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RESEARCH ARTICLE

Innovation and environmental total factor productivity in China: the moderating roles of economic policy uncertainty and marketization process

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Abstract

China's economic development practices are facing strict energy constraints and severe environmental pollution. Improvement of China's environmental total factor productivity (ETFP) through innovation is a major scientific focus of both policy-makers and academia. However, the boundary conditions where innovation affects ETFP are yet to be clarified. On this basis, the present study starts from two dimensions—policy context and market context, introduces economic policy uncertainty (EPU) and marketization process as moderating variables, and examines the impact mechanism of innovation on ETFP. The results show the following: (1) Innovation promotes ETFP. (2) Although EPU inhibits ETFP, it positively moderates the impact of innovation on ETFP. (3) The marketization process has an insignificant inhibitory effect on ETFP. Specifically, the development of product markets, the development of market intermediary organizations, and the legal system environment have a significant inhibitory effect on ETFP. In contrast, the marketization process positively moderates the impact of innovation on ETFP. (4) The impact of innovation on ETFP exhibits obvious regional heterogeneity. In regions with low pollution intensity, innovation and EPU promotes ETFP. The marketization process inhibits ETFP and shows a positive moderating effect. In regions with high pollution intensity, both innovation and EPU inhibits ETFP. Based on these conclusions, policy-makers should guide companies to increase investment in research and development, improve innovation capabilities, and focus on strengthening energy-saving and environmental protection technologies and process innovations. When formulating and adjusting economic policies, policy-makers should aim promote enterprise innovation and reduce the negative impact of economic policy uncertainty. Policies should fully utilize the decisive role of the market in the allocation of innovative factors and rely on market mechanisms to enhance the positive effect of innovation on regional ETFP.

Keywords Environmental total factor productivity · Innovation · Economic policy uncertainty · Marketization process · Pollution intensity

Highlights
Innovation can significantly promote regional ETFP.
EPU has a significantly inhibiting impact on regional ETFP.
EPU positively moderates the effect of innovation on ETFP.
Marketization process positively moderates the effect of innovation on ETFP.

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Introduction

With the increasingly downward pressure on the global economy and the aggravating environmental pollution, the transformation of development model has become one of the important alternatives for many countries to pursue the coordinated development of economy and environment. China's economic development practices are facing tightening energy constraints and severe environmental pollution. In 2019, China's external dependence on crude oil and petroleum both exceeded 70%, reaching the highest ratio in over 50 years. In 2016, the *2016 Environmental Performance Index* (EPI) published by Yale University showed that China's environmental performance scored merely 65.1, ranking 109 among 180 countries. In 2010, *Chinese Environmental and Economic Accounting Report* of Ministry of Environmental Protection (renamed as Ministry of Ecology and Environment in 2018) revealed that environmental degradation cost reached 1.1 trillion yuan, accounting for 2.51% of GDP. Therefore, improvement of the green level of China's economic development is a major scientific issue.

Environmental total factor productivity (ETFP) can reflect the relationship between regional resources, environment, and economic development. It represents the green development level or sustainable development level of an enterprise, industry, or region. ETFP refers to the potential to achieve more economic output with less resource input and reduced pollutant emission. Existing literatures mainly focus on the evaluation of ETFP. From a regional perspective, the ETFP of provinces and cities shows an increasing trend, and technological progress is the main driving force for the growth of ETFP (Liu et al. 2018; Liu and Xin 2019; Wen et al. 2018). In terms of industry, Du et al. (2018) and Liu and Feng (2019) respectively found that ETFP was also increasing. Some studies have explored the influencing factors of ETFP, mainly in the field of environmental regulation, and few have discussed the impact of innovation on ETFP (Shen et al. 2019b).

On the one hand, most studies are dependent on a stable policy environment. However, China's economic policy uncertainty index has increased from 179 in 2008 to 795 in 2019, which means the external environment of enterprises are faced with larger variations and risk, which is also likely to affect the innovation decisions of enterprises. Therefore, the impact of policies on enterprise innovation decisions in China and its effect on ETFP are key issues that need to be examined. On the other hand, market-oriented transformation is a distinctive feature of China ever since its economic reform. In addition, market-based environmental regulation tools, such as emission rights, environmental taxes (fees), environmental protection subsidies, and energy use rights, can effectively guide enterprises to achieve green development through innovation (Jaffe and Palmer 1997). Hence, another key issue to be examined is the effect of China's market-oriented reforms on ETFP.

The present paper contributes to knowledge as follows. First, the paper is the first empirical study to examine the impact of innovation on ETFP of China's regions. The existing research mainly discusses the evaluation of ETFP; however, the influence of innovation is rarely discussed. The present study also can be a beneficial expansion of the literature related to ETFP and that provide theoretical support and empirical evidence for China's effective implementation of innovation-driven strategy. Second, economic policy uncertainty is introduced as a moderating variable to discuss the policy scenarios of innovation's impact on regional ETFP and reveal the policy conditions for effective innovation investment. Therefore, the present study suggests that economic policies should be adjusted on the premise of promoting R&D investment to achieve ETFP. Third, for the market, marketization process is introduced as a moderating variable to discuss the structural scenarios of innovation's impact on regional ETFP and unveil the market conditions for innovation investment to take effect. Five dimensions of marketization process—the government–market relations, the development of non–state-owned economy, the development level of product market, the development degree of factor market, and the development of market intermediaries and the legal system environment—are examined to find out their impacts on regional ETFP, which is conducive to provide specific strategies for pushing forward market reforms under the goal of ETFP. Fourth, the different impact of innovation on ETFP is investigated by area. China is divided into the eastern, central, and western areas in the existing research according to the geographical location and economic development level. It will result in selective bias in the estimation process. To eliminate this problem, the present paper divides China into the low and high pollution intensity areas based on pollution intensity. Hence, the present study can provide targeted strategies for different areas to facilitate ETFP.The present paper is organized as follows. Section 1 positions the introduction. Section 2 follows as a literature review and research hypothesis. Section 3 describes the research design. Empirical results are included in Section 4. Section 5 displays the conclusions and policy implications.

Literature review and research hypothesis

Innovation and ETFP

In theory, the impact of innovation on ETFP includes the following four aspects:

First, innovation reduces energy and resource consumption per unit of output; therefore it is an important driver for ETFP (Chen and Golley 2014; Ghisetti and Rennings 2014; Yuan and Xiang 2018; Yuan 2019). The transition from general technological innovation to green innovation increases the utilization efficiency of energy and resources (Miao et al. 2018). Moreover, innovation contributes to the development and utilization of biofuels and renewable energy and provides a better substitution for fossil energy, which has a significant positive effect on pollution reduction (Liu et al. 2020; Wang et al. 2020a).

Second, innovation can reduce pollutants and CO_2 emissions as well as improve environmental performance (Long et al. 2018; Mensah et al. 2018; Dauda et al. 2019; Liang et al. 2019; Shen et al. 2019a; Zhou et al. 2019; Hao et al. 2020). From the corporate perspective, Carrión-Flores and Innes (2010) find that environmental innovation can reduce toxic gas emissions in US manufacturers. Long et al. (2017) show that environmental innovation promotes corporate environmental performance more than economic performance by examining Korean-funded companies in China. Singh et al. (2020) find that green innovation has a positive effect on environmental performance in UAE manufacturers. From the industry perspective, innovation inhibits industrial carbon emissions (Erdoğan et al. 2020) and promotes industrial green development (Li et al. 2019). From the regional perspective, Jiang et al. (2020) reveal that innovation has an inhibitory effect on SO_2 emissions in Chinese cities. Solarin and Bello (2020) show that energy technology innovation significantly reduces carbon emissions and promotes environmentally sustainable development. Zhu et al. (2020) find that innovation in renewable energy technology helps to reduce the concentration of nitrogen oxides (NO_x) and respirable suspended particles (PM_{10}). Chen and Lee (2020) reveal that technological innovation in high-income, high-tech, and high-carbon emission countries has an inhibiting effect on the CO_2 emissions of neighboring countries.

Third, innovation can promote industrial upgrading, shift production from low-value-added industries to high-value-added industries, and stimulate economic growth (Du and Li 2019). Innovation is a key factor affecting economic growth and an important means to deal with fierce market competition. Through innovation, companies can continue to develop technologies and products that meet the needs of consumers in diverse markets, realize the commercial transformation of innovation, and achieve sustainable economic development. Industrial upgrading is the process of gradually developing ever more complex manufacturing capabilities. Throughout modern industrialization, innovation is the basis and necessary condition for industrial upgrading (Verbano and Crema 2016). The induction of industrial upgrading is based on technological changes, and technological innovation is the starting point and foundation of industrial evolution. Innovation fills the technological gap in the upgrading of low-end industries, expands the cooperate space for development of high-end industries, promotes the upgrading of Chinese industries to high-level, high-tech value chains, and promotes the stable development of China's economy (Zhang and Gallagher 2016; Wang and Liu 2020). Moreover, the upgrading of industrial structures can promote energy efficiency and reduce pollutant emissions (Yu 2020; Dong et al. 2020).

Fourth, from the productivity growth perspective, innovation has a promoting effect on enterprise labor productivity and green productivity (Fu et al. 2018). Every technological change can be described as a shift in the isoquant curve of the economic development of a country or region. A neutral technological change means a parallel shift of the curve, while a biased technological change corresponds to a change in the slope of the curve. For technological innovations oriented toward energy conservation and emission reduction, this change in the innovation paradigm enables the country or region to achieve economic efficiency with lower technological options (Feder 2018). Peng (2020) and Martínez-Zarzoso et al. (2019) find that green innovation induced by environmental regulations can promote green productivity growth. Aldieri et al. (2019) show that environmental innovation can promote regional productivity by examining 85 regions in Russia. Du and Li (2019) find that green technological innovation can promote carbon productivity in developed countries by studying 71 economies. García-Pozo et al. (2018) reveal that innovation can promote economic growth and labor productivity in the Spanish service industry. Zhang et al. (2018), Yan et al. (2020), and Wang et al. (2020b) find that innovation has a significant role in promoting the green development of China's regions and industries. We hereby propose the following hypothesis:

H1: Innovation has a positive effect on regional ETFP.

EPU, innovation, and ETFP

EPU and ETFP

Economic policy uncertainty (EPU) refers to the fact that economic entities cannot accurately predict whether, when, and how the government changes current economic policies, which is an important part of economic uncertainty (Gulen and Ion 2016). Baker et al. (2016) built China EPU index based on coverage frequency of the *South China Morning Post*, the leading English-language newspaper in Hong Kong, to directly denote the uncertainty of overall economic policy. This method—the newspaper-based approach to measuring economic uncertainty—is also applied to construct EPU indices for other countries, including the USA, and it has been widely cited (Wang and Sun 2017; Raza et al. 2018).

The existing literature focuses on EPU's impacts on macroeconomic indicators and micro firm activities. At the macro level, EPU could hinder regional investment, economic development, industrial production, and also lead to increased inflation and unemployment (Pastor and Veronesi 2012; Baker et al. 2016). Moreover, domestic EPU would not only inhibit its own economic development but also limit economic growth in other countries (Fontaine et al. 2018). In addition, EPU would result in the rising prices of resources and energy, thus checking investment and growth (Wang and Sun 2017; Raza et al. 2018). Jin et al. (2019) also found that EPU has an inhibition effect on green development performance in less developed cities.

