The impact of economic policy uncertainty on PM2.5 pollution—evidence from 25 countries

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Abstract

We conduct theoretical and empirical study on the impact of economic policy uncertainty on PM2.5 pollution. Economic policy uncertainty has important impact on PM2.5 pollution through investment channel and innovation channel. Specifically, according to real option theory, increase in economic policy uncertainty can reduce investment, thereby reducing PM2.5 pollution. However, increase in economic policy uncertainty can hinder corporate's innovation activities, which in turn make PM2.5 pollution increase. Therefore, the impact of economic policy uncertainty on PM2.5 pollution depends on the combination effect of these two different effects. Furthermore, using 25 countries' unbalanced panel data and fixed effects estimation methods, we empirically test the impact of economic policy uncertainty on PM2.5 pollution. The results show that, with the increase of economic policy uncertainty, countries' PM2.5 pollution has significantly decreased. In addition, economic policy uncertainty has heterogeneous effect on countries' PM2.5 pollution. Compared with countries who have higher R&D input, increase in economic policy uncertainty makes the reduction of PM2.5 pollution in countries with relatively lower R&D input higher. By changing the measurement methods of economic policy uncertainty and PM2.5 pollution indicators, and using 2SLS methods to estimate the models, the conclusions of the paper are robust. Finally, we put forward corresponding policy implications.

Keywords Economic policy uncertainty · PM2.5 pollution · Investment · Innovation · Heterogeneous effect

Introduction

Since global financial crisis in 2008, the world economy begins to recover slowly, and people's living standards have gradually improved. However, in recent years, economic counter-globalization trends, Brexit, coronavirus (COVID-19) pandemic, and Sino-US economic and trade frictions have made the current global economic development facing many challenges. In order to promote economic growth, many countries' governments have implemented

a series of economic stimulus policies. The implementation of these economic policies, on the one hand, can make domestic economy out of recession as soon as possible and promote economic development. On the other hand, frequently implemented economic policies have also increased the uncertainty of economic policies faced by the economies, which are not conducive to the development of the real economy. Indeed, increase in economic policy uncertainty has important impact on economic development, and many economists have analyzed these effects. For example, economists have analyzed the impact of economic policy uncertainty on corporate investment, innovation behavior, economic growth, financial stability, employment, and have obtained rich research conclusions. Furthermore, economic policy uncertainty could influence regional environmental pollution. Environmental pollution is still an important challenge faced by countries in the world today. For example, air pollution is one of the focuses of attention in recent years, especially PM2.5 pollution. PM2.5 air pollution has an important impact on people's physical and mental health, as well as medical

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Fig. 1 World PM2.5 air pollution. Data resource: World bank WDI database

expenditure and economic development (Yang & Zhang, 2018; Pangaribuan et al., 2019; Signoretta et al., 2019; Dong et al., 2020; Guan et al., 2021b). Among the many air pollutants, PM2.5 pollution has become the main pollutant in recent years, especially in developing countries, such as China (Xu & Lin, 2018; Wu et al., 2020). And it has attracted the attention of many economists. PM2.5 pollutants are small, highly active, and easy to carry toxic and harmful substances and have a long residence time in the atmosphere and a long transportation distance. Thus, PM2.5 pollution has become the fifth leading cause of death, which caused 4.2 million deaths and 103.1 million disability-adjusted life years in 2015 (Cohen et al., 2017; Liu et al., 2019; Zhang et al., 2021). Therefore, it has a greater impact on human health and atmospheric environmental quality. Figure 1 has shown that, currently, nearly 91% population in the world has exposed to the levels of PM2.5 air pollution which are exceeding WHO guideline value. Donkelaar et al. (2014) argue that the PM2.5 concentrations above the WHO guideline level have increased from 22% in 1998–2000 to 30% in 2010–2012. And it is an important leading risk factor for premature mortality (Lim et al., 2012).

PM2.5 pollution is closely related to economic development, and economic policy uncertainty has important impact on economic development. Therefore, what impact will economic policy uncertainty have on PM2.5 pollution and what is the impact mechanism? Economists have not answered these questions. In addition, scholars have argued that increase in economic policy uncertainty will reduce corporate innovation (Xu, 2020), so will the impact of economic policy uncertainty on PM2.5 pollution be different due to country's innovation behavior? Currently, economists have not conducted in-depth research on the above issues. In view of this, based on the unbalanced panel data of 25 countries and using fixed effects estimation methods, we deeply study the relationship between economic policy uncertainty and

PM2.5 pollution from theoretical mechanisms and empirical tests. The study not only expands the economic policy uncertainty theory and environmental pollution theory, but also has important implications for the government's environmental policies.

Compared with previous studies, the main contribution of this paper is as following: Firstly, we analyze the determinants of PM2.5 pollution from a new view, which is economic policy uncertainty. Many scholars test the effect of socioeconomic factors or urbanization on the PM2.5 pollution, but they do not explore the effect of economic policy uncertainty on PM2.5 pollution. According to real option theory and corporate innovation theory, this paper explores the impact mechanism of economic policy uncertainty on PM2.5 pollution. Secondly, based on 25 countries' unbalanced panel data, this paper empirically tests the impact of economic policy uncertainty on PM2.5 pollution. Moreover, by dividing different samples, we also empirically test the heterogeneous effect of economic policy uncertainty on PM2.5 pollution in different countries, so we get more interesting results. Finally, in order to increase the robustness of the empirical results, we conduct robustness checks by changing the measurement methods of the economic policy uncertainty and PM2.5 pollution indicators, and using 2SLS methods to estimate the econometric models. In short, this paper not only reveals the relationship between economic policy uncertainty and PM2.5 pollution, but also provides some policy implications for reducing environmental pollution and promoting sustainable economic development.

The remaining structure of this paper is as following: The second part is literature review. The third part we explain the impact mechanism of economic policy uncertainty on PM2.5 pollution. The fourth part introduces the empirical strategy. The fifth part introduces the empirical results. Finally, we give the conclusions and policy implications.

