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Analysis of Coordinated Development of Energy and Environment in China's Manufacturing Industry under Environmental Regulation: A Comparative Study of Sub-Industries

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Abstract: In order to explore the impact of environmental regulation on the coordinated development of energy and the environment with the background of governance transition, we propose a three-stage integrated approach and use the panel data of China's manufacturing industry 27 sub-sectors during the period of 2006–2015. In the first stage, according to the environmental pollution intensity, the manufacturing industry is divided into heavily polluting industry, moderately polluting industry, and lightly polluting industry. The second stage is employed the slacks-based measure (SBM)-undesirable method to study the sub-industries' green energy-environmental efficiency under different environmental pollution intensities. Besides, the dynamic changes of technical innovation and efficiency among different industries are analyzed through the Malmquist productivity index. For the purpose of investigating the transmission mechanism of the Porter's hypothesis and exploring the compound effects of environmental regulation and governance transition on green development, in the third stage, we use the panel data analysis to conduct more in-depth research on the relationship between environmental regulation, governance transition, and technical innovation. Results show that the highest average green energy-environmental efficiency is lightly polluting industry, which is 0.52, followed by the heavily polluting industry at 0.40, and the lowest is the moderately polluting industry, which is 0.32. By decomposing total factor productivity, heavily polluting industry is at the forefront of technical innovation. Panel data analysis results indicate that investment in research and development and governance transition could promote the growth of total factor productivity for manufacturing.

Keywords: manufacturing industry; energy-environmental efficiency; total factor productivity; environmental regulation; transmission mechanism; governance transition

1. Introduction

China's economy is developing at a high speed, and manufacturing has become the mainstay of the national economy. China's manufacturing output surpassed the United States and became the world's largest manufacturing country in 2010 [1]. In 2017, China's industrial added value was 279.997 trillion Yuan, an increase of 6.4% over 2016. The added value of the six high energy-consuming industries increased by 3.0%, accounting for 29.7% of the industrial added value. Hence, while the development of the manufacturing industry is driving economic growth, it also poses certain harm to the environment. The development of manufacturing and economic growth are based on the consumption energy and raw materials, but carbon dioxide emission is mainly caused by the burning of fossil energy. Zhao, Ke et al. [2] pointed out that more than 50% of fossil fuels are consumed directly or indirectly by the manufacturing industry. Manufacturing is responsible for nearly a third of global energy consumption and 36% of carbon dioxide emissions [3]. Consequently, the goals of improving energy efficiency and reducing emission reduction have placed great demand on the manufacturing industry. At present, the main development patterns of China's manufacturing industry are high energy consumption and low efficiency. That is, as the manufacturing industry is in the process of development, more consideration is given to the basic function of the product, while ignoring the coordinated development of energy consumption and environment. The 2016 World Environmental Performance Index Report released by Yale University showed that China's environmental performance ranked 179th out of 180 countries [4]. Problems such as environmental pollution and resource depletion have occurred, which have seriously restricted the sustainable development of China's economy and society. Hence, it is extremely urgent to realize the green development of the manufacturing industry and improve the energy efficiency.

In order to promote sustainable development and green growth, according to the China–US Joint Statement on Climate Change issued by the 22nd APEC Economic Leaders' Meeting in November 2014, the Chinese government promised to stop increasing carbon dioxide emissions by 2030 [5]. Generally, governments around the world use environmental regulations to regulate the sustainable development of enterprises [6]. For instance, the government has enacted environmental regulations to reduce pollutant emissions, including command and control policies and market-related policies [7]. In 2013, it issued the Action Plan for Air Pollution Prevention and Control. In 2014, the Environmental Protection Law of the People's Republic of China was amended, and the most stringent environmental protection law in Chinese history was officially implemented on 1 January 2015. Additionally, the Chinese government has taken some policy measures to break this development bottleneck, such as energy conservation assessment (ECA) and environmental impact assessment (EIA) [8]. Thus, the creation of a resource-saving and environment-friendly society are imperative. Besides, when formulating environmental policies, the government attaches great importance to the relationship between technological progress and the environment, which is expected that technical innovation will play an important role in solving environmental problems while maintaining productivity growth [9]. In addition to that, the total investment for industrial environmental pollution control has also maintained a rising trend to achieve sustainable development, as shown in Figure 1 (China Statistical Yearbook). Furthermore, we learned from a World Bank survey that China's environmental costs have reached 12% of GDP.

Palmer et al. [10] and Gray et al. [11] hold the view that environmental regulation could impose an additional burden on companies in two ways, which will adversely affect competitiveness: The first is that the company will face direct costs from pollution control activities; the second is that under the limited financial budget, companies will generate opportunity costs because they are committed to complying with regulations, rather than investing in other profitable opportunities. However, Porter [12] and Porter and Van der Linde [13] argue that well-designed environmental regulation can encourage companies to carry out more innovative activities (i.e., improve the productivity and product quality of the enterprise), thereby offsetting the cost brought by environmental protection and improving the profitability of the company in the market, which may make domestic enterprises gain a competitive advantage in the international market. At the same time, it is possible to increase industrial productivity. This is known as Porter hypothesis. This hypothesis has attracted more attention and has been discussed by many scholars. Hence, green development promoted by technical innovation and environmental regulation has become a hot topic.