At the firm level, EPU would trigger stock market turmoil and further change the game rules and decision-making process of consumers and investors, making them tend to avoid risks by reserving more cash (Baker et al. 2014; Li et al. 2015). The increase of EPU would be accompanied by the uncertainty of market expectations, leading to the decline in corporate stock yield (Dakhlaoui and Aloui 2016), the increase in corporate financing cost (Hu and Gong 2019), and restraints on corporate investment and M&A (Merger and Acquisition) activities (Gulen and Ion 2016; Kang et al. 2014; Bonaime et al. 2018; Markel et al. 2018; Liu et al. 2018). In light of these arguments, we propose the following hypothesis:

- H2: EPU has a negative effect on regional ETFP.

The moderating effect of EPU

A small literature pays attention to the innovation impacts of EPU. Bloom (2007) argued that since R&D that is developmental and exploratory belongs to projects with high risk and long term, the adjustment cost of R&D investment is different from capital investment, leading to the impacts of EPU on them that may be different. Innovation is the source of economic growth. For enterprises, innovation is a means by which they can obtain market share and superprofit. When enterprises face market competition and risks, they tend to enhance market power by accelerating innovation under certain circumstances (Aghion et al. 2005). EPU may increase market risks, which is likely to facilitate enterprises to further step up innovation investment in order to maintain or regain market power. Besides, entrepreneurs are investors and decision-makers of their own innovation activities. Uncertainty is a key source of corporate profits. Corporate profits will disappear if the changes in the future can be predicted. As a result, EPU may prompt entrepreneurs to increase innovation investment.

The above arguments have been underpinned by several empirical studies. Atanassov et al. (2015) found that EPU can stimulate firm-level R&D, and the positive effect is stronger in hotly contested elections, in politically sensitive and hard-to-innovate industries, and in firms with higher growth options. Chen and Kettunen (2017) argued that carbon policy uncertainty can induce more investments in energy technologies in power-generating firms for this uncertainty can provide higher expected consumer surplus and lower expected electricity price. Jin et al. (2019) found that EPU helps to promote high-level innovation. Roper and Tapinos (2016) believed that firms can still take the risk of technological innovation in the uncertain environment in that innovation can bring the first-mover advantage to the firms and make them become a market leader. Therefore, we propose the following hypothesis:

- H3: EPU positively moderates the relationship between innovation and regional ETFP.

Marketization process, innovation, and ETFP

Marketization process and ETFP

ETFP is driven by two aspects: production technology progress induced by firm's R&D investment or technology introduction, and increased efficiency induced by the improvement of resources allocation (i.e., factors of production flow from enterprises, departments, or regions with low productivity to enterprises, departments, or regions with high productivity). Consequently, if institutional factors cannot enable resources to be allocated from low-productivity area to high-productivity area, there will be a loss of resource allocation, thus reducing the productivity of the whole society. In the area with high marketization degree, the government less intervenes in enterprises, and the legal system, factor market, and product market are generally more developed. It not only directly provides a competitive and orderly environment for market players but also boosts the productivity of the whole society through the improvement of industry competitive environment, which is beneficial for the transformation of economic growth (Zhao and Yu 2014). Feng and Wang (2019) argued that the marketization process is positively related to the green development of China's metal industry. Following the reasoning, we propose the hypothesis:

- H4: Marketization process has a positive effect on regional ETFP.

Considering that China's marketization process covers five dimensions (Fan et al. 2011; Wang et al. 2017), the present paper analyzes the influence mechanism of marketization process on regional ETFP from five dimensions, i.e., the government–market relations, the development of non–state-owned economy, the development level of product market, the development degree of factor market, and the development of market intermediaries and the legal system environment.

The government–market relations include three sub-items: "the proportion of economic resources allocated by the market," "the reduction in government intervention in enterprises," and "the reduction of government size," which reflects the decrease in government intervention in economy (Wang et al. 2017). For a long time, the Chinese government has laid more emphasis on the political goals of promoting economic development and increasing fiscal revenue. Due to promotion opportunities, local officials are more inclined to intervene in the investment behaviors of local enterprises. They will trade on fiscal and credit policies to help enterprises expand investment, leading to the increase in resources and energy consumption, labor input, and pollution emissions (You et al. 2019). Therefore, we propose the following hypothesis:

- H4a: The government–market relations have a positive effect on regional ETFP.

Existing studies mainly focus on the production efficiency of state-owned enterprises. Compared with private enterprises, state-owned enterprises are generally considered to be inefficient in resource allocation. Although the close relationship between state-owned enterprises and the government enables them to better obtain various organizational resources, state-owned enterprises lack the ability to effectively use these resources, leading to weak innovation ability (Chen et al. 2019; He et al. 2015). In contrast to the soft budget constraints of state-owned enterprises, private organizations have hard budget constraints, which require them to pay more attention to the efficiency of resource input to output. A critical financial focus in private enterprises is obtaining the largest economic and environmental benefits with the smallest resource investment. As central and local governments attach more importance to environmental protection, it increases the intensity and scope of environmental supervision. State-owned and private enterprises bear the same legal responsibilities and face comparable institutional pressure. This also urges private enterprises to boost technological process transformation and reduce pollutant emissions. From the perspective of economic development benefits, the National Development and Reform Commission Statistics show that the private economy accounted for more than 60% of GDP by the end of 2017. From January to July of 2019, tax revenue from private enterprises accounted for nearly 60% of the total, which illustrates the tremendous contributions that private enterprises make in promoting China's economy. Therefore, we propose the following hypothesis:

- H4b: The development of non–state-owned economy has a positive effect on regional ETFP.

The development degree of product market comprises "the extent to which prices are determined by the market" and "the decrease of local protection in the commodity market" (Wang et al. 2017). The high degree of product market development enables products exposed to more consumers. The consumers with more choices will force enterprises to continue to improve product quality. In the resource and environment market, the implementation of carbon emissions trading is based on the efficient market hypothesis, that is, the investors cannot obtain excess profits as the price can convey all the information (Montagnoli and de Vries 2010). When the prices of resource and energy, emission rights, and carbon emission rights are completely determined by the market, the price has the ability to accurately reflect the external cost and the scarcity of resources. Then the excessive consumption of resources and energy can be effectively contained, and the resource allocation efficiency will also be improved (Cui and Wei 2017). Therefore, we propose the following hypothesis:

- H4c: Product market development has a positive effect on regional ETFP.

The higher the development degree of factor market, the stronger the competition among the factor providers, and the higher the quality of factors, which helps to improve regional production efficiency. On the other hand, factor market development increases the mobility of factors, making the high-quality factors, such as the talent, finance, and foreign investment, flow to areas with payment price advantages. To a certain extent, it can also spur the area to ameliorate management methods and improve the utilization efficiency of factors. Conversely, lower factor prices can lead up to excessive consumption of resources and energy and produce a large amount of pollutants, thereby inhibiting the growth of environmental total factor productivity (Lin and Chen 2018; Yin et al. 2018). Therefore, we propose the following hypothesis:

- H4d: Factor market development has a positive effect on regional ETFP.

The development of market intermediaries and the improvement of the legal system help to clearly define the interests, permissions, and responsibilities of the participants in the market economy and form a fair and just competitive environment. The government's effective protection on producers' legitimate rights and intellectual property rights (IPR) can encourage enterprises to optimize management and improve total factor productivity by exploiting technological progress. On the other hand, the more sound the government's legal system in the field of energy conservation and environmental protection, the stronger the environmental enforcement intensity, the more likely it is to regulate enterprises to reduce energy consumption and pollutant discharge (Shimshack and Ward 2008; Droste et al. 2016). Therefore, we propose the following hypothesis:

- H4e: The development of market intermediaries and the improvement of the legal system have a positive effect on regional ETFP.

The moderating effect of marketization process

When marketization process is high in the area, changes will emerge in the relationship between innovation and ETFP. First, the local government is not apt to intervene in economic development. In so doing, the market decides the allocation of resources. The local enterprises are more proactive in carrying out innovation. Moreover, as the government increasingly adopts market-based environmental regulation to address environmental negative externalities, companies have greater flexibility in innovation investment in energy conservation and emission reduction (Jaffe and Palmer 1997), thus enhancing the impact of innovation on regional ETFP.

Second, the increase of non–state-owned economy can stimulate market vitality and competition, which will force state-owned enterprises to strengthen their competitiveness by increasing innovation investment (Hu et al. 2013). Therefore, the development of non–state-owned economy also positively moderates the impact of innovation on ETFP. Compared with private enterprises, state-owned enterprises are generally considered to be inefficient in resource allocation. Although the close relationship between state-owned enterprises and the government enables them to better obtain various organizational resources, state-owned enterprises lack the ability to effectively use these resources, leading to weak innovation ability (He et al. 2015; Chen et al. 2019).

Third, when the product market is highly developed, the commodities are priced by the market. It can motivate enterprises to improve product quality by investing in innovation so as to achieve high-quality development. Likewise, if emission rights are products in the carbon trading market and their prices are determined by the market, the efficiency of the carbon trading market can be greatly improved, which can more effectively guide enterprises to realize energy conservation and emission reduction through innovation. Therefore, product market development positively moderates the impact of innovation on ETFP.

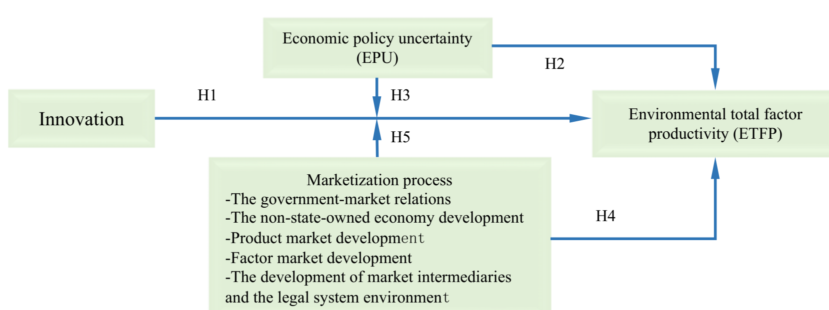
Fourth, enterprises have access to high-quality production factors, such as high-level talents, scientific and technological resources, and financial resources, when the factor market is highly developed, which can greatly enhance the effect of innovation. Moreover, to maintain the price advantage of factor payment and form a virtuous circle, companies need to continuously innovate to enhance market competitiveness.

Finally, when the development of market intermediaries and the legal system are sound, the rights of both producers and consumers can be safeguarded. Especially in the field of energy conservation and environmental protection, a sound legal system can bring to justice the polluting enterprises, and the cost of environmental negative externalities can be fully internalized, which can improve the firm's expectations to achieve green high-quality development through innovation. Hence, enterprises are more willing to propel ETFP via innovation. Therefore, we propose the following hypotheses:

- H5: Marketization process positively moderates the impact of innovation on ETFP.
- H5a: The government–market relations positively moderate the impact of innovation on ETFP.
- H5b: The development of non–state-owned economy positively moderates the impact of innovation on ETFP.
- H5c: The product market development positively moderates the impact of innovation on ETFP.
- H5d: The factor market development positively moderates the impact of innovation on ETFP.
- H5e: The development of market intermediaries and the legal system environment positively moderates the impact of innovation on ETFP.