Literature review

The impact of economic policy uncertainty on economic development and environmental pollution has always been the key issues of academic research (Bloom, 2007; Baker et al., 2012, 2016; Pirgaip & Dinçergök, 2020). Economists have found that increase in uncertainty inhibits corporate investment (Bloom et al., 2007; Julio & Yook, 2012; Stein & Stone, 2013; Dejuán & Ghirelli, 2018; Liu & Zhang, 2019). According to the theory of real option, the increase in uncertainty makes firm reduce current investment and increase future investment to obtain higher value, so firm will reduce current investment activities (Bernanke, 1983; McDonald & Siegel, 1986; Pindyck, 1990; Pindyck & Solimano, 1993; Leahy & Whited, 1996; Guiso & Parigi, 1999; Bulan, 2005). As a form of uncertainties, economists have justified that economic policy uncertainty has a large negative impact on corporate investment. For example, Wang et al. (2014) use data from Chinese listed companies to empirically test the impact of economic policy uncertainty on corporate investment. They find that increase in economic policy uncertainty reduces corporate investment. However, if the firm has a higher rate of return on investment capital, uses more internal financing or the firm is a non-state-owned enterprise, then the negative impact of economic policy uncertainty on corporate investment can be reduced. Kang et al. (2014) also find that the increase in economic policy uncertainty significantly inhibits corporate investment. This negative impact is greater for firms with higher economic policy uncertainty and during periods of economic recession. Gulen and Ion (2015) analyze the impact of policy uncertainty on corporate investment behavior based on the theory of real option and the irreversibility of investment. They find that the increase in policy uncertainty inhibits corporate capital investment. Moreover, this inhibitory effect is stronger for firms with relatively high degree of irreversibility of investment and relatively high dependence on government expenditures. Jens (2017) maintains that increase in political uncertainty reduces corporate investment. An empirical study by Drobetz et al. (2018) using the economic policy uncertainty index constructed by Baker et al. (2016) and firm-level data from 21 countries also finds that increase in economic policy uncertainty reduces corporate investment. They argue that economic policy uncertainty distorts the relationship between investment and capital cost. Liu and Zhang (2019) using data from China's listed companies also find that increasing economic policy uncertainty hinders corporate investment, but economic policy uncertainty has no impact on state-owned enterprises. Akron et al. (2020) conduct an empirical study using data from US hospital industry

companies and find that the increase in economic policy uncertainty reduces hospitality company's investment. In addition, economic policy uncertainty also has an important impact on enterprises' R&D investment or innovation behavior. For example, Stein and Stone (2013) argue that uncertainty encourages the R&D spending of enterprises. Atanassov et al. (2015) regard US gubernatorial elections as an exogenous source of government policy uncertainty and empirically test the impact of political uncertainty on corporate R&D investment. They find that rising political uncertainty has increased corporate R&D investment, and this impact is even stronger in fiercely competitive elections regions, in industries that are politically sensitive and difficult to innovate, and in companies with higher growth value and greater product market competition. However, some economists have found that the increase in economic policy uncertainty inhibits corporate R&D or innovation. For example, Xu (2020) argues that the increase in uncertainty of government economic policies increases the cost of capital of enterprises, which in turn reduces enterprise innovation. Companies with more severe credit constraints and companies that rely more on external finance suffer more negative effects. Finally, some economists have found that increase in economic policy uncertainty leads to a decline in employment (Leduc & Liu, 2012; Mulligan, 2014; Nodari, 2014; Baker et al., 2016), and increase in corporate cash holdings (Demir & Ersan, 2017), reduce financial stability (Phan et al., 2020), reduce trade credit (D'Mello & Toscano, 2020), and is not conducive to economic growth (Nilavongse et al., 2020). Overall, most scholars have justified that increase in economic policy uncertainty can significantly reduce corporate investment and innovation. From another point of view, corporate investment behavior and innovation behavior could influence regional PM_{2.5} pollution (Cheng et al., 2020; Yan et al., 2021). Therefore, economic policy uncertainty may influence PM_{2.5} pollution through investment and innovation channel.

In addition, there are few research about the effect of economic policy uncertainty on PM_{2.5} pollution. But some economists have analyzed the impact of economic policy uncertainty on environmental pollution, carbon emissions (Jiang et al., 2019), and renewable energy investment. Romano and Fumagalli (2018) point out that policy uncertainty has an important impact on the low-carbon technology investment behavior of the economy. Jiang et al. (2019) argue that economic policy uncertainty will affect the business environment of economic entities, which in turn affects the economic entities' decision-making, such as carbon emissions. They use US industry-level data from January 1985 to August 2017 to empirically test the linear and non-linear granger causality between economic policy uncertainty and carbon emissions. Their results show that,

overall, there is no causality between the uncertainty of US economic policy and the median quantile carbon emission growth. However, in terms of the growth of carbon emission in the upper and lower quantile, the impact of the US economic policy uncertainty on carbon emissions has granger causality. From an industry perspective, residential sector, electric power sector, and transportation sector, the impact of economic policy uncertainty on the carbon emissions of these industries and the overall impact are consistent. However, economic policy uncertainty has no significant impact on the carbon emissions of the commercial sector. Furthermore, Jiang et al. (2019) argue that economic policy uncertainty affects a country's carbon emissions by affecting the macroeconomic situation and household consumption decisions. Pirgaip and Dinçergök (2020) get similar results with Jiang et al. (2019). They use data from G7 countries to analyze the granger causal relationship between economic policy uncertainty, energy consumption, and carbon emissions. They find that economic policy uncertainty has a significant unidirectional causal relationship to Japan's energy consumption. Economic policy uncertainty has a significant unidirectional causal relationship to carbon emissions in the USA and Germany. Economic policy uncertainty has a significant unidirectional causal relationship both in energy consumption and CO₂ emissions in Canada. However, there is a bidirectional causality between economic policy uncertainty and energy consumption in Italy. Different from the above research, Adedoyin and Zakari (2020) get different point of view. They analyze the impact of economic policy uncertainty on carbon emissions using the UK's annual data from 1985 to 2017. Their empirical results find that economic policy uncertainty reduces Britain's carbon emissions in the short term. But in the long run, the increase in economic policy uncertainty will increase carbon emissions. Amin and Dogan (2021) also maintain that increase in economic policy uncertainty causes carbon emissions increasing in China. Wen and Zhang (2022) argue that in China, economic policy uncertainty will harm the environment and increase industrial pollution. Because economic policy uncertainty can encourage local authorities to reduce environmental supervision. Yu et al. (2021) construct provincial economic policy uncertainty index and test the effect of economic policy uncertainty on firm carbon emissions. They find that economic policy uncertainty has significantly positive impact on firms' carbon emission intensity. In addition, Liu et al. (2020) use panel data from 52 Chinese traditional energy companies and 116 renewable energy companies to analyze the impact of economic policy uncertainty on the investment behavior of different types of companies. Their results show that the increase in economic policy uncertainty hinders the investment behavior of coal and petroleum companies. On the contrary, the

increase of economic policy uncertainty has promoted the investment behavior of solar energy, geothermal energy and other renewable energy companies.