The level of manufacturing development is one of the important indicators for measuring the developmental level of a country or region. As is known to all, since the reform and opening up, China's economy has achieved rapid growth, and the process of reform and opening up is also the process of governance transition from a planned economic system to a market economic system. But this high-speed growth is based on high pollution and high energy consumption. China has entered a new era of development, under the background of China's transition economy, the government has promoted the reform of state-owned enterprises, which promotes the development of foreign enterprises and private enterprises. China's economic transition model is gradualism [14,15]. In 2013, the government report pointed out that the "basic role" of the market in resource allocation was revised to a "decisive role" and the supply-side structural reform was implemented in 2016. Moreover, the development of China's manufacturing industry is shifting from extensive development to intensive. Hence, during the transition period of economic governance, in the face of growing contradiction between economic development and environmental protection, for the sake of better realizing economic sustainable development, environmental factors must be considered. In China, manufacturing is not only the industry with the largest energy consumption, but also the industry with the largest carbon dioxide emissions. Therefore, studying the green energy-environmental performance and analyzing the dynamic changes of technical innovation and efficiency of manufacturing is decisive for achieving sustainable development in the context of governance transition. In this study, we use the panel data of China's manufacturing sub-industries during 2006 to 2015 to explore the green energy-environmental efficiency and dynamic changes of technical innovation and efficiency under environmental regulation. In order to explore the path of achieving coordinated development of energy and environment under environmental regulation during the period of governance transition, we propose an integrated evaluation approach. According to environmental pollution intensity, the manufacturing industry is divided into light pollution industry, heavy pollution industry, and moderate pollution industry. We measure the green energy-environmental efficiency of China's manufacturing sub-industries under the environmental regulations, and further decompose the total factor productivity to explore the dynamic changes of technical innovation and efficiency. From the heterogeneity of the manufacturing industry, the transmission mechanism of the Porter hypothesis and the compound effects of environmental regulation and governance transition on the green productivity are investigated.

The rest of the paper is as follows: Section 2 presents the literature review, methodology is described in Section 3, data sources and processing are listed in Section 4, Section 5 is the empirical results, and the last part encompasses the conclusions and implications.

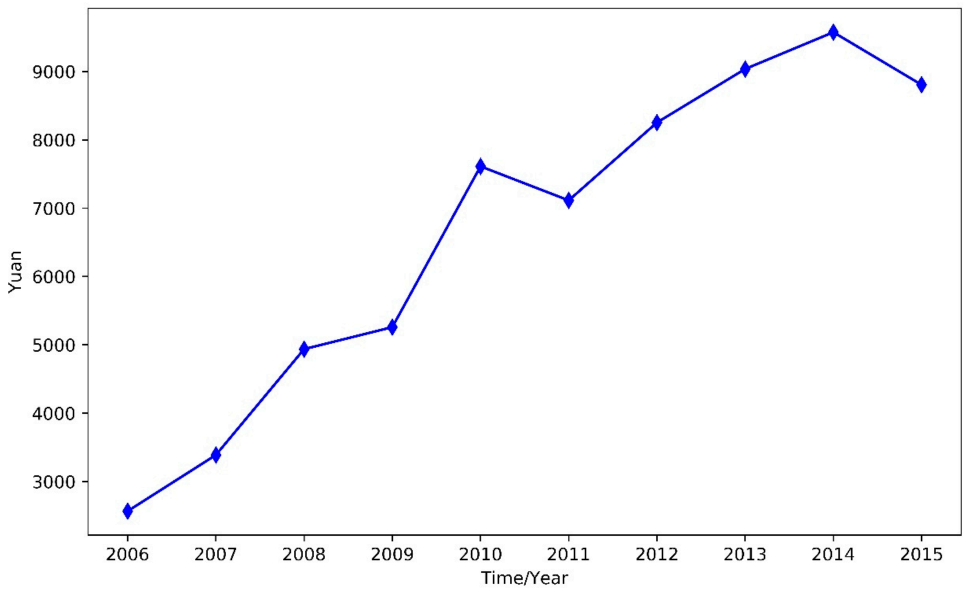

Figure 1. The total investment in industrial environmental regulation during the period of 2006–2015.

2. Literature Review

2.1. Environmental Regulation and Industry Performance

The existing literature on environmental regulation and industry performance can be categorized into two groups. The first is the impact of environmental regulation on the industrial environmental performance. Constrained by the dual mission of supporting economic growth and reducing emission, improving the green-development efficiency of China's industry will contribute to break the bottleneck of constraints and further to coordinate the development of economy and environment. Li, Fang et al. [16] measured the regional environmental efficiency during the period of 1991–2001 using the super slacks-based model considering undesirable outputs. Wu [17] proposed a new data envelopment analysis (DEA) model to analyze the data of 30 provinces and municipalities of China to evaluate the environmental efficiency. Emrouznejad and Yang [3] studied China's manufacturing industry's eco-efficiency with CO_2 emissions. Li and Lin [1] investigated the green productivity growth of China's manufacturing sectors through the Malmquist–Luenberger productivity index model. Zhang et al. [18] used the dynamic slacks-based measure (SBM) model to assess wastewater resources for research samples covering the 30 regions of China. Pan, Ai et al. [4] based their research on the large scale provincial panel data in China from 2006 to 2015 to study the internal dynamic relationship between the environment regulation, technological innovation, and energy intensity. Xie, Yuan et al. [19] employed the province-level data to estimate the industrial "green" productivity growth rates of China's 30 provinces based on the econometric model. Yuan, Ren et al. [20] employed the panel data of 28 sub-sectors in China's manufacturing industry during 2003–2013 to explore the impact of environmental regulation on technical innovation ("weak" Porter hypothesis) and eco-efficiency ("strong" Porter hypothesis).