The theoretical model of the present paper is shown in Fig. 1.

Fig. 1 Theoretical model



Research design

Model specification

Based on the abovementioned, the following econometric regression model is built. It is lagged when innovation is translated into economic and environmental benefits (Zhang et al. 2018). The impacts of EPU and marketization process on market players are also lagged (Hu and Gong 2019). Therefore, innovation, EPU, and marketization process have a lag of 2 years.

$$\ln ETFP_{it} = \alpha_0 + \alpha_1 \ln R\&D_{it-2} + \alpha_2 \ln EPU_{it-2} + \alpha_3 \ln R\&D_{it-2} \times EPU_{it-2} + \alpha_4 CONTROL_{it} + \varepsilon_{it} \quad (1)$$

$$\ln ETFP_{it} = \beta_0 + \beta_1 \ln R\&D_{it-2} + \beta_2 \ln MI_{it-2} + \beta_3 \ln R\&D_{it-2} \times MI_{it-2} + \beta_4 CONTROL_{it} + \varepsilon_{it} \quad (2)$$

$$\begin{aligned} \ln ETFP_{it} = {} & \theta_0 + \theta_1 \ln R\&D_{it-2} + \theta_2 \ln gov\_mar_{it-2} + \theta_3 \ln non\_state_{it-2} + \theta_4 \ln product\_mar_{it-2} \\ & + \theta_5 \ln factor\_mar_{it-2} + \theta_6 \ln law_{it-2} \theta_7 \ln R\&D_{it-2} \times gov\_mar_{it-2} + \theta_8 \ln RD_{it-2} \times non\_state_{it-2} \\ & + \theta_9 \ln R\&D_{it-2} \times product\_mar_{it-2} + \theta_{10} \ln RD_{it-2} \times factor\_mar_{it-2} + \theta_{11} \ln R\&D_{it-2} \times law_{it-2} \\ & + \theta_{12} CONTROL_{it} + \varepsilon_{it} \end{aligned} \quad (3)$$

where *ETFP* indicates environmental total factor productivity level, *R&D* denotes innovation level, *EPU* represents economic policy uncertainty, *MI* denotes marketization process, *gov_mar* is the government–market relations, *non_state* denotes the development of non–state-owned economy, *product_mar* denotes the development level of product market, *factor_mar* represents the development degree of factor market, *law* indicates the development of market intermediaries and the legal system environment, i is the region, t is the year, and ε is the random error term.

Variable definition and measurement

1. Environmental total factor productivity (ETFP). The point is that regional ETFP must lay emphasis on improving the utilization efficiency of resources and energy as well as reducing environmental costs (Chen and Golley 2014; Feng and Wang 2019; Jin et al. 2019). The present paper adopts SBM-DDF (slack-based measured directional distance function) to predict regional ETFP (Li 2014; Tone 2001).

First, each province is regarded as a DMU (decision-making unit). There is a need to construct a PPS (production possibility set) that covers both desirable or good output and undesirable or bad output, i.e., the environmental production technology.

A DMU uses N kinds of inputs $x = (x_1, \ldots, x_N) \in R_+^N$ to produce M kinds of desirable outputs $y = (y_1, \ldots, y_M) \in R_+^M$ and I kinds of undesirable outputs $b = (b_1, \ldots, b_I) \in R_+^I$, and the environmental production technology is expressed as

$$T = [(x, y, b) : x \text{ can produce } (y, b)] \quad (4)$$

$$\text{The set is expressed as : } \quad P(x) = [(y, b) : (x, y, b) \in T] \quad (5)$$

$$\text{i.e., } T = \left[(x, y, b) : (y, b) \in P(x), x \in R_+^N\right] \quad (6)$$

According to Färe et al. (2007), $P(x)$ is a bounded closed set with the following properties: (1) jointly weak disposability of desirable output and undesirable output, (2) strong or free disposability of input and desirable output, and (3) null-jointness of desirable output and undesirable output.

DEA can represent the environmental production technology. Assuming that in the period $t = 1, \ldots, T$, there are $k = 1, \ldots, K$ production units and the input–output vector is $\left(x_k^t, y_k^t, b_k^t\right)$.

$$P^t(x^t) = \begin{bmatrix} (y^t, b^t) : \sum_{k=1}^{K} z_k^t y_{k,m}^t \geq y_m^t, m = 1, \ldots, M; \\ \sum_{k=1}^{K} z_k^t b_{k,i}^t = b_i^t, \ i = 1, \ldots, I; \\ \sum_{k=1}^{K} z_k^t x_{k,n}^t \leq x_n^t, \ n = 1, \ldots, N; z_k^t \geq 0, k = 1, \ldots, K \end{bmatrix} \quad (7)$$

Equation (7) is the environmental production technology under constant returns to scale, expressed as $z_k^t \geq 0. z_k^t$ is the

Table 1 The definitions of all variables in the econometric regression models

Variable	Measure	Unit
Environmental total factor productivity (ETFP)	Calculated by SBM-DDF	–
Innovation (R&D)	Ratio of R&D investment to GDP	%
Economic policy uncertainty (EPU)	EPU index	–
Marketization process (MI)	The data on marketization index and the five sub-dimensions comes from the report of Wang et al. (2017)	–
The government–market relations (gov_mar)		
The development of non–state-owned economy (non_state)		
The development of product market (product_mar)		
The development of factor market (factor_mar)		
The development of market intermediaries and the legal system environment (law_mar)		
Energy intensity (EI)	Ratio of total energy consumption to GDP	–
Foreign trade (EXP)	Volume of total exports and imports	10,000 dollars
Foreign direct investment (FDI)	Amount of foreign investment	100 million dollars
Financial development efficiency (FD)	Ratio of savings to loans	–

density variable that denotes the weight when $DMU_k = 1, \ldots, K$ constructs the environmental technology structure.

The two inequality constraints of x and y represent their strong disposability, and the equality constraint of b represents its weak disposability, which together denote the jointly weak disposability of desirable output and undesirable output.

To express the null-jointness of expected output and unexpected output, assume that

$$\sum_{k=1}^{K} b_{k,i}^{t} > 0,\ i = 1, \ldots, I \tag{8}$$

$$\sum_{i=1}^{I} b_{k,i}^{t} > 0,\ k = 1, \ldots, K \tag{9}$$

Equation (8) indicates that at least one production unit is producing every kind of undesirable output. Equation (9) indicates that at least one kind of undesirable output is produced per production unit.

Following Tone (2001), based on Eq. (7), the present paper constructs a non-radial and non-oriented SBM-DFF model of the production unit $k'\left(x_{k'}^{t}, y_{k'}^{t}, b_{k'}^{t}\right)$ that contains undesirable output in period t.

$$\begin{aligned}
\overrightarrow{S_C^t}\left(x_{k'}^{t}, y_{k'}^{t}, b_{k'}^{t}\right) = \rho^* = \min \frac{1-\left[\frac{1}{N}\sum_{n=1}^{N} s_n^x / x_n^{k'}\right]}{1+\left[\frac{1}{M+I}\left(\sum_{m=1}^{M} s_m^y / y_m^{k'} + \sum_{i=1}^{I} s_i^b / b_i^{k'}\right)\right]} \\
s.t. \sum_{k=1}^{K} z_k^t y_{k,m}^t - s_m^y = y_{k',m}^t, m = 1, \ldots, M; \\
\sum_{k=1}^{K} z_k^t y_{k,i}^t + s_i^b = b_{k',i}^t, i = 1, \ldots, I; \\
\sum_{k=1}^{K} z_k^t y_{k,n}^t + s_n^x = x_{k',n}^t, n = 1, \ldots, N; \\
z_k^t \geq 0, s_m^y \geq 0, s_i^b \geq 0, s_n^x \geq 0, k = 1, \ldots, K.
\end{aligned} \tag{10}$$

In Eq. (10), ρ^* denotes regional ETFP level; s^x, s^y, and s^b represent the slack of input and output, respectively. ρ^* is strictly decreasing and defined on an interval [0, 1]. When $\rho^* = 1$, the production unit is completely efficient. When $\rho^* < 1$, the production unit has an efficiency loss, and there is still room for further improvement in input and output. Input indicators comprise labor input, fixed-asset investment, and energy consumption in each province (Shen et al. 2019a). The indicator of desirable output is GDP of each province (Shen et al. 2019a). The indicators of undesirable output include waste water discharge amount, SO_2 emission, and solid waste discharge amount in each province (Shen et al. 2019b).

2. Innovation (R&D). As the consumption of resources and energy is a cost expenditure for enterprises, the treatment of waste water, waste gas, and solid waste also needs to increase the cost expenditure. Therefore, for the sake of cost saving, the technological innovation of industrial enterprises should have the nature of energy saving and emission reduction (Zhang et al. 2018). The current proxies for innovation cover R&D investment, the number of patents, and new product output value (Amable et al. 2016; Zhang et al. 2018). In the previous discussion, both EPU and marketization process affect the innovation behaviors of market players. The changes in R&D investment can directly reflect this impact. Zhou et al. (2019) also believed that R&D reflects the technological level of environmental pollution control. Therefore, the proportion of R&D investment in GDP in each province is used to measure innovation level.

3. Economic policy uncertainty (EPU). We adopt the EPU index developed by Baker et al. (2016). The index is based on newspaper coverage frequency. Using the similar newspaper-based approach, they constructed EPU indexes for other major economies.[1] For China, Baker et al. (2016) relied on the frequency of articles in the *South China Morning Post*, the leading English-language newspaper in Hong Kong, and constructed China's EPU index using text search and filter methods. The arithmetic average of the monthly data is converted into annual EPU index.

[1] For detailed information and related data on this index, please refer to http://policyuncertainty.com/china_monthly.html.

4. Marketization process (MI). The marketization index developed by Wang et al. (2017) and Fan et al. (2011) is used to measure the marketization process of each province, which includes the government–market relations (*gov_mar*), the development of non–state-owned economy (*non_state*), the development level of product market (*product_mar*), the development degree of factor market (*factor_mar*), and the development of market intermediaries and the legal system environment (*law_mar*).

5. Control variables (CONTROL). We select energy intensity (EI), foreign trade (EXP), foreign direct investment (FDI), and financial development efficiency (FD) as control variables (Yue et al. 2018; Hao et al. 2020). The measures for variables are presented in Table 1.

Data source and processing

The panel data of 30 provinces in China from 2005 to 2016 is used for analysis in the present paper. Due to the lack of data in Tibet, Hong Kong, Macao, and Taiwan, they are excluded in the study. R&D investment, the number of labor force, fixed assets investment, energy consumption, discharge amount of waste water, SO_2 emission, discharge amount of solid waste, GDP, volume of total exports and imports, and foreign direct investment are collected from *China Statistical Yearbook*. The amount of savings and the amount of loans in each province come from *Almanac of China's Finance and Banking*. The data on EPU is from the website http://policyuncertainty.com/china_monthly.html. The marketization index and the five sub-dimensions are based on the calculation by Wang et al. (2017) and Fan et al. (2011). Table 2 summarizes the descriptive statistics of all variables in the econometric models.