Finally, many scholars have analyzed the determinants of PM_{2.5} pollution. For example, Wang et al. (2018) find that democracy, political globalization, and urbanization have important impact on the PM_{2.5} concentration level of G20 countries. Dong et al. (2018) have verified that there is an environmental Kuznets curve relationship between PM_{2.5} pollution and per capita GDP in the long run. Ji et al. (2018) argue that income, urbanization level, and service industry development have important effects on PM_{2.5} pollution. Jiang et al. (2018) find that compared with other sectors, industrial activities cause more PM_{2.5} pollution. City size and residents' activities will also have important impact on PM_{2.5} pollution. Cao et al. (2019) show that there is a U-shaped relationship between a prefecture's party secretary's years in office and its average annual PM_{2.5} level. In addition, there are many studies that analyze the influencing factors of PM_{2.5} pollution from the perspective of urbanization. For example, the research results of Wang et al. (2019) show that urbanization has a significant effect on PM_{2.5} concentration, but the degree of its impact varies among groups of countries with different development levels. Dong et al. (2020) using panel data from 216 countries from 1990 to 2016 show that the relationship between urbanization and PM_{2.5} pollution density are in an inverted U-shaped curve. That is, urbanization will initially increase the density of PM_{2.5} pollution. However, urban agglomeration effect and technological progress will reduce PM_{2.5} density in the late stage of urbanization. Zou and Shi (2020) using the Bayesian hierarchical spatial quantile regression model also find that total population, urbanization rate, industrialization level, and energy efficiency have important effects on the level of PM_{2.5} pollution concentration. Finally, some economists analyze the determinants of PM_{2.5} pollution based on environmental regulations and government policy perspectives. For example, Zhang et al. (2020) using the spatial panel model show that environmental regulations and industrial structure rationalization have significantly reduced PM_{2.5} pollution. Xie et al. (2020) also find that China's central heating policy effectively reduces PM_{2.5} concentration.

In summary, existing studies have conducted in-depth discussions and analyses on the impact of economic policy uncertainty on carbon emissions, green investment, and economic development. However, there are few studies on the impact of economic policy uncertainty on PM_{2.5} pollution. And the relevant impact mechanisms have not been analyzed. Moreover, current studies select single country or G7 countries sample to analyze the impact of economic policy uncertainty on environmental pollution or CO₂

emissions, and the sample size is relatively small. In view of this, in this paper we will use the unbalanced panel data of 25 countries from 1976 to 2018 as the research sample to conduct theoretical and empirical research on the impact of economic policy uncertainty on PM2.5 pollution. This study has important implications for reducing environmental pollution.

Theoretical mechanism and hypothesis development

Economic policy uncertainty has an important impact on economic development (Ahsan et al., 2021), and economic development will influence PM2.5 pollution (Luo et al., 2021). Therefore, the economic policy uncertainty could affect PM2.5 pollution through the channel of economic development. Specifically, the increase of economic policy uncertainty hinders enterprise investment and employment (Ghosal & Ye, 2015; Liu & Zhang, 2019), so it is not conducive to economic development. On the one hand, increase in economic policy uncertainty makes companies more cautious about the cost of future government regulation and tax policy changes, and their investment behavior will become more cautious (Kang et al., 2014). In addition, according to the real option theory, the increase in economic policy uncertainty makes the value of enterprises waiting for investment and increasing future investment greater, thus inhibiting the current investment behavior of enterprises (Gulen and Ion, 2015). The decline in firm's investment means a decline in economic output, which in turn will reduce PM2.5 pollution. Increase economic output may generate more pollutant emissions and worsen environmental quality (Ji et al., 2018). Thus, decline in economic output could reduce PM2.5 pollution. On the other hand, increase in economic policy uncertainty may lead to an increase in investment in renewable energy (Liu et al., 2020). Corporate investment, including foreign direct investment, has an important impact on environmental pollution (Xin & Zhang, 2020). Therefore, increase in investment in renewable energy will further lead to a decrease in PM2.5 pollution.

However, increase in economic policy uncertainty could inhibit the innovative behavior of enterprises, which will increase PM2.5 pollution. Atanassov et al. (2015) conduct an empirical study by considering the state elections in the USA as an exogenous source of government policy uncertainty. They find that the increase in political uncertainty has led to an increase in corporate R&D investment. That is, compared with non-election years, the company increased R&D investment by 4.6% on average in election years. However, Jiang et al. (2020) find that the more stable the local policy environment, the more stable the innovation subsidies for enterprises, which promote the number

of patent applications by enterprises. Conversely, if the policy environment is unstable, the innovation subsidies of enterprises will be affected, which is not conducive to the innovation of enterprises. Xu (2020) also finds that the increase in economic policy uncertainty has led to a decline in both innovation input and innovation output. Because the increase in economic policy uncertainty makes the cost of capital for enterprises increase, which in turn reduces their innovation activities. Cui et al. (2021), Guan et al. (2021a), and Lou et al. (2022) also confirm that economic policy uncertainty is significantly negatively related with corporate innovation. In short, the increase of economic policy uncertainty restrains the innovation behavior of enterprises. Furthermore, the decline of enterprise innovation behavior is not conducive to the improvement of green production efficiency, thus worsening environmental quality (Chien et al., 2021; Yan et al., 2021). Therefore, through the innovation channel, economic policy uncertainty will increase the country's PM2.5 pollution.

Overall, the impact of economic policy uncertainty on PM2.5 pollution may have positive effect and negative effect, which ultimately depend on the combination effect of the two effects. Therefore, we propose the following two research hypotheses:

Hypothesis 1a: The increase in economic policy uncertainty reduces corporate investment and increases investment in renewable energy, thereby reducing PM2.5 pollution. However, the increase of economic policy uncertainty will also hinder the innovative behavior of enterprises, which will increase the PM2.5 pollution. Overall, the negative effect of economic policy uncertainty on PM2.5 pollution is greater than the positive effect of economic policy uncertainty on PM2.5 pollution. Therefore, the increase in economic policy uncertainty reduces PM2.5 pollution.

Hypothesis 1b: The increase in economic policy uncertainty reduces corporate investment and increases investment in renewable energy, thereby reducing PM2.5 pollution. However, the increase of economic policy uncertainty will also hinder the innovative behavior of enterprises, which will increase the PM2.5 pollution. Overall, the positive effect of economic policy uncertainty on PM2.5 is greater than the negative effect of economic policy uncertainty on PM2.5 pollution. Therefore, economic policy uncertainty increases PM2.5 pollution.

Furthermore, the impact of economic policy uncertainty on PM2.5 pollution may also be heterogeneous and depends on countries' R&D input scale. Economic policy uncertainty hinders corporate innovation (Cui et al., 2021; Lou et al., 2022). Innovation, especially green technology innovation,

Fig. 2 The impact mechanism of economic policy uncertainty on PM2.5 pollution

could significantly reduce PM2.5 pollution (Feng et al., 2021; Shan et al., 2021; Chien et al., 2021; Khattak et al., 2022). So, economic policy uncertainty could affect a country's PM2.5 pollution through corporate innovation channel. However, there are large differences in the innovation behavior of countries, which will make the impact of economic policy uncertainty on PM2.5 heterogeneous across countries. Economists have found that economic policy uncertainty has heterogeneous effect on environmental pollution. For example, Pirgaip & Dinçergök (2020) show that the impact of economic policy uncertainty on CO2 emissions of G7 countries is very different. Generally, countries with higher R&D input have strong innovation capabilities. Thus, the increase in economic policy uncertainty has a greater negative impact on the country's corporate innovation activities. That is, increase in economic policy uncertainty can cause a big decline in country's innovation activity. Conversely, countries with lower R&D input have limited innovation capabilities. The negative effect of economic policy uncertainty on countries R&D input may be small. Therefore, the impact of increase in economic policy uncertainty on the innovation activities of these countries is relatively weak.