Besides, the relationship between environmental regulation and industrial economic growth is also a hot topic for scholars to discuss. Li and Lin [21] used the super efficiency DEA model to study the relationship between investment-driven economic growth model, the industrial structure and green productivity during the period of 1997–2010 in 30 Chinese provinces. Ouyang et al. [22] adopted 30 Organization for Economic Co-operation and Development (OECD) countries' data to examine the non-linear effect of environmental regulation and economic growth on the $PM_{2.5}$ (contaminant). Chong et al. [23] tested a spatial econometric model employing panel data of the three largest urban agglomerations in China from 2003 to 2013 to examine the influence of environmental regulation on sustainable economic growth, from both theoretical and empirical perspectives.

2.2. Environmental Regulation and Technical Innovation

The traditional view is that environmental regulation is an additional cost imposed by the government on the enterprise, which reduces the international competitiveness of the enterprise. It is achieved through two aspects of the effect. On the one hand, the government implements environmental regulation; in order to meet environmental standards, enterprises must increase investment related to environmental protection, and resulting in crowding out. On the other hand, environmental regulation is equivalent to the implementation of new constraints on the production decision of the enterprise, which leads to increasing difficulty in production management and sales, and has a binding effect on the enterprise [19]. The essence of the two effects is to internalize the external costs of the environment, which is that the environmental costs borne by the society are charged by the polluting enterprises, resulting in an increase in the cost of the enterprises and loss of competitiveness. In the 1990s, Porter [12] and Porter and Claas van der Linde [13] challenged this view. They systematically explained the possibility of a "win–win" outcome between environmental protection and corporate competitiveness [24]. That is to say, more rigorous but well-designed environmental regulations (especially market-based environmental policies such as taxes, pollution permits, etc.) can spur innovation and partially or even completely offset the costs of complying with environmental regulations, making manufacturers more competitive in the international market. However, the regulatory mechanism that is at the core of the Porter hypothesis is still under debate.

The Porter hypothesis is concerned with whether environmental regulation can ultimately improve the competitiveness of enterprises through technological advancement [25]. Leiter, Parolini et al. [26] employed the European data of manufacturing industries to explore the environmental regulation on investment. Ramanathan, He et al. [27] drew inspiration from the Porter hypothesis and used nine cases studies of United Kingdom (UK) and Chinese firms to study the relationships between environmental relationships, enterprises' innovation, and private sustainability benefits. Shen, Liao et al. [28] utilized the Chinese industry in the period of 2000–2016 and adopted meta-frontier Malmquist–Luenberger to study the effect of technology gaps and pollution emissions on the total factor productivity. Hashmi et al. [29] examined the effects of environmental regulation and innovation on the carbon emission reduction of OECD countries during the period of 1999–2014. Wang et al. [30] used panel data of OECD countries' industrial sectors to analyze the stringency of environmental regulation policies and measure green productivity growth employing an extended SBM directional distance function approach. The results showed that the Porter hypothesis was validated, which is that the environmental policy had a positive impact on green productivity growth and the impact turned to adverse when the environmental regulation policy was stringent over a certain level, as the compliance cost effect was higher than innovation offset effect. Li and Chen [31] used the data obtained from the industrial pollution database and the Chinese industrial enterprise database to calculate the green total factor productivity (GTFP) at enterprise level using the Malmquist-Luenberger productivity index. The results indicated that environmental regulations would have negative impacts on enterprises' GTFP in the short run. But, in the long run, the implementation of environmental policies would achieve the win–win goal in terms of enterprises' competitiveness and environmental protection. Zhu et al. [32] based their research on the panel data of industrial enterprises in China from 2006 to 2015 to investigate the spatial features of technological innovation efficiency and examine the relationship between technology innovation efficiency and environmental regulations from a spatial perspective. The results indicated that voluntary regulation positively affected the technological innovation efficiency of industrial enterprises at the provincial level, while mandatory regulation had no significant impact.