To eliminate the impact of inflation, we use current price/PPI (Producer's Price Index for Manufactured Products) to convert current year's prices (current data) into constant price of 2005. Investment in fixed assets of each industry is computed with Perpetual Inventory Method. Following Zhang et al. (2004) and Zhang et al. (2018), Eq. (11) is used to calculate capital stock.

$$K_{it} = I_{it} + (1-\delta)K_{it-1} \tag{11}$$

$K_{it}$is the capital stock of each province in the period of t. δ, the depreciation rate, equals 9.6%. I_{it} is the investment amount of period t.

To further analyze the regional heterogeneity in the impact of innovation on ETFP, we group the 30 provinces in China. Since most studies divide 30 provinces of China into the eastern, central, and western areas based on administrative division, this leads to selective bias in the estimation process. To overcome this problem, we divide 30 provinces into low pollution intensity area and high pollution intensity area according to pollution intensity (Table 3). The classification method is specified as below (Wang and Shen 2016):

(1) Calculate the discharge amount of each pollutant per unit output value in the province

$$UP_{ij} = P_{ij}/GDP_i \tag{12}$$

where i represents the province; j represents the type of pollutant; j equals 1, 2, 3, which indicates discharge amount of waste water, SO2 emission, and discharge amount of solid waste respectively; P_{ij} is the discharge amount of j pollutant in the i province; and GDP_i is GDP of the i province.

Table 2 The descriptive statistics of variables

Variable	Mean	SD	Minimum	Maximum	Observations
ETFP	0.822	0.139	0.414	1.000	360
R&D	1.399	1.055	0.178	6.010	360
EPU	152.060	81.805	64.962	364.833	360
MI	6.300	1.827	1.170	10.920	360
gov_mar	6.458	1.759	0.296	10.338	360
non_state	6.231	2.471	0.161	10.571	360
product_mar	7.735	1.232	1.460	9.847	360
factor_mar	4.660	2.296	0.053	13.883	360
law_mar	4.653	3.655	0.010	19.8	360
EI	1.085	0.601	0.268	4.140	360
EXP	1.02e+07	1.95e+07	49023.100	1.28e+08	360
FDI	982.366	1492.788	7.000	8799.000	360
FD	1.046	0.515	0.039	4.406	360

Table 3 Results of regional grouping in China

Group	Provinces
Low pollution intensity area (PL < 0.280)	Beijing, Tianjin, Shanghai, Jiangsu, Shandong, Zhejiang, Jilin, Hainan, Guangdong, Heilongjiang, Fujian, Hubei, Shaanxi, Hunan, Henan
High pollution intensity area (PL ≥ 0.280)	Liaoning, Sichuan, Anhui, Chongqing, Inner Mongolia, Hebei, Xinjiang, Gansu, Jiangxi, Yunnan, Guangxi, Qinghai, Shanxi, Guizhou, Ningxia

(2) The pollutant discharge index is obtained through the dimensionless method at the interval [0,1]

$$\overline{UP}_{ij} = \left(UP_{ij} - \min\left(UP_j\right)\right) / \left(\max\left(UP_j\right) - \min\left(UP_j\right)\right) \quad (13)$$

where max(UP_j), min(UP_j) are the maximum and minimum discharge amount of j pollutant per unit output value among 30 provinces, respectively.

(3) Sum the pollutant discharge index of each province by the arithmetic average method to obtain the pollution intensity index of each province (PL_i)

$$PL_i = \sum_{j=1}^{3} \overline{UP}_{ij} \quad (14)$$

Empirical results

Stationary test and co-integration test

We conduct stationary test on the data before the econometric regression analysis. In the present paper, four methods—Levin, Lin and Chu (LLC), IPS, ADF-Fisher, and PP-Fisher—are applied to the unit root test. The unit root test equation includes constant term and time trend term. The results show that all variables are first-order stationary series (Table 4).

To address the spurious regression phenomenon, the co-integration relationship between R&D intensity, EPU, marketization process, and ETFP must be examined prior to estimating the parameters of panel data. We perform the co-integration test proposed by Pedroni (2004). The results show that the panel co-integration relationships reside between R&D intensity, EPU, marketization process, and ETFP (Table 5).

Analysis of the calculation results of ETFP

Table 6 lists the ETFP values of Chinese provinces from 2005 to 2016. Overall, China's ETFP value decreased 20.24%, from 0.914 in 2005 to 0.729 in 2016. This shows that during the period from 2005 to 2016, while China's economic development has achieved remarkable results, it has caused considerable damage to environmental quality. Moreover, since 2014, China's ETFP value has been in a clear downward trend, which shows that China's current environmental

Table 4 The results of unit root test

Variable	Test type	LLC test	IPS test	ADF-Fisher test	PP-Fisher test	Conclusion
lnETFP	(C, T, 1)	− 17.377***	− 6.835***	166.461***	250.232***	First-order stationary
lnR&D	(C, T, 1)	− 19.654***	− 8.024***	205.436***	311.691***	First-order stationary
lnEPU	(C, T, 1)	− 12.503***	− 2.625***	113.546***	116.522***	First-order stationary
lnMI	(C, T, 1)	− 17.944***	− 6.612***	184.522***	242.524***	First-order stationary
lngov_mar	(C, T, 1)	− 18.382***	− 6.792***	200.060***	377.111***	First-order stationary
lnnon-state	(C, T, 1)	− 16.123***	− 5.758***	176.079***	438.326***	First-order stationary
lnproduct-mar	(C, T, 1)	− 6.772***	− 1.656***	84.041***	518.482***	First-order stationary
lnfactor-mar	(C, T, 1)	− 15.472***	− 4.796***	152.646***	302.149***	First-order stationary
lnlaw_mar	(C, T, 1)	− 14.399***	− 1.407*	97.305***	151.795***	First-order stationary
lnEI	(C, T, 1)	− 18.111***	− 6.666***	177.421***	351.706***	First-order stationary
lnEXP	(C, T, 1)	− 17.964***	− 5.355***	156.407***	280.712***	First-order stationary
lnFDI	(C, T, 1)	− 12.397***	− 4.027***	127.377***	184.822***	First-order stationary
lnFD	(C, T, 1)	− 12.315***	− 2.440***	92.624***	154.641***	First-order stationary

C, T, and N stand for intercept, trend, and lag periods, respectively. ***, **, and * indicate significance at the 1, 5, and 10% levels, respectively

Table 5 The results of co-integration test

Statistics	Hypothesis	Test type	Results							
			lnR&D—lnETFP	lnEPU—lnETFP	lnMI—lnETFP	lngov_mar—lnETFP	lnnon_state—lnETFP	lnproduct_mar—lnETFP	lnfactor_mar—lnETFP	lnlaw_mar—lnETFP
Within groups	H_0: $\rho = 1$	Panel v-Stat.	3.441***	2.126**	2.531***	2.538***	4.318***	5.320***	3.544***	1.080
	H_1: $\rho < 1$	Panel ρ-Stat.	− 2.013**	− 2.967***	− 1.651**	− 4.001***	− 3.202***	− 4.389***	− 3.010***	0.978
		Panel PP-Stat.	− 3.951***	− 4.984***	− 3.487***	− 6.226***	− 5.449***	− 13.481***	− 5.720***	− 2.357***
		Panel ADF-Stat.	− 1.222	− 0.511	− 1.011	− 2.507***	− 3.046***	− 3.047***	− 3.433***	− 2.119***
Between groups	H_0: $\rho = 1$	Group ρ-Stat.	0.139	− 0.336	0.843	− 0.685	− 0.398	6.993	− 0.091	3.100
	H_1: $\rho < 1$	Group PP-Stat.	− 4.461***	− 4.630***	− 3.336***	− 4.894***	− 4.971***	− 15.969	− 5.150***	− 3.802***
		Group ADF-Stat.	− 0.320	0.734	1.122	− 0.516	− 1.079	− 1.198	− 2.051	− 4.090***

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

governance issues are urgent. From the perspective of specific provinces (Fig. 2), those with high ETFP values include Guangdong, Shandong, Jiangxi, Qinghai, and Inner Mongolia, with an average ETFP value above 0.963. In contrast, provinces with low ETFP values are Xinjiang, Heilongjiang, Gansu, Hubei, and Jilin, with an average ETFP value below 0.7.

From the perspective of regional distribution, the ETFP value is not strictly in accordance with the distribution of eastern, central, and western regions of China. This shows that there is misrepresentation in studies that group the eastern, central, and western regions. Looking further into each group (Fig. 3), ETFP in low pollution intensity regions decreased 14.32%, from 0.915 in 2005 to 0.784 in 2016. In comparison, ETFP in high pollution intensity regions decreased 26.26%, from 0.914 in 2005 to 0.674 in 2016. This shows that the two major regions are showing a trend of "competition for the last place." Therefore, the improvement of ETFP in various regions of China is an especially prominent issue.

Full sample estimation

Table 7 is the full sample estimation results. When the regional ETFP level is high, it means that the region has achieved a win-win result in economic development and environmental protection, which may signal a reverse causal relationship between ETFP and innovation. High ETFP increases the fiscal revenue of the local government, which can better invest in innovation activities. Therefore, we first conduct an endogenous test on the R&D variables. The results of the Hausman test are all significant at the 1% level, indicating that there is indeed an endogenous problem in innovation. To address the endogenous bias, we approach this problem from two aspects: First, the present study uses the R&D value at two-phase lag as an independent variable, allowing for examination of the lag effect of R&D as it takes a certain amount of time to transform innovation investment into income, which can also avoid the reverse impact of ETFP. Second, the present study adopts the three- or four-phase lag of R&D as instrumental variables and uses the IVTobit model to estimate the effect of innovation on ETFP. The Wald exogenous exclusion test in Table 7 rejects the null hypothesis, indicating that R&D is endogenous. At the same time, the robustness test of weak instrumental variables rejects the null hypothesis, indicating that there is no "weak instrumental variable."