Hence, we propose the following research hypothesis:

Hypothesis 2: The influence of economic policy uncertainty on PM2.5 pollution may be heterogeneous with country's innovation activities.

In summary, economic policy uncertainty affects country's PM2.5 pollution through corporate investment channel and innovation channel, as shown in Fig. 2. In addition, this impact depends on country's R&D input, so it is heterogeneous in different countries. Next, we will use cross-country unbalanced panel data from 25 countries and panel data fixed effects estimation methods to empirically test the overall impact of economic policy uncertainty on PM2.5 pollution and the heterogeneous impact on different countries.

Empirical strategy

Empirical model

In order to empirically test the impact of economic policy uncertainty on PM2.5 pollution, according to Dong et al. (2020) and Pirgaip and Dinçergök (2020), we use the following econometric model:

$$PM_{it} = \beta_0 + \beta_1 EPU_{it} + \varphi' X_{it} + \omega_i + \mu_{it}$$

In the model, i represents the country and t means year. PM is variable of country's PM2.5 pollution emissions. EPU is variable of economic policy uncertainty, and variable set X includes a series of control variables, including real GDP per capita, square terms of real GDP per capita, financial development, and so on. ω_i is the country fixed effect and μ_{it} is the random error term. β_0 and β_1 are the parameters to be estimated. In addition, we use the fixed effects method to estimate the econometric model.

Variables and data

The dependent variable is PM2.5 pollution emission. The data for the PM2.5 pollution are from the World Bank's World Development Indicators (WDI) database and use mean annual exposure level (micrograms per cubic meter) to measure. For the robustness checks section, we use the population exposed to levels exceeding WHO guideline value (% of total) to measure PM2.5 pollution.

For economic policy uncertainty (EPU) variable, there are many ways to measure. We use the data of Baker et al. (2016) to construct the economic policy uncertainty index in the paper. Many economists have used this indicator when analyzing the impact of economic policy uncertainty on the real economy, such as Liu et al. (2020), Sha et al. (2020), and Xu (2020). However, in the Baker et al. (2016)'s research, the economic policy

Table 1 Definition of variables

Variable	Definition	Data source	Literature
PM	PM2.5 pollution, Mean annual exposure (micrograms per cubic meter)	World bank WDI	Dong et al. (2020)
EPU	Economic policy uncertainty	Baker et al., 2016	Adedoyin and Zakari (2020), Liu et al. (2020), Sha et al. (2020)
lnGDPPC	Logarithm of real GDP per capita	World bank WDI	Ji et al. (2018), Pirgaip and Dinçergök (2020)
lnGDPPC2	Square of logarithm of real GDP per capita	World bank WDI	Dong et al. (2018), Gao et al. (2019), Ding et al. (2020)
FD	Financial development, domestic credit to private sector (% of GDP)	World bank WDI	Churchill et al. (2018)
Fixed	Gross fixed capital formation (% of GDP)	World bank WDI	Wang et al. (2018)
Trade	Trade value (% of GDP)	World bank WDI	Du et al. (2018)
Pop	Population growth rate (annual %)	World bank WDI	Wang et al. (2018)
Urban	Urban population (% of total population)	World bank WDI	Xu and Lin (2018)

uncertainty data are monthly data, and all variables such as PM2.5 pollution in this paper are annual data. Therefore, the monthly data of economic policy uncertainty need to be converted into annual data. According to Phan et al. (2020), we take the annual arithmetic average of the monthly data of 12 months each year to calculate the annual economic policy uncertainty data for each country. Currently, the economic policy uncertainty data include only 25 countries in Baker et al. (2016)'s research.¹ Thus, based on data availability and research needs, the sample used in this paper mainly includes data from 25 countries from 1976 to 2018. These countries include the USA, Australia, Belgium, Brazil, Canada, Chile, China, Colombia, Croatia, France, Germany, Greece, India, Ireland, Italy, Japan, South Korea, Mexico, Netherlands, Pakistan, Russia, Singapore, Spain, Sweden, and UK.

In addition, except economic policy uncertainty, according to Churchill et al. (2018), Pirgaip and Dinçergök (2020), and Dong et al. (2020)'s research, we also control other factors that may affect PM2.5 pollution emissions. These variables are included in the variable set *X*, as follows:

The logarithmic value of real GDP per capita (lnGDPPC), and GDPPC is the real GDP per capita of each country which is calculated by the price of USD in 2020 as the base period.

The square term of lnGDPPC (lnGDPPC2). The reason for controlling the real GDP per capita and its square term is to test the environmental Kuznets effect (Grossman & Krueger, 1995; Ding et al., 2019). That is: the increase in the level of economic development will deteriorate the environmental quality at the beginning. But after a threshold value, as the level of economic development increases, environmental pollution will decline. Therefore,

the relationship between economic development and environmental pollution may be an inverted U-shaped curve.

Financial development (FD) is measured by the ratio of domestic credit to private sector to GDP.

Fixed is measured by gross fixed capital formation (% of GDP).

Trade is the ratio of import trade and export trade to GDP. Import and export trade have important impact on PM2.5 pollution emissions, so we also control this variable in the paper.

Pop is population growth rate.

Urban is the urbanization rate, which is expressed by urban population (% of total population).

Finally, the definition information of all these variables is shown in Table 1.

Descriptive statistics

Table 2 is the descriptive statistics of main variables. It can be seen from Table 2 that the maximum value of PM is 97.5994, the minimum value is 6.1143, and the average value is 21.2221. The maximum value of EPU is 6.4691,

Table 2 Descriptive statistics

Variable	Obs	Mean	Std. Dev	Min	Max
PM	261	21.2221	18.9371	6.1143	97.5994
EPU	261	1.4120	0.8319	0.1299	6.4691
lnGDPPC	261	9.9548	1.0507	6.8951	10.9572
lnGDPPC2	261	100.1978	19.4577	47.5422	120.0609
FD	244	122.7842	59.8130	20.8142	278.1189
Fixed	261	22.6815	6.1776	11.5442	45.6899
Trade	261	73.1925	62.5699	16.6795	420.4305
Pop	261	0.7137	0.6638	−1.8537	2.4534
Urban	261	77.1845	15.8421	29.2350	100.0000

¹ <http://www.policyuncertainty.com/>.