However, there are many previous literatures that study the impact of environmental regulation on industry performance and the relationship between environmental regulation and technical innovation, but overlook the heterogeneity of the industry and the particularity of China's economic development. In fact, first, there are significant differences in pollution intensity of different industries, and the degree of impact of environmental regulations on industrial innovation activities vary. Although some studies have considered the heterogeneity of the industry, they focus on exploring the existence of the "Porter hypothesis" and lack a discussion on the transmission mechanism. Furthermore, to date, the theoretical community still lacks a clear answer as to how to set environmental regulations that can effectively guide green technical innovation and promote green economic development. Second, in China, state-owned enterprises are more likely to receive subsidies from the government. The survival pressure is lower than that of private enterprises, and the competitive pressure is relatively low. In contrast, the survival pressure of private enterprises is greater than that of state-owned enterprises, and the marketization of incentive mechanisms for private enterprises could encourage innovators to continuously breakthrough innovation. In the early stage of environmental regulation, the advantages of gradual innovation of state-owned enterprises are more obvious. But in the later stage of environmental regulation, the breakthrough innovation of private enterprises may be realized, so that green competitiveness may exceed state-owned enterprises [33]. Therefore, the innovation characteristics of different ownership enterprises show differences in the innovation stage due to different governance mechanisms. However, few studies explore this situation. Therefore, this paper considers the governance transformation in the context of China's transition economy into the model to explore China's green development trajectory under the dual influences of governance transition and environmental regulation. In order to fulfill this research gap, in this study, we propose an integrated approach. First, we employ the SBM-undesirable to evaluate the green energy-environmental efficiency of manufacturing to understand the coordinated development of energy and environment in sub-industries. Then, the Malmquist index is used to evaluate and decompose the total factor productivity to analyze the dynamic changes of technical innovation and efficiency in sub-industries. Besides, we analyze the relationship between characteristics of industry, environmental regulation, governance transition, and technical innovation at different levels of pollution intensity, as well as try to open the innovative black box mentioned in the Porter hypothesis. Lastly, we give policy suggestions on how to set environmental regulations on different industries to achieve coordinated development of energy and environment with the background of governance transition.

3. Methodology

In order to explore how to set different environmental regulations in different industries to achieve the optimal value of green development efficiency, we developed an integrated approach. The proposed integrated approach is shown in Figure 2. As demonstrated in Figure 2, this proposed approach is mainly composed of three steps: The first step, according to the environmental regulation intensity, is to divide the manufacturing into heavy pollution industry, medium pollution industry, and light pollution industry. Then, the next step is employ the SBM, considering undesirable output to measure the green energy-environmental efficiency in different polluting industries. The Malmquist index method was used to measure the dynamic changes of the technical innovation and efficiency. Lastly, we investigated the transmission mechanism of the Porter hypothesis through panel data analysis.

3.1. Industry Division

Due to the different industrial characteristics between manufacturing industries, environmental regulation has different effects on different pollution intensity industries. Therefore, it is too rough to discuss the relationship between environmental regulation and energy environment efficiency from the perspective of the industry as a whole. Regarding the classification of the manufacturing industry, the China Statistical Yearbook of the manufacturing industry is based on the National Economic Industry Classification (GB/T4754-2011) [3]. According to the China Statistical Yearbook, the manufacturing is divided into 28 sub-sectors. Due to the lack of data on the waste resources and waste materials recycling industry, we analyzed the 27 manufacturing sub-sectors in this study. In order to make the research more specific, we used Li et al.'s [34] proposed method to classify 27 manufacturing sub-sectors into heavily polluting industries, moderately polluting industries, and lightly polluting industries, according to the calculation results of pollution intensity in various industries. This classification method is based on linear standardization to calculate the pollution emission intensity of each industry, as follows:

First of all, calculating the cost of controlling pollution value of each industry's output value: $UE_{ij} = \frac{E_{ij}}{O_i}$, where E_{ij} is the emission of major pollutant j (j = 1,2, … ,n) from industry i (i = 1,2, … m), and O_i is the total output value of each industry. Then, linearly standardize the pollution emission values of various industries according to the value range of 0–1:

$$UE^s_{ij} = \left[UE_{ij} - \min\left(UE_j\right)\right] / \left[\max\left(UE_j\right) - \min\left(UE_j\right)\right] \tag{1}$$

In model (1), UE_{ij} is the original value of the indicator, $\max\left(UE_j\right)$ and $\min\left(UE_j\right)$, is the maximum and minimum values of the main pollutant j in all industries, respectively, and UE^s_{ij} is the normalized value. Also, the average scores are aggregated to obtain the average value of the pollution intensity coefficient γ^i of the industry over the years. Table 1 shows the identification results of pollution emission intensity in various industries: If $\gamma^i > 0.2042$, the industry is a heavily polluting industry. If $0.0367 < \gamma^i < 0.2042$, the industry belongs to the moderately polluting industry category. If $\gamma^i < 0.0367$, the industry is a lightly polluting industry.

Table 1. Industrial pollution intensity division result.