In Table 7, model (1) examines the impact of innovation on regional ETFP. The results show that innovation significantly promoted ETFP ($\alpha = 0.073$, $p < 0.01$), supporting Hypothesis 1. This shows that technological innovation for energy conservation and emission reduction enables China to achieve its set economic growth goals with lower technological choices. Lower technological choice means that China can use less capital investment, labor investment, energy input, and less

Table 6 ETFP of Chinese provinces

Area	Province	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Average	Ranking
Low pollution intensity area	Guangdong	1.000	1.000	1.000	0.964	1.000	1.000	0.965	1.000	1.000	1.000	1.000	1.000	0.994	1
	Shandong	1.000	1.000	0.902	0.917	0.934	0.913	1.000	1.000	1.000	1.000	1.000	1.000	0.972	2
	Jiangsu	1.000	0.855	0.882	0.904	0.948	0.951	1.000	1.000	0.933	1.000	1.000	1.000	0.956	6
	Shanghai	1.000	0.897	0.899	0.892	0.966	1.000	0.921	0.931	0.954	1.000	0.945	1.000	0.950	7
	Hainan	1.000	0.918	0.947	1.000	1.000	1.000	0.977	0.998	0.979	1.000	0.648	0.623	0.924	8
	Tianjin	0.914	0.771	0.769	0.819	0.852	0.853	0.798	0.842	0.922	1.000	0.865	0.898	0.859	12
	Beijing	0.782	0.654	0.680	0.695	0.751	0.749	0.787	0.851	0.942	1.000	0.954	1.000	0.820	16
	Zhejiang	0.876	0.755	0.762	0.752	0.780	0.801	0.801	0.807	0.844	0.882	0.712	0.723	0.791	17
	Fujian	1.000	0.749	0.750	0.745	0.794	0.781	0.761	0.766	0.839	0.818	0.699	0.717	0.785	18
	Henan	1.000	0.811	0.781	0.749	0.740	0.737	0.771	0.780	0.809	0.799	0.713	0.671	0.780	19
	Shaanxi	0.868	0.748	0.729	0.743	0.723	0.743	0.781	0.794	0.779	0.807	0.681	0.606	0.750	22
	Hunan	0.815	0.694	0.709	0.705	0.717	0.723	0.740	0.768	0.829	0.857	0.681	0.646	0.740	23
	Jilin	0.746	0.616	0.624	0.624	0.660	0.680	0.733	0.780	0.788	0.832	0.645	0.602	0.694	26
	Hubei	0.723	0.596	0.640	0.654	0.682	0.692	0.695	0.724	0.757	0.781	0.657	0.661	0.689	27
	Heilongjiang	1.000	0.606	0.598	0.601	0.587	0.590	0.627	0.645	0.670	0.713	0.649	0.613	0.658	29
	Average	0.915	0.778	0.778	0.784	0.809	0.814	0.824	0.846	0.870	0.899	0.790	0.784	0.824	
High pollution intensity area	Jiangxi	1.000	0.887	0.940	0.913	0.921	0.937	1.000	1.000	1.000	1.000	1.000	1.000	0.967	3
	Qinghai	1.000	1.000	0.927	1.000	0.867	0.914	1.000	1.000	0.977	1.000	1.000	0.909	0.966	4
	Inner Mongolia	1.000	1.000	0.927	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.893	0.735	0.963	5
	Hebei	1.000	0.941	0.884	0.839	0.826	0.876	1.000	1.000	1.000	1.000	0.768	0.755	0.907	9
	Ningxia	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.942	0.884	0.857	0.566	0.494	0.895	10
	Shanxi	1.000	0.810	0.844	0.893	0.796	0.837	1.000	0.961	0.918	0.865	1.000	0.670	0.883	11
	Guangxi	1.000	0.876	1.000	1.000	0.923	0.900	0.784	0.806	0.802	0.833	0.683	0.657	0.855	13
	Liaoning	0.841	0.712	0.756	0.737	0.750	0.735	0.829	0.835	0.898	1.000	1.000	0.762	0.821	14
	Guizhou	1.000	1.000	0.922	0.891	0.872	0.850	0.778	0.743	0.766	0.757	0.651	0.622	0.821	15
	Yunnan	0.794	0.648	0.643	0.643	0.649	0.645	1.000	0.826	0.902	0.838	0.777	0.754	0.760	20
	Anhui	0.819	0.675	0.678	0.697	0.726	0.737	0.796	0.826	0.822	0.859	0.701	0.716	0.754	21
	Chongqing	0.919	0.806	0.772	0.761	0.772	0.743	0.676	0.708	0.756	0.784	0.583	0.557	0.736	24
	Sichuan	0.844	0.686	0.720	0.703	0.690	0.717	0.720	0.758	0.746	0.771	0.625	0.618	0.717	25
	Gansu	0.813	0.675	0.683	0.673	0.664	0.679	0.726	0.703	0.652	0.659	0.519	0.453	0.658	28
	Xinjiang	0.680	0.591	0.598	0.609	0.609	0.633	0.638	0.647	0.644	0.631	0.462	0.414	0.596	30
	Average	0.914	0.820	0.820	0.824	0.804	0.814	0.863	0.850	0.851	0.857	0.749	0.674	0.820	
Average of all provinces		0.914	0.799	0.799	0.804	0.807	0.814	0.843	0.848	0.860	0.878	0.769	0.729		

environmental pollutant emissions to achieve economic growth goals. Therefore, innovation plays an important and positive role in easing the pressure on China's economic growth and resource.

Model (2) introduces EPU. The results show that it significantly inhibited regional ETFP ($\alpha = -0.092$, $p < 0.01$), supporting Hypothesis 2. This means that if the uncertain factors of economic policy are separately considered, it will negatively impact regional ETFP. Because the increase in economic policy uncertainty will affect the investment environment and trade environment of regional enterprises, uncertain economic policies or frequently adjusted economic policies will lower the expectations of enterprises for future fixed asset investment and foreign direct investment. Lower investment expectations mean that regional enterprises may reduce the scale of investment, which will have a negative effect on regional economic growth.

Model (3) introduces the interaction terms of R&D and EPU. The results show that EPU had a significant positive moderating effect on innovation and ETFP ($\alpha = 0.074$, $p < 0.1$), supporting Hypothesis 3. This means that when considering the combined effect of economic policy uncertainty and innovation, as the economic policy uncertainty increases, the role of innovation in promoting regional ETFP will also increase, and there is good coupling between innovation and economic policy uncertainty effect. The main reason is that

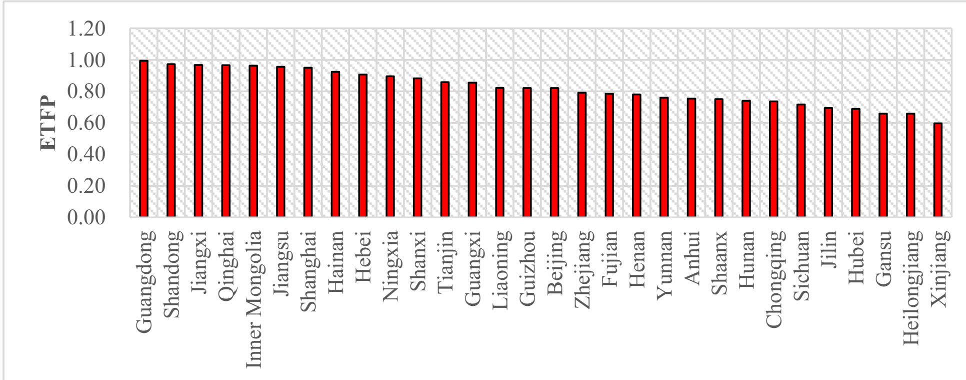


Fig. 2 Average ETFP of Chinese provinces

in an environment of high economic policy uncertainty, although regional companies may reduce fixed asset investment, mergers and acquisitions, and other activities, innovation can change the company's yield curve and provide new opportunities for future economic developments. Therefore, companies will reduce investment in fixed assets and expand investment in innovation to promote the growth of regional ETFP.

Model (4) shows that the marketization process insignificantly inhibited regional ETFP, rejecting Hypothesis 4. China's economic reform has achieved remarkable results, which has stimulated market competition and improved labor productivity. However, market-oriented reforms in the field of resources and environment have been slow to advance. For example, compared with the EU and developed countries, China's carbon emissions trading market is still immature. In 2016, only 2391 companies participated in the carbon emissions trading program, and the carbon emission quota was only 1.2 billion tons. The efficiency and scale of the carbon trading market are relatively low, showing "low trading volume and an appearance of prosperity" (Weng and Xu 2018; Zhao et al. 2017).

Model (5) examines the influence of each sub-item in the marketization process on regional ETFP. The results show that the government–market relations were not significant at promoting ETFP, rejecting Hypothesis 4a. The transformation of local government functions and the reformation of governance models in China potentially promoted regional ETFP. The promotion of ETFP by non–state-owned economic development was not significant, rejecting Hypothesis 4b. China's emphasis on the development of private enterprises in recent years has begun to show results, and private enterprises may promote coordinated development of regional economy and environment. Product market development had a significant inhibitory effect on ETFP ($\theta = -0.281$, $p < 0.01$), rejecting Hypothesis 4c. It is possible that the government strongly intervened in transaction prices, such as resource and energy prices, emission rights, and carbon emission rights, and is determined by the market to a lesser extent. The price of resources and energy does not reflect external costs, and the scarcity of resources led to serious resource allocation failure and environmental pollution (Cui and Wei 2017).

The inhibitory effect of factor market development on ETFP was not significant, rejecting Hypothesis 4d. It is possible that the factor market remained distorted. The price and liquidity of low factors make it difficult for the regional economy to obtain high-quality factor resources for intensive development, thereby inhibiting the region's transition to green and high-quality development (Lin and Chen 2018). The development of market intermediaries and the legal system environment had a significant inhibitory effect on ETFP ($\theta = -0.050$, $p < 0.01$), rejecting Hypothesis 4e. It is possible that the size of intermediary organizations in the Chinese market was