Table 3 Basic results

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
EPU	− 1.2054*** (0.2093)	− 1.2054** (0.4512)	− 0.9611* (0.5229)	− 0.8916* (0.4800)	− 0.9133* (0.5285)	− 0.8301 (0.4924)	− 0.7905* (0.4397)	− 0.7693* (0.4191)	− 0.8216* (0.4074)
lnGDPPC			− 2.0809 (1.4056)	8.3986* (4.0216)	8.2075 (8.116)	4.7732*** (1.3081)	5.9110* (3.2578)	3.6982 (5.5308)	9.5423*** (2.8040)
lnGDPPC2				− 0.5918*** (0.1156)	− 0.5577 (0.4028)	− 0.3934*** (0.0295)	− 0.4896* (0.2684)	− 0.3745 (0.3082)	− 0.6022*** (0.1369)
FD					− 0.0055 (0.0076)	− 0.0036 (0.0067)	− 0.0033 (0.0064)	− 0.0048 (0.0071)	0.0044 (0.0072)
Fixed						0.1280 (0.0802)	0.1737* (0.0988)	0.2103 (0.1247)	0.1892 (0.1277)
Trade							0.0319 (0.0325)	0.0353 (0.0327)	0.0407 (0.0332)
Pop								0.5595* (0.3025)	− 0.6413 (0.5784)
Urban									− 0.1721*** (0.0230)
Constant	22.8050*** (0.2989)	22.8050*** (0.5926)	43.1989*** (13.3448)	− 1.9173 (38.8588)	− 2.2122 (40.1256)	12.2567 (30.713)	7.046 (32.5484)	17.0321 (26.3106)	− 5.0346 (39.7357)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	261	261	261	261	244	244	244	244	244
R-squared	0.1237	0.1237	0.1548	0.1674	0.1579	0.1772	0.1987	0.2061	0.2215
Number of country	25	25	25	25	25	25	25	25	25

Note: Each model in the table is estimated by panel data fixed effects method. Robust standard errors are reported in parenthesis. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively

while the minimum value is 0.1299, and the average value is 1.4120. Next, we will empirically test the impact of economic policy uncertainty on PM_{2.5} pollution emissions.

Results

Basic results

Table 3 shows the basic regression results. In Table 3, model 1 only controls the economic policy uncertainty (EPU) variable and uses standard errors. It can be seen that the coefficient of EPU is negative and significant at the 1% level. This means that the increase in economic policy uncertainty has significantly reduced regional PM_{2.5} pollution, which is consistent with Anser et al. (2021)'s conclusions. They find that, in the short run, a 1% increase in world uncertainty index mitigates CO₂ emissions by 0.11%. On the one hand, according to the real option theory, increase in EPU can significantly reduce corporate investment (Gulen and Ion 2015; Drobetz et al., 2018; Liu and Zhang 2019), while decline in investment can reduce regional PM_{2.5} emission. Moreover, the increase in EPU can also increase

investment in renewable energy (Liu et al., 2020), which will also reduce regional PM_{2.5} pollution. But on the other hand, the increase in EPU will increase capital costs and inhibit the R&D investment of enterprises (Xu, 2020), which is not conducive to the green innovation of enterprises, thereby increasing PM_{2.5} pollution emissions. Therefore, the impact of EPU on PM_{2.5} pollution depends on the combination effect of these two effects. From the empirical results, the increase in economic policy uncertainty will eventually reduce PM_{2.5} pollution emissions. This verifies Hypothesis 1a, and Hypothesis 1b has not been verified. The negative effect of economic policy uncertainty on PM_{2.5} pollution is greater than the positive effect of economic policy uncertainty on PM_{2.5} pollution. Therefore, the increase in economic policy uncertainty reduces PM_{2.5} pollution. And the results are similar to the conclusion of Adedoyin and Zakari (2020)'s research. In models 2–9 of Table 3, we use robust standard errors. In model 2, only the variable EPU is controlled, and the coefficient of EPU is still significantly negative. In models 3–9, lnGDPPC, lnGDPPC2, FD, Fixed, Trade, Pop, and Urban variables are added in sequence, and the coefficient of EPU is still significantly negative, except in model 6. Therefore,

overall, the increase in EPU significantly reduces PM_{2.5} air pollution.

Other variables have different impact on PM_{2.5} pollution. The result of model 3 shows that the coefficient of $\ln\text{GDPPC}$ is not significant, which indicates that the impact of economic development on PM_{2.5} pollution may not be significant. But in model 4, the coefficient of $\ln\text{GDPPC}$ is positive, which is significant at the 10% level. Moreover, the coefficient of $\ln\text{GDPPC}^2$ is negative and significant at the 1% level. That is, the increase in economic activities at the beginning deteriorates the environmental quality. However, after a certain threshold is exceeded, as economic scale increases, the service industry in the economy grows rapidly, and new technologies are also used in large quantities. Therefore, the environment quality will be improvement and PM_{2.5} pollution emissions also decrease. This shows that the relationship between PM_{2.5} pollution and economic development is an inverted U-shaped curve, which verifies the environmental Kuznets curve, and is consistent with Dong et al. (2018), Du et al. (2018), and Ding et al. (2019)'s research. Although the coefficients of $\ln\text{GDPPC}$ and $\ln\text{GDPPC}^2$ in model 5 and model 8 are not significant, they are also positive and negative values respectively in other models. In addition, in model 6, model 7, and model 9, the existence of the environmental Kuznets curve is verified. The impact of financial development and international trade on PM_{2.5} emissions are not obvious, which can be seen from model 5, model 6, model 7, model 8, and model 9. The empirical result of model 7 shows that the fixed capital formation increases PM_{2.5} emissions, which is not conducive to the improvement of environmental quality. This is consistent with the conclusion obtained by Wang et al. (2018). The increase in population growth rate has significantly increased PM_{2.5} emissions, as shown in model 8. Generally, the increase in population growth rate increases energy consumption, which in turn increases PM_{2.5} pollution emissions. Finally, the result of model 9 shows that with the increase of urbanization, PM_{2.5} pollution decreases significantly, which is consistent with the research of Ji et al. (2018) and Xu and Lin (2018). The agglomeration effect and technological progress effect of urbanization will significantly reduce PM_{2.5} pollution (Dong et al., 2020).

In short, economic policy uncertainty can influence PM_{2.5} pollution through investment channel and innovation channel. The former channel reduces PM_{2.5} pollution, while the latter channel increases PM_{2.5} pollution. Therefore, the impact of EPU on PM_{2.5} pollution depends on the combination effect of these two channels. From the empirical results, the increase in economic policy uncertainty significantly reduces PM_{2.5} emissions. The impacts of other variables on PM_{2.5} pollution are different. There is an inverted U-shaped curve relationship between economic development and PM_{2.5} pollution. Fixed capital formation and population

growth rate increase PM_{2.5} pollution, while urbanization reduces PM_{2.5} pollution. The impacts of other variables on PM_{2.5} pollution are not significant.