Pollution Emission Coefficient	Classification	Industries
$\gamma^i > 0.2042$	Heavily polluting industry	Paper products industry, oil processing industry, non-metallic products industry, chemical industry, chemical fiber manufacturing industry, ferrous metal industry, beverage manufacturing industry, textiles industry, non-ferrous metal industry
$0.0367 < \gamma^i < 0.2042$	Moderately polluting industry	Food processing industry, pharmaceutical industry, agricultural and sideline processing industry, cultural, educational, and sports products industry, leather products industry, rubber and plastics industry, garment manufacturing industry, metal products industry
$\gamma^i < 0.0367$	Lightly polluting industry	Tobacco products industry, special-purpose equipment industry, instrument and meter industry, general-purpose equipment manufacturing industry, furniture industry, wood processing industry, printing media industry, communication facilities industry, electrical machinery industry, cardboard manufacturing

3.2. SBM with Undesirable Output

Data envelopment analysis (DEA) is an efficiency evaluation method proposed by the famous American operation researchers Charnes and Cooper. It is the main method for evaluating and analyzing efficiency in numerous research methods and empirical literatures [16]. Traditional DEA models mostly use angle and radial measures to calculate the efficiency of the decision-making unit (DMU). But they can only be used from the perspective of input or output, and it is difficult to fully consider the slacks of input and output. The measure of the degree of inefficiency only includes the proportion of all inputs (outputs) that are proportionally reduced (increased). For the invalid decision unit, the slack improvement part—other than the proportional improvement part—is not reflected in the efficiency measurement of the traditional DEA model. Based on this, Tone [35] introduced the slack variable directly into the objective function, and proposed a non-radial and non-angle slacks-based measure (SBM). At the same time, the inefficiency is measured from both the input and output perspectives, avoiding the effects of radial and angular selection. The output of the basic SBM model is set to the expected output, ignoring the external negative effects of the environment generated in the production process, so the SBM model considering the undesired output is derived from the basic SBM model. Suppose the system has n DMUs, and each decision unit has m input elements, s output factors, where S_1 is the expected output factor, S_2 is the undesirable output element, and 3 elements expressed as: X, y^g, y^b are defined as follows:$X = [X_1, \ldots, X_n] \in R^{m\times n}$, $Y^g = \left[y_1^g, \ldots, y_n^g\right] \in R^{s1\times n}$, $Y^b = \left[y_1^b, \ldots, y_n^b\right] \in R^{s2\times n}$, among them, $x_i > 0, y_i^g > 0, y_i^b > 0$. The SBM model considering undesirable output can be expressed as:

$$\rho^* = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2}\frac{s_r^b}{y_{r0}^b}\right)}$$

$$\text{s.t.}\begin{cases} x_0 = X\lambda + s^- \\ y_0^g = Y^g\lambda - s^g \\ y_0^b = Y^b\lambda + s^b \\ \lambda \geq 0, s^- \geq 0, s^g \geq 0, s^b \geq 0 \end{cases} \quad (2)$$

In model (2), λ is the weight vector, s^{-},s^{g}, and s^{b} are slack variables for inputs, the expected outputs, and undesirable outputs, respectively. The objective function ρ^{*} takes a value range of (0,1), and the relationship between the objective function and the three slack variables is strictly decreasing. If and only if $\rho^{*} = 1$, the evaluated decision making unit (DMU) is efficient, and the values of the three slack variables are $s^{-} = 0$, $s^{g} = 0$, and $s^{b} = 0$. The DMU is inefficient if $0 < \rho^{*} < 1$.

3.3. Malmquist Productivity Index

When the DMU data are evaluated as panel data, including observations at multiple time points, the dynamic changes of productivity, efficiency, and technological innovation can be analyzed. This is the commonly used Malmquist total factor productivity index (TFP) analysis. The Malmquist total factor productivity index was proposed by Malmquist in 1953. Fare et al. [36] first used the DEA method to calculate the Malmquist index and further decompose the Malmquist index into two aspects: One is the evaluation of the technical efficiency change of the DMU in two periods, and the other is the change in technical innovation, which reflects the changes in the production frontier in the DEA analysis.

$$M_{i,t+1}(h_i^t, k_i^t, h_i^{t+1}, k_i^{t+1}) = \sqrt{\frac{D_i^t(h^{t+1}, k^{t+1})}{D_i^t(h^t, k^t)} \times \frac{D_i^{t+1}(h^{t+1}, k^{t+1})}{D_i^{t+1}(h^t, k^t)}} \quad (3)$$

In model (3), where h_i^t and h_i^{t+1} are the inputs of the ith in the period between t and $t + 1$, k_i^t and k_i^{t+1} are the outputs of the ith DMU in the period between t and $t + 1$. $D_i^t(h^t, k^t)$ and $D_i^{t+1}(h^t, k^t)$ are the technological level-based distance functions of the inputs and outputs between periods t and $t + 1$. The Malmquist productivity index in model (3) can be further decomposed into technical efficiency change (EC) and the technological change (TC):

$$Malmquistindex(M) = TC \times EC \quad (4)$$

The technical efficiency change (EC):

$$EC_{i,t+1} = \frac{D_i^{t+1}(h^{t+1}, k^{t+1})}{D_i^t(h^t, k^t)} \quad (5)$$

The technological change (TC):

$$TC_{i,t+1} = \sqrt{\frac{D_i^t(h^{t+1}, k^{t+1})}{D_i^{t+1}(h^{t+1}, k^{t+1})} \frac{D_i^t(h^t, k^t)}{D_i^{t+1}(h^t, k^t)}} \quad (6)$$

In the model (4), the Malmquist index represents the total factor productivity index. In model (5) EC means the technical efficiency change in two periods, which reflects changes in regulations or business management. In model (6) TC represents the technological change, which reflects the change of production frontier. The meaning of the Malmquist index is that a value greater than 1 indicates an increase in total factor productivity, and a value less than 1 indicates a decrease in total factor productivity; the same is true of EC and TC. That is, EC > 1 indicates that the technical efficiency change of the decision-making unit is continuously improving, approaching the production frontier, and vice versa, indicating that the existing technology and resources cannot be reasonably fully utilized. TC is the technological change index; that is, the impact of changes in production frontiers on decision-making units. TC > 1 indicates technological innovation or technical progress, and vice versa is technical regression.