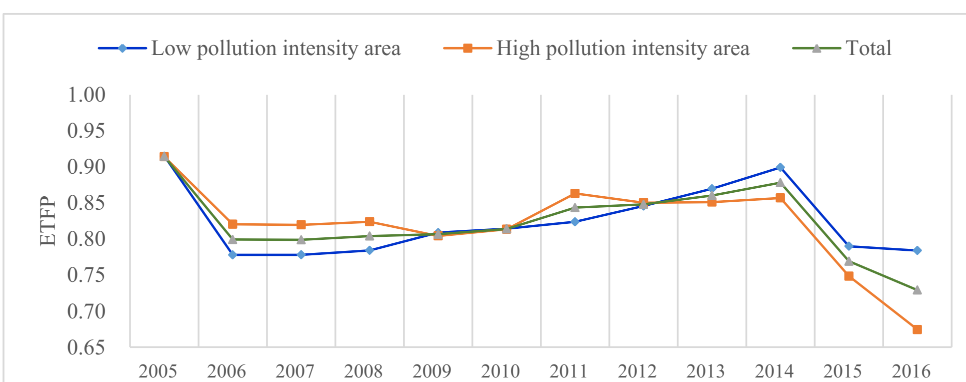


Fig. 3 ETFP trends in groups

Table 7 Full sample estimation results

Models	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$\ln R\&D_{t-2}$	0.073*** (3.17)	0.070*** (3.14)	0.071*** (3.16)	0.070*** (3.05)	0.072*** (2.60)	0.084*** (3.77)	0.089*** (2.99)
$\ln EPU_{t-2}$		− 0.092*** (− 3.30)	− 0.093*** (− 3.33)				
$\ln MI_{t-2}$				− 0.070 (− 1.35)		− 0.056 (− 1.11)	
$\ln gov\_mar_{t-2}$					0.026 (0.59)		0.010 (0.20)
$\ln non\_state_{t-2}$					0.011 (0.44)		0.021 (0.83)
$\ln product\_mar_{t-2}$					− 0.281*** (− 4.33)		− 0.131 (− 1.56)
$\ln factor\_mar_{t-2}$					− 0.005 (− 0.18)		− 0.011 (− 0.33)
$\ln law\_mar_{t-2}$					− 0.050*** (− 3.04)		− 0.003 (− 0.12)
$\ln R\&D_{t-2} \times \ln EPU_{t-2}$			0.074* (1.70)				
$\ln R\&D_{t-2} \times \ln MI_{t-2}$						0.274*** (5.00)	
$\ln R\&D_{t-2} \times \ln gov\_mar_{t-2}$							0.131* (1.70)
$\ln R\&D_{t-2} \times \ln non\_state_{t-2}$							0.079* (1.69)
$\ln R\&D_{t-2} \times \ln product\_mar_{t-2}$							0.125 (1.19)
$\ln R\&D_{t-2} \times \ln factor\_mar_{t-2}$							0.038 (0.77)
$\ln R\&D_{t-2} \times \ln law\_mar_{t-2}$							0.123*** (3.29)
lnEI	0.100*** (2.78)	0.131*** (3.59)	0.131*** (3.58)	0.102*** (2.82)	0.080** (2.24)	0.096*** (2.78)	0.128*** (3.45)
lnEXP	− 0.038** (− 2.37)	− 0.042*** (− 2.70)	− 0.042*** (− 2.68)	− 0.037** (− 2.30)	− 0.004 (− 0.21)	− 0.046*** (− 2.95)	− 0.005 (− 0.28)
lnFDI	0.126*** (5.69)	0.137*** (6.28)	0.135*** (6.17)	0.138*** (5.80)	0.119*** (4.49)	0.144*** (6.31)	0.100*** (3.60)
lnFD	− 0.012 (− 0.58)	− 0.003 (− 0.13)	− 0.003 (− 0.16)	− 0.009 (− 0.42)	− 0.003 (− 0.16)	0.005 (0.22)	0.009 (0.45)
_cons	0.660*** (4.32)	0.214 (1.06)	0.218 (1.08)	0.695*** (4.48)	0.751*** (4.62)	0.732*** (4.92)	0.538*** (2.92)
Adj R^2	0.9769	0.9768	0.9767	0.9770	0.9769	0.9769	0.9772
Wald χ^2	52.40***	64.88***	67.35***	54.41***	80.42***	81.92***	102.75***
AR	10.23***	10.02***	10.13***	9.48***	6.87***	14.51***	9.10***
Wald test	6.37**	6.20	6.31**	6.99***	6.98***	8.28***	6.04**
Observations	270	270	270	270	270	270	270

The *z*-statistics are in parentheses. ***, **, and * indicate significance at the 1, 5, and 10% levels, respectively. AR represents the robustness test of weak instruments. Wald test represents an exogenous exclusion test

relatively small and the degree of specialization was low, especially since China has vigorously developed strategic emerging industries since 2008 while less focus is placed on intermediary organizations supporting the emerging industries, which limited the rapid development of China's economy.

Model (6) introduces the interaction items of R&D and marketization process. The results show that the marketization process had a significant positive regulatory effect on innovation and ETFP ($\beta = 0.274, p < 0.01$), supporting Hypothesis 5. This shows that with the increased maturity of regional markets, economic system reform has created significant development vitality, which had a clear positive effect on promoting innovation in regional enterprises. The main reason is that the government reduced extra-tax burden of enterprises, which increased the market's ability to determine product prices and enhanced the level of marketization of scientific and technological achievements and the protection of intellectual property rights. These reform measures provided a good market environment that encouraged enterprises to increase R&D investment and to implement innovation-driven strategies.

Last, model (7) examines the moderating effects of each sub-item of the marketization process on innovation and ETFP. The results show that the government–market relations positively moderated the promotion effect of innovation on ETFP ($\theta = 0.131$, $p < 0.1$), supporting Hypothesis 5a. This means that as the relationship between the government and the market improves, the role of innovation in promoting regional ETFP will also increase. The main reason is that the government reduces the non-tax burden of enterprises, which better aligns the talents, capital, and other elements required for innovation with the market mechanism. Hence, regional enterprises have more high-quality innovation resources, which produces a stronger promotional effect for ETFP.

The non–state-owned economic development has a significant positive moderation on innovation and ETFP ($\theta = 0.079$, $p < 0.1$), supporting Hypothesis 5b. This means that with the development of the non–state-owned economy, the role of innovation in promoting regional ETFP will also increase. This is consistent with the development status of China's private economy. According to the "China Private Economy Report 2019," as of July 2019, private enterprise invention patents accounted for more than 75% of total patents, which is the main force of China's technological innovation. Private enterprise investment accounted for more than 60%, and specifically private investment in manufacturing accounted for over 80%, which is the biggest driving force for investment.

The positive moderation of product market development and factor market development were not significant, rejecting Hypotheses 5c and 5d. The reason for this result is the distortion problems existing in China's product and factor markets, especially the prices of resources, energy, and emission rights are obviously priced by the government. The market pricing mechanism and competition mechanism were not fully established, so the incentive effect on innovation was minor. The development of market intermediary organizations and the legal system environment positively moderated the effect of innovation on ETFP ($\theta = 0.123$, $p < 0.01$), supporting Hypothesis 5e. This means that with the development of market intermediary organizations and the improvement of the legal system, the role of innovation in promoting regional ETFP will also increase. The core reason is that strengthening the protection of intellectual property rights can prevent the imitation and absorbance of enterprise innovation by competitors. This mechanism has a positive effect on ensuring the innovation income of enterprises and can effectively encourage enterprises to improve ETFP through innovation.

Regional estimation

Low pollution intensity regions

Models (1)–(7) in Table 8 are the estimation results of low pollution intensity regions. Model (1) shows that innovation played a significant role in promoting ETFP in low pollution intensity regions ($\alpha = 0.068$, $p < 0.01$), supporting Hypothesis 1. This means that the marginal economic and environmental benefits of innovation are higher for regions with low pollution intensity, and it has a positive effect on the achievement of coordinated economic and environmental development. From the perspective of the economic development characteristics of the region, most are regions with relatively high levels of economic development, and the innovation foundation and innovation capabilities are relatively strong, so its promotional effect on regional ETFP is also stronger.

Model (2) introduces EPU. The results show that EPU had a significant promotion effect on ETFP in low pollution intensity regions ($\alpha = 0.078$, $p < 0.05$), rejecting Hypothesis 2, which is inconsistent with the results of the full sample. It is possible that the region's energy and environmental policy system was relatively comprehensive, and companies had consistent expectations for the tightening of national energy conservation and emission reduction policies for the future. Moreover, these regions had high levels of innovation and market competitiveness, and changes in economic policies helped companies to seize the market high point and opportunities.

Model (3) introduces the interaction terms of R&D and EPU. The results show that the positive moderating effect of EPU on innovation and ETFP was not significant in low pollution intensity regions, rejecting Hypothesis 3. The stimulating effect of economic policy uncertainty on innovation input was not obvious. It is possible that provinces in low pollution intensity regions acted as the vanguard for the reform of China's economic system, political system, and environmental protection system. Compared with the national average reform efforts, regions with low pollution intensity had greater reform efforts and more frequent economic policy adjustments. Excessive uncertainty has hindered innovation activities in the region to a certain extent.

Model (4) shows that the marketization process had a significant inhibitory effect on ETFP in regions with low pollution intensity ($\beta = -0.290$, $p < 0.01$), rejecting Hypothesis 4. It is possible that market-oriented reforms had accelerated the pace of economic development, but market-oriented reforms since 2005 led to more extensive economic developments and relatively low input–output efficiency.

Table 8 Subregional estimation results

Models	Low pollution intensity area							High pollution intensity area						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
lnR&D$_{t-2}$	0.068***	0.064***	0.066***	0.054**	0.072**	0.009	0.014	− 0.199***	− 0.208***	− 0.208***	− 0.199***	− 0.202***	− 0.196***	− 0.158 *
	(3.00)	(2.90)	(2.94)	(2.49)	(2.18)	(0.42)	(0.30)	(− 4.07)	(− 4.35)	(− 4.24)	(− 4.07)	(− 3.59)	(− 3.97)	(− 1.70)
lnEPU$_{t-2}$		0.078**	0.077**						− 0.097**	− 0.097**				
		(2.26)	(2.22)						(− 2.34)	(− 2.34)				
lnMI$_{t-2}$				− 0.290***		− 0.305***					0.007		0.011	
				(− 3.32)		(− 3.98)					(0.11)		(0.16)	
lngov_mar$_{t-2}$					− 0.117		− 0.154					− 0.205**		− 0.293 ***
					(− 1.24)		(− 1.42)					(− 2.57)		(− 3.34)
lnnon_state$_{t-2}$					− 0.030		0.007					0.006		0.144
					(− 0.60)		(0.15)					(0.06)		(1.33)
lnproduct_mar$_{t-2}$					− 0.389***		− 0.087					0.144		0.270
					(− 3.90)		(− 0.62)					(1.06)		(1.48)
lnfactor_mar$_{t-2}$					0.019		0.018					− 0.229***		− 0.304 ***
					(0.46)		(0.46)					(− 3.36)		(− 4.14)
lnlaw_mar$_{t-2}$					− 0.098***		− 0.059**					0.017		0.004
					(− 3.38)		(− 1.96)					(0.46)		(0.09)
lnR&D$_{t-2}$ × lnEPU$_{t-2}$			0.026							0.094				
			(0.51)							(1.01)				
lnR&D$_{t-2}$ × lnMI$_{t-2}$						0.402***							− 0.029	
						(5.38)							(− 0.23)	
lnR&D$_{t-2}$ × lngov_mar$_{t-2}$							0.010							− 0.268
							(0.07)							(− 1.17)
lnR&D$_{t-2}$ × lnnon_state$_{t-2}$							− 0.120							0.262
							(− 1.49)							(1.42)
lnR&D$_{t-2}$ × lnproduct_mar$_{t-2}$							0.246*							0.356
							(1.76)							(0.64)
lnR&D$_{t-2}$ × lnfactor_mar$_{t-2}$							0.239***							0.062
							(3.61)							(0.34)
lnR&D$_{t-2}$ × lnlaw_mar$_{t-2}$							− 0.015							− 0.307 **
							(− 0.29)							(− 2.57)
lnEI	− 0.050	− 0.005	− 0.009	− 0.021	0.009	0.097*	0.123	0.053	0.075	0.077	0.053	0.003	0.054	0.010
	(− 0.92)	(− 0.09)	(− 0.16)	(− 0.40)	(0.12)	(1.92)	(1.45)	(1.02)	(1.45)	(1.50)	(1.02)	(0.06)	(1.04)	(0.16)
lnEXP	0.034	0.018	0.020	0.029	0.106***	0.039*	0.106***	− 0.101***	− 0.105***	− 0.107***	− 0.101***	0.054	− 0.101***	0.064
	(1.39)	(0.72)	(0.80)	(1.25)	(4.31)	(1.92)	(4.48)	(− 4.68)	(− 4.96)	(− 5.03)	(− 4.68)	(1.51)	(− 4.65)	(1.83)
lnFDI	0.065*	0.090**	0.086**	0.124***	0.061*	0.113***	0.026	0.159***	0.168***	0.169	0.158***	0.070	0.157***	− 0.003
	(1.92)	(2.58)	(2.42)	(3.32)	(1.80)	(3.46)	(0.79)	(5.28)	(5.67)	(5.69)	(4.93)	(1.41)	(4.87)	(− 0.05)
lnFD	− 0.013	− 0.012	− 0.012	− 0.006	− 0.019	− 0.019	− 0.012	0.070**	0.084**	0.084**	0.070**	0.103***	0.069*	0.074 *
	(− 0.60)	(− 0.55)	(− 0.57)	(− 0.28)	(− 0.88)	(− 1.02)	(− 0.54)	(2.04)	(2.48)	(2.47)	(2.01)	(2.61)	(1.96)	(1.82)
_cons	− 0.149	− 0.423*	− 0.430*	0.092	− 0.013	0.040	− 0.460*	1.372***	0.905***	0.902***	1.371***	− 0.016	1.365***	0.060