Heterogeneous effect

The increase in economic policy uncertainty has significantly reduced regional PM_{2.5} pollution emissions through investment channel and innovation channel. However, this effect may be heterogeneous. For example, Pirgaip and Dinçergök (2020) maintain that the impact of economic policy uncertainty on carbon emissions and energy consumption are very different within G7 countries. Dong et al. (2020) find that the impact of urbanization on PM_{2.5} pollution is also very different in OECD countries, non-OECD countries, and poor countries. Hence, the impact of economic policy uncertainty on PM_{2.5} pollution is likely to be dependent on countries' R&D input. Therefore, we reclassify the sample according to countries' R&D input. Here we use countries' research and development expenditure (% of GDP) to express R&D input. And these data are from world bank WDI database. If country's R&D input is greater than the average value of the R&D input in the sample, then it is defined as a country with higher R&D input, and vice versa. Finally, after we classify the sample according to R&D input, the higher R&D countries include the USA, Australia, Canada, Germany, UK, France, Belgium, Iceland, Japan, South Korea, Netherlands, Singapore, and Sweden. And there are 12 lower R&D countries, which are Brazil, Chile, China, Colombia, Croatia, Greece, India, Italy, Mexico, Pakistan, Russia, and Spain. Then, the results are shown in Tables 4 and 5.

Higher R&D input countries

First, we conduct empirical tests on samples in which R&D input is greater than the average value, which are the higher R&D input countries. The results are shown in Table 4. Model 1 in Table 4 uses standard errors, while the other 8 models use robust standard errors. It can be seen from model 1 in Table 4 that the coefficient of EPU is -0.6595 , which is significant at the 1% level. This once again shows that the increase in economic policy uncertainty significantly reduces PM_{2.5} pollution, and verifies Hypothesis 1a. After re-estimating the model using robust standard errors in model 2, the coefficient of EPU is still significantly negative. Then adding $\ln\text{GDPPC}$, $\ln\text{GDPPC}^2$, FD, Fixed, Trade, Pop, and Urban variables in turn, in model 3, model 4, model 8, and model 9, the coefficient of EPU is still significantly negative. In addition, by comparing the results of Tables 3 and 4, it can be seen that the coefficient of EPU in Table 4 is greater than the coefficient of EPU in Table 3. This means that for countries with higher R&D input, the increase in economic policy uncertainty will

Table 4 The relationship between EPU and PM2.5 pollution in countries with higher R&D input

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
EPU	−0.6595*** (0.1502)	−0.6595*** (0.1835)	−0.3343** (0.1435)	−0.2498* (0.1330)	−0.2357 (0.1358)	−0.2395 (0.1374)	−0.2401 (0.1358)	−0.2417* (0.1340)	−0.2218* (0.1072)
lnGDPPC			−3.4997*** (0.9056)	32.6831*** (10.2426)	35.7990*** (10.0863)	35.0326*** (10.0009)	35.2445*** (10.7761)	35.7336*** (10.8691)	28.5601*** (8.7756)
lnGDPPC2				−1.7896*** (0.5363)	−1.9687*** (0.5278)	−1.9340*** (0.5234)	−1.9432*** (0.5559)	−1.9687*** (0.5561)	−1.5825*** (0.4644)
FD					0.0027 (0.0036)	0.0027 (0.0036)	0.0028 (0.0036)	0.003 (0.0028)	0.0027 (0.0030)
Fixed						−0.0122 (0.0219)	−0.0145 (0.0257)	−0.0209 (0.0484)	−0.0536 (0.0618)
Trade							−0.0012 (0.0099)	0.0021*** (0.0005)	0.0005 (0.0110)
Pop								0.0727 (0.4112)	0.0491 (0.4102)
Urban									−0.0953* (0.0460)
Constant	13.8266*** (0.2237)	13.8266*** (0.2514)	50.6740*** (9.5497)	−131.6532*** (48.2619)	−144.6831*** (47.6186)	−140.1794** (47.2272)	−141.2343*** (51.2797)	−143.4010** (51.9627)	−102.1191*** (41.8471)
Country FE	Yes	Yes	Yes	Yes		Yes	Yes	Yes	Yes
Obs	142	142	142	142		129	129	129	129
R-squared	0.1309	0.1309	0.3045	0.3608		0.3252	0.3258	0.3263	0.3454
Number of country	13	13	13	13		13	13	13	13

Note: Each model in the table is estimated by panel data fixed effects method. Robust standard errors are reported in parenthesis. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively

Table 5 The relationship between EPU and PM2.5 pollution in countries with lower R&D input

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
EPU	−2.0004*** (0.4346)	−2.0004** (0.7458)	−1.8390* (0.9855)	−1.7595* (0.8930)	−1.3259* (0.7191)	−0.8530*** (0.2080)	−0.9088 (0.7123)	−0.8564** (0.3396)	−0.4116 (0.6339)
lnGDPPC			−1.0553 (2.1481)	22.4417*** (7.0445)	30.0229 (32.0702)	36.3268 (29.3611)	33.2244 (26.0643)	32.8671 (26.2253)	58.2554* (31.1124)
lnGDPPC2				−1.4192*** (0.4881)	−1.8068 (1.8009)	(2.405) (−1.7763)	−2.2415 (1.5813)	−2.2438 (1.6253)	−3.3807* (1.8125)
FD					−0.0336*** (0.0046)	−0.0212 (0.0289)	−0.0162 (0.0279)	−0.0183 (0.0276)	−0.0046 (0.0198)
Fixed						0.4014** (0.1798)	0.4221** (0.1471)	0.4632** (0.1843)	0.4882** (0.1739)
Trade							0.0915 (0.0978)	0.0738 (0.1129)	0.1122 (0.0952)
Pop								−0.6701 (1.1626)	−1.0788 (1.1773)
Urban									−0.6373* (0.2898)
Constant	33.6173*** (0.5883)	33.6173*** (0.9292)	43.0387** (18.4097)	−51.8543 (111.4448)	−85.2708 (138.2654)	−103.2727 (119.9097)	−94.3685 (105.4417)	−90.3146 (103.0505)	−187.2331 (134.0382)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	119	119	119	119	115	115	115	115	115
R-squared	0.1666	0.1666	0.1729	0.1933	0.2195	0.2987	0.3318	0.3344	0.379
Number of country	12	12	12	12	12	12	12	12	12

Note: Each model in the table is estimated by panel data fixed effects method. Robust standard errors are reported in parenthesis. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively

make the country's innovation activities drop a lot, so this will greatly increase PM2.5 pollution emissions. This will mitigate the negative effect of economic policy uncertainty on PM2.5 pollution through investment channel. Therefore, for higher R&D input countries, the increase in economic policy uncertainty makes PM2.5 pollution decrease little. Furthermore, it can be seen from Table 4 that there is still an inverted U-shaped curve relationship between PM2.5 pollution and economic development. The coefficient of Trade variable in model 8 is significantly positive. That is, the increase in international trade increases PM2.5 pollution. This means that trade leads to more economic activities, which in turn increases PM2.5 pollution. Model 9 shows that urbanization significantly reduces PM2.5 pollution.