3.4. Econometric Model

In order to explore the transmission mechanism of environmental regulation to different industries, we need to conduct more in-depth research on the relationship between environmental regulations, industrial characteristics, and technical innovation to open the black box of Porter's hypothesis. Ordinary least square estimates may be biased and inconsistent due to the neglect of individual and fixed time effects in the panel data setup. Therefore, the fixed effects or random effects in the panel data setting were considered. Hence, the research model was as follows:

$$y_{it} = \beta x_{it} + \mu_i + \varepsilon_{it} \quad (7)$$

In the formula, i indicates the sub-industry, t represents the year, μ_i is an individual effect, ε_{it} denotes the residual error term.

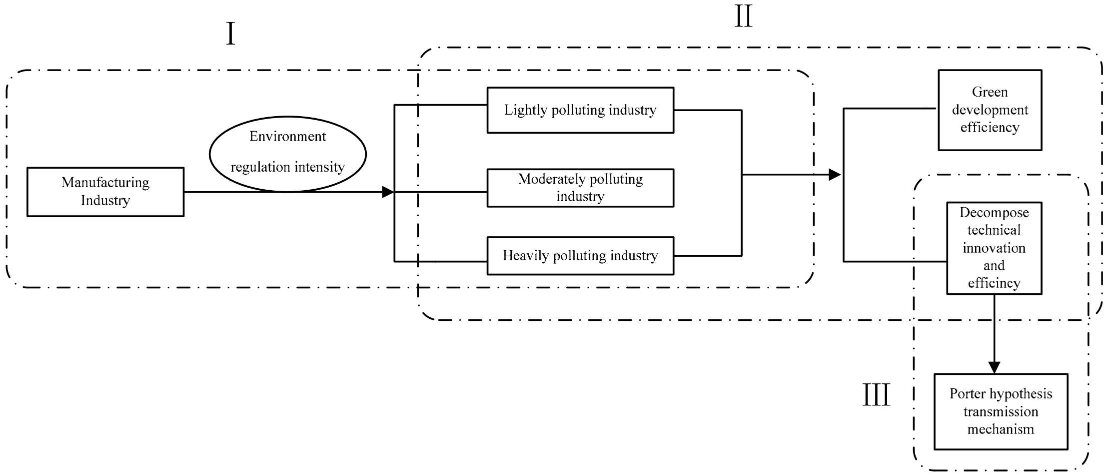

Figure 2. Proposed integrated approach to explore how to set different environmental regulations in different industries to achieve the optimal value of green development efficiency.

4. Indicators and Data

4.1. Indicators of Energy-Environment Efficiency

We employed the slacks-based model with undesirable output and the Malmquist productivity index research method to analyze China's manufacturing of the green energy-environmental efficiency and the total factor productivity during the period of 2006–2015. Capital investment, labor input, and energy input are three elements of the production process [37]. Therefore, input variables are capital stock, labor force, and energy consumption. The manufacturing industry output value is the desirable output, and the undesirable output is CO_2 emissions from the fossil fuel energy consumption. In the previous literatures, the capital stock is estimated by using the perpetual inventory method. The calculated equation is as follows:

$$K_t = I_t + (1 - \eta)K_{t-1} \quad (8)$$

In model (8), K_t and K_{t-1} are the capital stock of the t and $t - 1$ period, respectively. I_t is the capital investment amount in the t period, and η is the depreciation rate. However, it is difficult to obtain the subdivided industrial data. Huang, Zheng et al. [38] point out one method that is basically consistent with the perpetual inventory method, which is that the net value of fixed asset is the balance between the initial value of fixed assets and accumulated depreciation. The net value of fixed assets is changed into the constant price of the year 2000 (100 million RMB). The data can be collected from the China Industrial Statistical Yearbook. Liu et al. [39] explore the relationship between technological and manufacturing capacities on job creation. Previous literatures usually use the number of employees to indicate labor input. Therefore, this paper employed the average number of employees in various industries as an indicator of labor input (measured in 10,000 persons), and the data were collected from the China Industrial Statistical Yearbook. In terms of energy input, this paper used the total energy consumption of manufacturing (million ton of coal equal, Mtce), which was obtained from the China Energy Statistical Yearbook.

For the expected output indicator, we use the industrial production value of each industry, transformed into the 2010 constant price, measured in 100 million RMB, and collected from the China Industrial Statistical Yearbook. China is a major emitter of carbon dioxide, and carbon dioxide is the main source of the greenhouse effect. Therefore, in this paper, carbon dioxide is the undesirable output. CO_2 emission is mainly derived from the combustion of fossil fuels such as coal, coke, crude oil, gasoline, diesel oil, fuel oil, and natural gas in industrial production. According to previous research by Xie, et al. [40], the calculation method is introduced by the Intergovernmental Panel on Climate Change (IPCC, 2006), and the data is gathered from the China Energy Statistical Yearbook. All the indicators and data sources are summarized in Table 2.