Table 8 (continued)

Models	Low pollution intensity area							High pollution intensity area						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	(− 0.73)	(− 1.81)	(− 1.83)	(0.45)	(− 0.05)	(0.22)	(− 1.77)	(6.05)	(3.04)	(3.10)	(5.92)	(− 0.04)	(5.84)	(0.12)
Adj R^2	0.9846	0.9845	0.9844	0.9846	0.9846	0.9846	0.9852	0.9333	0.9328	0.9323	0.9338	0.9550	0.9336	0.9575
Wald χ^2	99.12***	108.18***	108.20***	114.41***	171.41***	169.58***	243.22***	36.56***	43.43***	44.48***	36.52***	53.03***	36.55***	65.18***
AR	11.78***	9.92***	11.79***	6.84**	4.86*	6.75**	4.67*	17.63***	20.33***	20.26***	17.61***	13.72***	16.79***	3.14*
Wald test	3.05*	2.78*	2.87*	2.96*	3.27*	3.37*	3.01*	9.13***	10.20***	10.29***	9.15***	5.52**	8.97***	10.06***
Observations	120	120	120	120	120	120	120	135	135	135	135	135	135	135

The *z*-statistics are in parentheses. ***, **, and * indicate significance at the 1, 5, and 10% levels, respectively. AR represents the robustness test of weak instruments. Wald test represents an exogenous exclusion test

Model (5) examines the impact of each sub-item of the marketization process on ETFP in low pollution intensity regions. The results show that the government–market relations and the development of the non–state-owned economy did not significantly inhibit ETFP in low pollution intensity regions, rejecting Hypotheses 4a and 4b. Product market development had a significant inhibitory effect on ETFP in low pollution intensity region ($\theta = -0.389$, $p < 0.01$), rejecting Hypothesis 4c. The development of the factor market had an insignificant promotion effect on the ETFP in low pollution intensity regions, rejecting Hypothesis 4d, which indicates that the distortion of the factor configuration in the low pollution intensity region was relatively low. The development of market intermediaries and the legal system environment had a significant inhibitory effect on ETFP in low pollution intensity regions ($\theta = -0.098$, $p < 0.01$), rejecting Hypothesis 4e. This indicates that low pollution intensity regions had shortcomings in product marketization reform and the development of market intermediary organizations.

Model (6) introduces the interaction items of R&D and marketization process. The results show that the marketization process had a significant positive moderating effect on innovation and ETFP ($\beta = 0.402$, $p < 0.01$), supporting Hypothesis 5. This means that as the level of marketization in the region increases, the role of innovation in promoting regional ETFP will also increase. The main reason is that environmental protection issues belong to the field of public goods and require the intervention of forces outside of the market to be more effective. If only considering the improvement of marketization, it will easily lead to extensive developments of the regional economy, while it will ignore regional environmental protection issues. Innovation activities, especially those in the environmental field, play a key role in regional environmental protection. Therefore, the joint effect of innovation and marketization can achieve a win-win situation for regional economic development and environmental protection.

Last, model (7) examines the moderating effects of each sub-item of the marketization process on innovation and ETFP in regions of low pollution intensity. The results show that the government–market relations exhibited an insignificant positive moderating effect, rejecting Hypothesis 5a. Non–state-owned economic development had an insignificant negative moderating effect of innovation on ETFP in low pollution intensity regions, rejecting Hypothesis 5b. For regions with low pollution intensity, non–state-owned economic development had weakened the region's overall innovation investment. Product market development and factor market development both positively moderated the effect of innovation on ETFP in low pollution intensity regions ($\theta = 0.246$, $p <$ 0.1; $\theta = 0.239$, $p < 0.01$), supporting Hypotheses 5c and 5d. This means that as the development of product markets and factor markets increases, the role of innovation in promoting regional ETFP will also increase. The negative moderation of the development of market intermediaries and the legal system environment played a role in regional ETFP, but it was not significant, rejecting Hypothesis 5e. This means that for the development of market intermediary organizations and the reliability of the legal system, innovation may reduce the promotion of ETFP in the region. A possible reason is that the intellectual property protection system, while providing protection for technological innovators, also brings a certain degree of technological monopoly, which may hinder the technological innovation process, thereby reducing the role of innovation in promoting ETFP in the region.

High pollution intensity region

Models (8)–(14) in Table 8 are the estimation results of regions with high pollution intensity. Model (8) shows that innovation had a significant inhibitory effect on ETFP in high pollution intensity regions ($\alpha = -0.199$, $p < 0.01$), rejecting Hypothesis 1. It is possible that regions with high pollution intensity had more prominent characteristics of high energy consumption, high emissions, high pollution, and low growth, and the level of green innovation was lower. Therefore, while promoting economic development, it produced more energy consumption and pollutant emissions, that is, the "energy rebound effect" was more obvious (Ruzzenenti and Basosi 2008).

Model (9) introduces EPU. The results show that EPU had a significant inhibitory effect on ETFP in high pollution intensity regions ($\alpha = -0.097$, $p < 0.05$), supporting Hypothesis 2. The main reason is that compared with low pollution intensity areas, economic development in high pollution areas is more dependent on economic policies. For example, frequent adjustments of economic policies are bound to seriously affect the investment and production activities of enterprises (in the western and central regions), and have a restraining effect on economic growth. When economic growth is limited, local governments invest in environmental protection will be significantly reduced, leading to a decrease in ETFP in the region.

Model (10) introduces the interaction terms of R&D and EPU. The results show that EPU had an insignificant positive moderating effect on innovation and ETFP, rejecting Hypothesis 3 for high pollution intensity regions. This means that as economic policy uncertainty increases, the inhibitory effect of innovation on ETFP in the region will weaken. The uncertainty of economic policies can bring certain development opportunities for enterprises, including new benefits obtained by enterprises to implement green transformation, which enabled enterprises to invest in green innovation and have a potential role in promoting regional ETFP.

Model (11) shows that the marketization process had a positive impact on ETFP in the high pollution intensity regions, but it was not significant, rejecting Hypothesis 4. The main reason is that compared with areas with low pollution intensity, areas with high pollution intensity have a lower level of economic development. Therefore, when the degree of marketization continues to increase, the allocation efficiency of factors such as energy, resources, technology, capital, and talents will also increase. This will not only help enterprises in the region to obtain high-quality and low-cost production materials but also help the region to imitate and learn green technologies from developed regions, and achieve green development through technology spillover effects.

Model (12) examines the impact of each sub-item of the marketization process on ETFP in regions with high pollution intensity. The results show that the government–market relations had a significant inhibitory effect on regional ETFP ($\theta = -0.205$, $p < 0.05$), rejecting Hypothesis 4a. It is possible that the governments in the high pollution intensity regions had a higher degree of economic intervention, and the local governments made full use of fiscal and taxation policies to support enterprises to expand economic investment, which resulted in increased energy consumption, labor input, and pollutant emissions. The development of non–state-owned economy, product markets, market intermediaries, and the legal system environment have shown insignificant positive effects on ETFP in high pollution intensity regions, rejecting Hypotheses 4b, 4c, and 4e. This means that the region's non–state-owned economy development, product market development, market intermediary organization development, and legal system reforms are insufficient, and the promotion of regional ETFP is not obvious. The development of the factor market had a significant inhibitory effect on ETFP in the region ($\theta = -0.229$, $p < 0.01$), rejecting Hypothesis 4d. It is possible that the imperfect factor market in high pollution intensity regions led to factor allocation distortion, which had an inhibitory effect on ETFP. Moreover, the factor market development index of Qinghai, Gansu, Xinjiang, Yunnan, Jiangxi, and other regions was relatively low, and the allocation efficiency of production factors such as finance, labor, science, and technology was also relatively low, which greatly limited the improvement of ETFP in high pollution intensity regions.

Model (13) introduces the interaction items of R&D and marketization process. The results show that the marketization process had an insignificant negative moderating effect on innovation and ETFP, rejecting Hypothesis 5. This implies that as the degree of marketization increases, the inhibition effect of innovation on ETFP will also weaken. Therefore, it is necessary to speed up the reformation of marketization for regions with high pollution intensity, especially in the field of green development.

Last, model (14) examines the moderating effects of each sub-item of the marketization process on innovation and ETFP in high pollution intensity regions. The results show that government–market relations negatively moderated the effect of innovation on ETFP, but it was not significant, rejecting Hypothesis 5a. In regions with high pollution intensity, the government's intervention in the market was significant, which affected enterprise's perception of innovation value, potentially reducing innovation enthusiasm. Non–state-owned economic development, product market development, and factor market development positively moderated the effect of innovation on ETFP, but it was not significant, rejecting Hypotheses 5b, 5c, and 5d. The development of private economy and the market-based pricing of products and factors potentially promoted regional innovation enthusiasm and quality. The development of market intermediaries and legal system environment had a negative moderating effect on ETFP ($\theta = -0.307$, $p < 0.05$), rejecting Hypothesis 5e. This implies that with the development of market intermediaries and legal system environment, the inhibition effect of innovation on ETFP will also weaken. Therefore, it is necessary to speed up the reform of market intermediary organizations, and protect the legal rights and interests of producers and consumers for regions with high pollution intensity.

Robustness test

To test the robustness of the empirical results, we use the number of invention patents in various regions to measure the level of regional innovation and the IVTobit model for regression. The results for models (1)–(7) are listed in Table 9. Next, we employed the truncated regression model, and the results for models (8)–(14) are listed in Table 9. The results show that, except for individual variables that differ, independent variables, moderating variables, and dependent variables only changed in coefficient size. Except for inconsistency of the moderating effect of factor market development in model (7) of Table 9 with Table 7, other hypothesis tests are consistent with Table 7. Overall, the empirical results of the present paper are robust and reliable.

Conclusions and policy implications

Conclusions

The present paper draws the following research conclusions:

1 Innovation is an important driving force for the coordinated development of regional economy and environment. This conclusion is in line with the research of Ghisetti and Rennings (2014), and Chen and Golley (2014), which posited that innovation can promote green development.