Lower R&D input countries

Table 5 reports the empirical results by using sample of countries whose R&D input is less than the average value. Similarly, model 1 in Table 5 uses standard errors, while other models use robust standard errors. As in model 1, the coefficient of EPU is −2.0004, which is significant at the 1% level. That is, the increase of economic policy uncertainty significantly reduces PM2.5 pollution. After adding

lnGDPPC, lnGDPPC2, FD, Fixed, Trade, Trade, Pop, and Urban variables in sequence, except for model 7 and model 9, the coefficients of EPU in models 3–8 are all significantly negative. And the coefficients of economic policy uncertainty in Table 5 are smaller than that of economic policy uncertainty in Table 3. That is, for countries with lower R&D input, the increase in economic policy uncertainty causes decline in investment, which in turn leads to decline in PM2.5 emissions. However, for countries with relatively lower R&D input, the increase in economic policy uncertainty leads to a smaller decline in R&D input, which also leads to a limited increase in PM2.5 pollution. Therefore, overall, for countries with lower levels of R&D input, increase in economic policy uncertainty will have a greater negative effect on the reduction of PM2.5 pollution.

In short, the effect of economic policy uncertainty on PM2.5 emissions is heterogeneous. That is, for countries with higher R&D input, the increase in economic policy uncertainty will greatly reduce R&D investment or innovation, which will increase PM2.5 pollution. Therefore, to a certain extent, the increase in economic policy uncertainty makes the reduction of PM2.5 pollution in countries with higher R&D input smaller. However, for countries with lower R&D input, their own R&D input is relatively small,

Table 6 Robustness tests with new EPU index

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
EPU2	−0.7296*** (0.1677)	−0.7296*** (0.2514)	−0.5347* (0.2974)	−0.4924* (0.2739)	−0.4865* (0.281)	−0.4217 (0.2648)	−0.3924 (0.2313)	−0.3751* (0.2174)	−0.3382 (0.2180)
lnGDPPC			2.5417** (1.1780)	9.8442 (8.2792)	8.7453 (8.1895)	4.9848 (6.2888)	7.1320* (3.7412)	3.8060 (5.503)	10.5825 (9.3465)
lnGDPPC2				−0.6970 (0.4378)	−0.6079 (0.4215)	−0.4261 (0.3443)	−0.5232* (0.2872)	−0.4019 (0.3175)	−0.6628 (0.4659)
FD					−0.0062 (0.0084)	−0.0042 (0.0073)	−0.0038 (0.0070)	−0.0055 (0.0078)	−0.0048 (0.0078)
Fixed						0.1376 (0.0843)	0.1848* (0.1042)	0.223 (0.1323)	0.1962 (0.1326)
Trade							0.0330 (0.0331)	0.0364 (0.0335)	0.0426 (0.0343)
Pop								−0.5836 (0.6065)	−0.6733 (0.6130)
Urban									−0.1991*** (0.0355)
Constant	22.2523*** (0.2657)	22.2523*** (0.355)	47.2797*** (11.3391)	−6.2413 (38.4729)	−2.9721 (39.1536)	12.7752 (29.2426)	7.4662 (31.1793)	17.9377 (25.0016)	−7.8732 (41.3045)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	261	261	261	261	244	244	244	244	244
R-squared	0.0746	0.0746	0.1234	0.1411	0.1319	0.1543	0.1772	0.1852	0.2063
Number of country	25	25	25	25	25	25	25	25	25

Note: Each model in the table is estimated by panel data fixed effects method. Robust standard errors are reported in parenthesis. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively

so increase in economic policy uncertainty will cause more reduction of PM_{2.5} pollution. Therefore, compared with countries with higher R&D input, the increase in economic policy uncertainty makes the reduction of PM_{2.5} pollution in countries with lower R&D investment greater. This also verifies the Hypothesis 2.

Robustness checks

In order to verify the robustness of the above empirical results, we use three methods to conduct robustness checks, which are changing the calculation method of EPU, changing the calculation method of PM_{2.5} index, and estimating the models using 2SLS methods.

First, Baker et al. (2016)'s economic policy uncertainty data are monthly data, and we calculate the annual value of economic policy uncertainty through the annual weighted average method. In order to ensure the reliability of the annual economic policy uncertainty data, according to Demir and Ersan (2017), we use the economic policy uncertainty data in December of each year as the EPU value of the current year. The estimation results are shown in Table 6. It can be seen that in model 1 and model 2, the EPU coefficient

is significantly negative. After adding each control variable, the EPU coefficients are significantly negative in model 3, model 4, model 5, and model 8. Therefore, the results still show that the increase in economic policy uncertainty significantly reduces PM_{2.5} pollution.

Secondly, we use population exposed to levels exceeding WHO guideline value (% of total) to calculate PM_{2.5} pollution emissions, and estimate the models. The results are shown in Table 7. Obviously, in the 9 models of Table 7, the coefficients of EPU are all significantly negative, which again shows that the increase of economic policy uncertainty significantly reduces PM_{2.5} pollution.

Finally, considering the potential endogenous problem, we use the one-period lagged EPU variable as the instrumental variable, and use the panel data instrumental variable methods to estimate the econometric model. The estimation results are shown in Table 8. In model 1, the coefficient of EPU is significantly negative. After controlling a series of other variables, as shown in the results of models 2–8, the coefficients of EPU are still significantly negative. In addition, the environmental Kuznets assumption still holds, as shown in model 7. Fixed and Trade variable significantly increase PM_{2.5} emissions, as shown in model 5, model 6, model 7, and model 8. The result of model 8 shows that

Table 7 Robustness tests with new PM2.5 index

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
EPU	−3.8753*** (0.6499)	−3.8753*** (0.9104)	−3.5084*** (0.8673)	−3.0121*** (0.9808)	−3.3961*** (1.1107)	−3.2330*** (1.0572)	−3.2551*** (1.0458)	−3.3378*** (1.0335)	−2.9396*** (1.0371)
lnGDPPC			−3.1253 (3.8505)	71.7252** (29.8796)	82.1814** (36.3547)	75.4465** (35.1676)	74.8117** (35.6302)	83.4524** (39.5895)	109.9767** (46.584)
lnGDPPC2				−4.2269** (1.8304)	−5.0064** (2.2741)	−4.6842** (2.2144)	−4.6305* (2.2487)	−5.0799** (2.4461)	−6.1135** (2.5971)
FD					0.0403 (0.0285)	0.0441 (0.0327)	0.0439 (0.0326)	0.0500 (0.0351)	0.0521 (0.0355)
Fixed						0.2510 (0.2932)	0.2254 (0.2896)	0.0824 (0.2602)	−0.0133 (0.2957)
Trade							−0.0178 (0.036)	−0.0308 (0.0445)	−0.0059 (0.052)
Pop								2.1847 (1.9995)	1.8134 (1.8857)
Urban									−0.7810 (0.5055)
Constant	82.2022*** (0.9279)	82.2022*** (1.1957)	112.8323*** (38.4338)	−209.4131* (115.3398)	−238.7299* (136.8561)	−210.3545 (132.8933)	−207.4473 (135.1133)	−246.4415 (153.8023)	−346.5943* (182.6315)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	261	261	261	261	244	244	244	244	244
R-squared	0.1314	0.1314	0.1386	0.2047	0.1974	0.2053	0.2061	0.218	0.2522
Number of country	25	25	25	25	25	25	25	25	25

Note: Each model in the table is estimated by panel data fixed effects method. Robust standard errors are reported in parenthesis. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively

the agglomeration effect and technological progress effect caused by the increase in urbanization have significantly reduced PM2.5 pollution.