Table 2. Data of input and output indicators.

Indicator	Definition	Data Sources
Inputs	Net value of fixed assets (100 million Yuan)	China Industrial Statistical Yearbook
	Number of employees (10,000 persons)	China Industrial Statistical Yearbook
	Energy consumption of industrial sector (Mtce)	China Energy Statistical Yearbook
Desirable outputs	Industrial added value (100 million Yuan)	China Industrial Statistical Yearbook
Undesirable outputs	CO_2 emissions (Mtce)	China Energy Statistical Yearbook

4.2. Indicators of Econometric Regression

4.2.1. Environmental Regulation (er)

Environmental regulation is to ensure the sustainable development of the environment, and to formulate a series of legal regulations and policies to regulate the production behavior of enterprises [7]. Manello [24] point out that in many heavily polluting production processes, environmental protection is a key issue. For industries with limited profit margins and numerous competitors, the additional constraints imposed by regulation can affect management decisions [41]. Different countries will adopt different environmental regulations. In China, environmental regulation measures have long been dominated by administrative means [42]. Its forms mainly include restrictions on the amount of pollutants discharged, the establishment of sewage standards, and the collection of sewage charges. In 2006, after the 11th Five-Year Plan (2006–2010), environmental issues prompted the Chinese government to take more stringent measures to solve some of China's major environmental problems [43]. However, the improvement of environmental quality is not achieved easily and it will cost a lot [44]. According to the Ministry of Ecology and Environment of China, the annual economic loss caused by environmental pollution is about 54 billion US dollars, and the natural disasters and treatment costs caused by environmental ecology account for about 5% of the total national economic output. However, the effectiveness of environmental regulation to reduce environmental pollution is ultimately reflected in the degree of emission reduction efforts of various industries. Therefore, the intensity of environmental regulation should be measured by the actual effect of regulation. Compared with the government's sewage charges and other indicators, the company's pollution discharge treatment expenditure can better reflect the extent of its emission reduction efforts [45]. Generally, the stricter the environmental regulation of an industry, the greater the expenditure on pollution discharge control; that is, higher environmental regulation intensity requires more pollution treatment expenditure. Therefore, based on the rationality of the indicators and the availability of data, this paper used the proportion of waste gas treatment cost in various industries to account for the proportion of the main business income of each industry to express the intensity of environmental regulation. These data were collected from the China Environmental Statistical Yearbook and the China Industrial Statistical Yearbook.

4.2.2. Research and Development Investment (rd)

Peuckert [46] studied the relationship between the research and development (R&D) expenditures or innovation survey responses with the environmental regulation, and pointed out that the regulatory pressure of environmental regulation was an incentive for technological innovation. Aldieri et al. [47] based their research on a dataset composed of 85 Russian regions during 2010 to 2014 to study the relationship between productivity and innovation through the knowledge spillover effects. Results showed that R&D significantly affected Russian regions' productivity and that productivity spillover across regions matter. Considering the availability of data and the consistency of statistics, this paper employed the R&D internal expenditure to represent the R&D investment of enterprises, and the data were obtained from the Statistics Yearbook on Science and Technology Activities of Industrial Enterprises.

4.2.3. Governance Transition (gt)

Lanoie et al. [45] argue that the Porter hypothesis is more applicable to industries with more pollution or more international competition. Chen [48] and Wang et al. [49] included the ownership structure variables in the model to explore its impact on technological innovation, and concluded that the ownership structure has a positive impact on the technical innovation. Zhang et al. [50] believe that the influence of state-owned enterprises on technical innovation is negative. Therefore, this issue has been controversial. According to Du et al. [33], the indicator of governance transition is measured by the ratio of the income from the main business of the private economy, including private industrial enterprise, foreign investment, and the Hong Kong, Macao, and Taiwanese investment industrial enterprises to the main business income of the state-owned and state-controlled industrial enterprises. These data were obtained from the China Industrial Statistics Yearbook.

4.2.4. Foreign Indirect Investment (fdi)

After China's economy achieved rapid growth, the drawback of the traditional rough growth mode seriously restricted the sustainable development of China's economy and environment. Breaking the bottle of traditional resources and environment on China's economic development, it is urgent for China to achieve industrial structure transformation and upgrading, and promote innovation capability. Foreign direct investment (FDI), as an important international technology spillover channel, not only brings advanced management experience, but also has a certain impact on the trading country's environment [51]. The representative theory of the impact of environmental regulation on foreign direct investment is the "pollution shelter" hypothesis [52]. In this paper, we adopted the total output value of foreign-invested enterprises and Hong Kong, Macao, and Taiwan investment enterprises, measured by the proportion of industry, to explore the relationship between environmental regulations and foreign direct investment about the manufacturing in China. These data were collected from the China Trade and External Economic Statistical Yearbook.