2 EPU has an inhibitory effect on regional ETFP, but it positively moderates the promotional effect of innovation on ETFP. This shows that EPU and R&D can form a good coupling effect. This conclusion supports the view of Baker et al. (2016), Pastor and Veronesi (2012), Gulen and Ion (2016), Kang et al. (2014), and Jin et al. (2019), which suggest that China's EPU has a negative effect on fixed asset investment, employment, and GDP, leading to a suppression of regional economic development. The results further show that EPU has a significant positive moderating effect on innovation and ETFP, which means that, at the core, innovation investment is different from general fixed asset investment. With high EPU, companies tend to use innovation to resolve market risk and seize market advantage, which produces better economic and environmental benefits. However, this shows that EPU can be a double-edged sword, which can enhance regional ETFP only when economic policy adjustments are based on the promotion of enterprise innovation.

3 Overall, China's marketization process has a potential inhibitory effect on ETFP. This is mainly due to the underdeveloped product market and legal system environment. Moreover, the distortion of the factor market had a potential negative impact on ETFP. The results further show that when the marketization index is high, it can guide market entities to increase R&D investment and promote regional ETFP. As government intervention in the market is reduced, the development of the non–state-owned economy and the protection of intellectual property rights are strengthened, which effectively encourages enterprises to implement innovation which promotes ETFP. This conclusion shows that the effectiveness of ETFP promotion depends on the government's support for innovation, private enterprise's active investment in innovation, and the improvement of the institutional environment.

4 The impact of innovation on ETFP has strong regional heterogeneity. In regions with low pollution intensity, innovation and EPU can promote ETFP. Marketization process, including developments of product markets, market intermediaries, and the legal system environment, can prevent ETFP. In addition, the marketization process, including the development of product markets and factor markets, has a positive moderating effect. In regions with high pollution intensity, both innovation and EPU can prevent ETFP. The government–market relations and the development of factor markets have a significant inhibitory effect on ETFP. The development of market intermediaries and the legal system environment has a negative moderating effect.

Policy implications

1 Innovation powers China's ETFP. On the one hand, to improve firm's capability of independent innovation, the Chinese government should encourage enterprises to step up R&D intensity, large and medium-sized industrial

Table 9 Robustness test results

Models	Substitution variables							Truncated regression						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
$lnPAT_{t-2}$	0.086***	0.098***	0.101***	0.088***	0.087***	0.084***	0.099***	0.059***	0.070***	0.071***	0.060***	0.057***	0.044***	0.053***
	(6.27)	(7.33)	(7.50)	(6.36)	(7.05)	(5.36)	(6.31)	(5.34)	(6.32)	(6.42)	(5.34)	(5.48)	(3.57)	(4.25)
$lnEPU_{t-2}$		− 0.127***	− 0.127***						− 0.082***	− 0.088***				
		(− 4.88)	(− 4.92)						(− 4.00)	(− 4.24)				
$lnMI_{t-2}$				− 0.093	− 0.080						− 0.010	− 0.027		
				(− 1.62)	(− 1.53)						(− 0.27)	(− 0.76)		
$lngov\_mar_{t-2}$						0.055	0.008						0.046	0.079**
						(1.25)	(0.17)						(1.41)	(2.28)
$lnnon\_state_{t-2}$						0.043	0.072**						0.017	0.008
						(1.56)	(2.23)						(1.19)	(0.31)
$lnproduct\_mar_{t-2}$						− 0.171***	0.097						− 0.230***	− 0.054
						(− 2.75)	(1.27)						(− 3.89)	(− 0.75)
$lnfactor\_mar_{t-2}$						0.008	0.066**						0.008	0.033
						(0.29)	(2.47)						(0.42)	(1.52)
$lnlaw\_mar_{t-2}$						− 0.026*	− 0.032						− 0.021*	0.001
						(− 1.69)	(− 1.53)						(− 1.88)	(0.06)
$lnR\&D_{t-2} \times lnEPU_{t-2}$			0.036**							0.024*				
			(2.20)							(1.71)				
$lnR\&D_{t-2} \times lnMI_{t-2}$					0.123***							0.102***		
					(7.31)							(5.80)		
$lnR\&D_{t-2} \times lngov\_mar_{t-2}$							0.102***							0.105***
							(2.69)							(3.06)
$lnR\&D_{t-2} \times lnnon\_state_{t-2}$							0.027*							0.004*
							(1.70)							(1.74)
$lnR\&D_{t-2} \times lnproduct\_mar_{t-2}$							0.002							0.004
							(0.06)							(0.12)
$lnR\&D_{t-2} \times lnfactor\_mar_{t-2}$							0.060***							0.017
							(3.45)							(1.22)
$lnR\&D_{t-2} \times lnlaw\_mar_{t-2}$							0.003**							0.011**
							(2.34)							(2.22)
lnEI	0.057*	0.090***	0.089***	0.057*	0.031	0.056*	0.022	0.012	0.043	0.043	0.012	0.002	0.018	0.007
	(1.66)	(2.67)	(2.65)	(1.67)	(0.99)	(1.63)	(0.69)	(0.41)	(1.49)	(1.51)	(0.43)	(0.08)	(0.67)	(0.26)
lnEXP	0.004	0.004	0.003	0.006	0.008	0.031*	0.014	0.002	0.003	0.003	0.002	− 0.006	0.019	0.003
	(0.22)	(0.25)	(0.20)	(0.34)	(0.55)	(1.69)	(0.81)	(0.13)	(0.23)	(0.24)	(0.14)	(− 0.52)	(1.39)	(0.23)
lnFDI	0.131***	0.150***	0.151***	0.148***	0.138***	0.116***	0.099***	0.088***	0.104***	0.105***	0.090***	0.101***	0.068***	0.064***
	(6.32)	(7.41)	(7.45)	(6.57)	(6.78)	(4.68)	(4.25)	(5.57)	(6.55)	(6.64)	(5.12)	(5.96)	(3.72)	(3.53)
lnFD	− 0.005	0.007	0.005	− 0.001	0.020	0.009	0.016	0.010	0.016	0.015	0.010	0.022	0.016	0.023
	(− 0.25)	(0.37)	(0.24)	(− 0.05)	(1.10)	(0.47)	(0.85)	(0.67)	(1.15)	(1.07)	(0.70)	(1.62)	(1.08)	(1.63)
_cons	0.763***	0.144	0.170	0.807***	0.764***	0.815***	0.492	0.750***	0.348**	0.317**	0.755***	0.789***	0.852***	0.690***

Table 9 (continued)

Models	Substitution variables							Truncated regression						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	(5.43)	(0.78)	(0.92)	(5.68)	(5.87)	(5.36)	(2.65)	(6.21)	(2.27)	(2.05)	(6.19)	(6.58)	(6.07)	(3.87)
Wald χ^2	85.53***	115.80***	119.38***	89.50***	158.17***	108.50***	188.93***	63.98***	81.95***	84.72***	63.97***	101.46***	84.83***	113.98***
AR	39.77***	54.81***	57.31***	40.92***	50.79***	29.30***	41.65***							
Wald test	3.93**	4.39**	3.87**	3.52*	4.65**	3.60*	11.46***							
Adj R^2	0.9875	0.9875	0.9876	0.9875	0.9875	0.9878	0.9882							
Observations	270	270	270	270	270	270	270	237	237	237	237	237	237	237

The z-statistics are in parentheses. ***, **, and * indicate significance at the 1, 5, and 10% levels, respectively. AR represents the robustness test of weak instruments. Wald test represents an exogenous exclusion test

enterprises to establish R&D institutions, or enterprises to establish collaborative innovation centers with universities and scientific research institutions. In addition, the intensity of energy-saving and environmental technology and process innovations should be strengthened to push enterprises to transform from high-consumption, high-pollution, low value-added development to high-quality development with low carbon and energy conservation. On the other hand, the government is suggested to set up a major project pool of key and generic technologies in the industry and continue to support the fundamental research to break through the bottleneck of key technologies.

2 EPU can inhibit regional ETFP, whereas EPU and R&D form a good coupling effect. In light of this, when relevant departments frequently formulate and adjust economic policies, they should adhere to the principle of benefiting corporate innovation to diminish the negative effect of EPU. The governments ought to commit themselves to build a benign economic environment to stimulate the innovation vitality of enterprises. Especially in the current condition with increasing economic downward pressure and the constraints of resources and environment, the government should maintain the goals of economic growth, energy conservation, and emission reduction, and to avoid short-sighted policies when formulating economic goals.

3 Future market reforms should focus on the following aspects. First, China must further reduce excessive government intervention in the market, accelerate the reform of administrative approval system, promote negative list management system, let the market play the decisive role in allocating resources, and improve the efficiency of government work. Second, the intensive level of non–state-owned economy should be raised to improve the utilization efficiency of resources and energy. Third, China should optimize the pricing mechanism of resources and energy and the trading mechanisms of energy-consuming rights, carbon emission rights, water-consuming rights, and emission rights to improve transaction efficiency. Fourth, China must further improve the quality of the labor force and scientific and technological results and introduce the foreign investment of low-pollution industries. Fifth, China must ameliorate relevant laws and regulations concerning environmental protection, IPR protection, and the protection on economic behaviors of market players to ensure the legal operation of market mechanism.

4 From the perspective of regional variations, innovation, EPU, and marketization, low pollution intensity regions can significantly promote ETFP. Therefore, these regions should further improve and consolidate science and technology innovation policies, accelerate policy reform for green innovation, and implement market-oriented reforms for green development. However, for regions with high pollution intensity, green innovation support should be increased to avoid excessive pursuit of economic

efficiency and damage environmental quality, which is achievable by accelerating the cultivation of product markets and factor markets, reducing government intervention, increasing market-based pricing of resources, energy, and carbon emission rights, and guiding the flow of high-quality production factors to the region.

Limitations and further research

The present study also has certain limitations, which provide directions for future research. First, although the number of invention patents was used in the robustness tests, the type of patents was not considered. In future studies, energy-saving and environmentally friendly patents can be used to measure the level of green innovation in the region and measure the impact of green innovation on ETFP. Second, data on the marketization process comes from the report published by Wang et al. (2017) of the National Institute of Economics. Due to the difference in statistical indicators between the 2011 and 2016 reports and only having data of 2008–2014 in the 2016 report, the present study performs linear fitting based on existing data to predict the data of other years, which may deviate from the actual scenario. Third, due to the availability of data, the EPU index data used in the present paper is at the national level instead of at the province level, which may produce bias in regional heterogeneity analysis. Future studies can evaluate the EPU level in each province by developing a measurement tool for the various provinces in China, and further study its impact on innovation and environmental quality. Fourth, the present study only considered the linear effects of innovation, economic policy uncertainty, and the process of marketization on regional ETFP. Future research can further explore the nonlinear effects of these factors.

Availability of data and materials The datasets used during the current study are available from the corresponding author on reasonable request.

Authors' contributions B.Y.: conceptualization, methodology, writing—original draft preparation, software and revising. C.L.: data collection and processing. X.X.: data collection, writing—reviewing and editing. All authors read and approved the final manuscript.

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Compliance with ethical standards

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