In summary, by changing the calculation methods of economic policy uncertainty and PM2.5 indicators, and selecting appropriate instrumental variable for 2SLS estimation, the empirical results still show that the increase in economic policy uncertainty significantly reduces PM2.5 pollution. Thus, the empirical results of the paper are robust.

Conclusions and policy implications

Reducing environmental pollution is an important way to promote sustainable economic development. This paper conducts theoretical and empirical study on the impact of economic policy uncertainty on PM2.5 pollution. Economic policy uncertainty has important impact on PM2.5 pollution through investment channel and innovation channel. Specifically, according to real option theory, increase in economic policy uncertainty can reduce investment, thereby reduce PM2.5 pollution. However, increase in economic policy uncertainty can hinder corporate's innovation activities, which in turn make PM2.5 pollution increase. Therefore, the impact of economic policy uncertainty on

PM2.5 pollution depends on the combination effect of these two different effects. Furthermore, using 25 countries' unbalanced panel data and fixed effects estimation methods, we empirically test the impact of economic policy uncertainty on PM2.5 pollution. The results show that, with the increase of economic policy uncertainty, countries' PM2.5 pollution has significantly decreased. In addition, economic policy uncertainty has heterogeneous effect on countries' PM2.5 pollution. Compared with countries that have higher R&D input, increase in economic policy uncertainty makes the reduction of PM2.5 pollution in countries with relatively lower R&D input higher. By changing the measurement methods of economic policy uncertainty and PM2.5 pollution indicators, and using 2SLS methods to estimate the models, the conclusions of the paper are robust.

The paper may have some limitations. Firstly, we use country-level data to do the empirical analysis. But there are many differences across countries, for example, development level of manufacturing industry, culture, and political regime, etc. All these factors may influence the PM2.5 pollution. We cannot control all these variables in the empirical models. Secondly, the economic policy uncertainty data are annual data in the paper. But in Baker et al. (2016)'s research, the economic policy uncertainty data are monthly data. So annual data may

Table 8 2SLS estimation results

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
EPU	−1.5085*** (0.2774)	−1.0279*** (0.3086)	−1.0214*** (0.3136)	−1.0762*** (0.3629)	−0.8974** (0.3683)	−0.9101** (0.3654)	−0.8848** (0.3653)	−0.7702** (0.3724)
lnGDPPC		3.6387*** (0.8926)	−2.8540 (6.5215)	−2.9461 (7.3531)	5.1326 (7.3285)	3.4491 (7.3255)	12.4538* (6.4394)	−0.8478 (7.6848)
lnGDPPC2			−0.0433 (0.3565)	−0.8229* (0.4107)	0.9039** (0.4075)	−0.0458 (0.4087)	−0.9589*** (0.3139)	−0.1017 (0.4172)
FD				−0.0054 (0.0061)	−0.0037 (0.0060)	−0.0033 (0.0060)	−0.0048 (0.0061)	−0.0047 (0.0060)
Fixed					0.1293** (0.0576)	0.1648*** (0.0605)	0.2050*** (0.0667)	0.1773*** (0.0670)
Trade						0.0249* (0.0129)	0.0285** (0.0131)	0.0337** (0.0132)
Pop							0.5589 (0.3876)	0.6267 (0.3857)
Urban								−0.1697** (0.0834)
Constant	22.8540*** (0.3831)	58.5609*** (8.7038)	55.0799* (29.9599)	55.1534* (33.1475)	64.8616** (33.0311)	56.3863* (33.0502)	65.2300* (33.5485)	48.744 (34.0758)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	257	257	257	240	240	240	240	240
R-squared	0.0089	0.6749	0.6697	0.6388	0.7529	0.7412	0.7498	0.8260
Number of country	25	25	25	25	25	25	25	25

Note: Each model in the table is estimated by panel data fixed effects method. Robust standard errors are reported in parenthesis. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively

lose some information about economic policy uncertainty. Thirdly, we classify the sample according to countries R&D input and find that the effect of economic policy uncertainty on PM2.5 pollution is heterogeneous and depends on country's R&D input scale. However, there may be some other factors which also will cause the heterogeneous effect of economic policy uncertainty on PM2.5 pollution. Finally, we analyze the influence mechanism of economic policy uncertainty on PM2.5 pollution, but lack mathematical model to describe this effect. Thus, for future research, we will do more work in the following aspects. First, we will try to use micro-level data, for example, firm-level data within one country, to empirical test the effect of economic policy uncertainty on environmental pollution. Thus, we may get more interesting empirical results. Second, monthly data may have more information about economic policy uncertainty. For future work, we will try to use monthly economic policy uncertainty data to do the empirical analysis. Furthermore, we may find more factors that could influence the effect of economic policy uncertainty on PM2.5 pollution. Finally, we will construct mathematical models to straightforward analyze the effect on economic policy uncertainty on environmental pollution.

The study has important policy implications. First of all, for the government, while introducing a series of economic policies to promote economic development, it must also be inclined to promote investment in renewable energy. Secondly, government should create a good external and financial environment, increase continuous subsidies for innovation, and promote enterprise innovation, especially green technology innovation. Moreover, continuous subsidies for corporate innovation are also important. This requires the government to support corporate innovation in financing policies and pay attention to the sustainability of subsidies. Finally, government should also increase efforts to promote urbanization, continuously improve the effect of talent agglomeration and technological progress, and provide continuous impetus for the green development of the real economy. In short, increase in economic policy uncertainty can reduce PM2.5 pollution emissions. But this does not mean that the government should frequently introduce a series of economic stimulus policies to improve environmental quality and reduce environmental pollution. Because if the government has introduced too many economic policies, it is not conducive to the innovation activities of enterprises, and it will also deteriorate the environmental quality. For the sustainable development,

it is essential to increase investment in renewable energy, eliminate outdated production capacity, optimize industrial structure, increase subsidies for innovation and promote urbanization to reduce regional PM2.5 pollution and improve environmental quality.

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