETFEE. Additionally, the impact of different innovation on ETFEE has obvious regional heterogeneity. Specifically, effectiveness-based innovation and efficiency-based innovation in the eastern region can significantly propel ETFEE. The improvement of ETFEE in the central region can be realized only by effectiveness-based innovation. In the western region, neither effectiveness-based nor efficiency-based innovation has a significant impact on ETFEE.

(2) Without considering the synergy of environmental regulation, command-and-control, market-based, and voluntary regulations have significant and inhibitory impacts on effectiveness-based innovation and efficiency-based innovation of provincial industries.

(3) The interaction term of command-and-control and market-based regulations has a significant and positive impact on effectiveness-based innovation and efficiency-based innovation, indicating that with the improvement of market-based regulation, command-and-control regulation can be transformed from an inhibitor to an impetus. However, the interaction term of command-and-control and voluntary regulations has a significant and inhibitory impact on efficiency-based innovation while the interaction term of market-based and voluntary regulations can promote efficiency-based innovation.

(4) The interaction term of three environmental regulation tools has a significant and negative impact on effectiveness-based innovation, which demonstrates that these regulation tools generate a jointly inhibitory impact on effectiveness-based innovation. Conversely, three environmental regulation tools can synergistically promote efficiency-based innovation. It manifests that the industrial enterprises in Chinese provinces have acted in response to the government's environmental policies with efficiency-based innovation.

Author contributions Baolong Yuan finished all the writing of the paper.

Funding information This research work is supported by the National Natural Science Foundation of China (71703171), the Social Science Foundation of Hunan Province (18YBQ133; 18YBQ042; 18YBQ138), and the Natural Science Foundation of Hunan Province (2018JJ3889).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

In this study, suppose that there were n DMUs with m input indicators, s_1 desirable output indicators, and s_2 undesirable output indicators, the inputs, desirable outputs, and undesirable outputs were respectively expressed as $x \in R^m$, $y^g \in R^{S_1}$, and $y^b \in R^{S_2}$. The input vector was $X = (x_{ij}) \in R^{m \times n}$. The desirable output vector was $Y^g = \left(y_{rj}\right) \in R^{s_1 \times n}$. The undesirable output vector was $Y^b = \left(y_{rj}\right) \in R^{s_2 \times n}$. The SBM model with undesirable outputs was expressed as follows.

$$\min\rho^* = \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\left(s_i^-/x_{i0}\right)}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\left(s_r^g/y_{r0}^g\right) + \sum_{r=1}^{s_2}\left(s_r^b/y_{r0}^b\right)\right)} \quad s.t.\begin{cases} x_0 = X\lambda + s^- \\ y_0^g = Y^g\lambda - s^g \\ y_0^b = Y^b\lambda + s^b \\ \lambda, s^-, s^g, s^b \geq 0 \end{cases} \tag{3}$$

where s^-, s^g, and s^b refer to slack variables of input, desirable output, and undesirable output, respectively. $\lambda$is weight vector. When $\rho^* = 1$, namely, $s^- = 0, s^g = 0, s^b = 0$, the DMU is effective.

The super efficiency SBM model was expressed as follows.

$$\min\delta^* = \frac{\frac{1}{m}\sum_{i=1}^{m}\left(\bar{x}/x_{i0}\right)}{\frac{1}{s}\sum_{r=1}^{s}\left(\bar{y}_r/y_{r0}^g\right)} \quad s.t.\begin{cases} \bar{x} \geq X\lambda \\ \bar{y} \leq Y\lambda \\ \bar{x} \geq x_0, \bar{y} \leq y_0 \\ \lambda \geq 0, \bar{y} \geq 0 \end{cases} \tag{4}$$

According to the models (3) and (4), the super efficiency SBM model with undesirable outputs was expressed as follows (Yang et al. 2018).

$$\min\alpha^* = \frac{\frac{1}{m}\sum_{i=1}^{m}\left(\bar{x}/x_{io}\right)}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\left(s_r^g/y_{r0}^g\right) + \sum_{r=1}^{s_2}\left(s_r^b/y_{r0}^b\right)\right)} \quad s.t.\begin{cases} \bar{x}_0 \geq X\lambda \\ \overline{y^g} \leq Y^g\lambda \\ \overline{y^b} \geq Y^b\lambda \\ \bar{x} \geq x_o, \overline{y^g} \leq y_0^g, \overline{y^b} \leq y_0^b, \lambda > 0 \end{cases} \tag{5}$$

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