5. Empirical Results

5.1. Results of Manufacturing Energy-Environmental Efficiency

We apply the DEA to evaluate the manufacturing industry's energy-environmental efficiency. The results are shown in Table 3. The highest average efficiency is the lightly polluting industry with 0.52, followed by the heavily polluting industry with 0.40, and the lowest average efficiency is the moderately polluting industry with 0.32. From the perspective of the average efficiency values of various sub-industries, green energy-environmental efficiencies have different performances in different industries.

Table 3. Results of manufacturing green energy-environmental efficiency.

Classification	Industries	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average
Heavily polluting industry	Paper products industry	0.17	0.16	0.30	0.29	0.16	0.15	0.14	0.14	0.02	0.15	0.17
	Oil processing industry	1.00	0.21	1.00	1.00	1.00	0.37	1.00	1.00	1.00	1.00	0.86
	Non-metallic Products industry	0.24	0.05	0.32	0.34	0.18	0.20	0.08	0.21	0.03	0.04	0.17
	Chemical industry	0.34	0.15	0.60	0.68	0.39	0.42	0.14	0.51	0.10	0.70	0.40
	Chemical fiber manufacturing industry	0.33	0.32	0.28	0.28	0.28	0.31	0.28	0.25	0.04	0.25	0.26
	Ferrous metal industry	0.63	0.13	1.00	1.00	1.00	1.00	0.17	0.68	0.19	0.66	0.65
	Beverage manufacturing industry	0.26	0.19	0.36	0.41	0.22	0.32	0.27	0.26	0.07	0.29	0.27
	Textiles industry	0.18	0.23	0.32	0.34	0.25	0.30	1.00	0.33	0.01	0.35	0.33
	Non-ferrous metal industry	0.28	0.16	0.78	0.79	0.55	0.57	0.19	0.63	0.19	0.88	0.50
	Average						0.40					
Moderately polluting industry	Food processing industry	0.22	0.20	0.37	0.42	0.23	0.32	0.23	0.31	0.03	0.35	0.27
	Pharmaceutical industry	0.24	0.19	0.40	0.46	0.28	0.36	0.24	0.36	0.04	0.45	0.30
	Agricultural and sideline food processing industry	0.34	0.36	0.91	1.00	0.55	0.78	0.29	0.91	0.04	0.79	0.60
	Cultural, educational, and sports products industry	0.43	0.55	0.35	0.34	0.27	0.30	0.57	0.37	0.03	0.17	0.34
	Leather products industry	0.33	0.45	0.47	0.49	0.28	0.37	0.33	0.23	0.01	0.23	0.32
	Rubber and plastics industry	0.23	0.22	0.13	0.14	0.14	0.15	0.19	0.28	0.02	0.29	0.18
	Metal products	0.16	0.27	0.42	0.45	0.21	0.26	0.15	0.31	0.03	0.31	0.26
	Garment manufacturing industry	0.25	0.34	0.44	0.48	0.20	0.31	0.30	0.29	0.01	0.31	0.29
	Average						0.32					
Lightly polluting industry	Tobacco products industry	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Special-purpose equipment industry	0.23	0.31	0.51	0.59	0.44	0.53	0.27	0.51	0.08	0.48	0.39
	Instrument and meter industry	0.20	0.69	0.57	0.51	0.35	0.43	0.43	0.36	0.08	0.37	0.40
	General-purpose equipment Manufacturing industry	0.32	0.28	0.59	0.62	0.46	0.52	0.19	0.50	0.05	0.46	0.40
	Furniture industry	1.00	0.63	0.52	0.52	0.34	0.42	0.52	0.39	0.01	0.27	0.46
	Wood processing industry	0.20	0.22	0.22	0.26	0.16	0.18	0.16	0.16	0.01	0.18	0.17
	Printing media industry	0.28	0.27	0.30	0.29	0.21	0.23	0.24	0.22	0.05	0.22	0.23
	Communication facilities industry	1.00	1.00	1.00	1.00	1.00	1.00	0.54	1.00	0.50	1.00	0.90
	Electrical machinery industry	0.44	0.51	0.85	0.91	0.77	0.81	0.38	0.80	0.50	0.82	0.68
	Cardboard manufacturing	0.14	0.25	0.14	0.14	0.13	0.14	0.07	0.12	0.04	0.13	0.14
	Average						0.52					

About the heavily polluting industry, although the green energy-environment efficiency of various industries is slightly fluctuating, overall, it is showing an increasing trend. During the research time, the average efficiency is 0.40. Among them, the green energy-environmental efficiency about the oil processing industry, ferrous metal industry, non-ferrous metal industry, and chemical industry is 0.86, 0.65, 0.50 and 0.40, respectively. The green energy-environment efficiency of these industries is better than the other industries in the heavily polluting industry. According to the Ministry of Ecology and Environment of the People's Republic of China, policies for reducing emissions, limiting production, and even suspending production have been proposed for heavily polluting industries. Therefore, from the results, we could find that coordinated development of energy and the environment has been improved. The efficiency of the chemical fiber manufacturing industry, beverage manufacturing industry, textiles industry, paper products industry, and non-metallic products industry is 0.26, 0.27, 0.33 and 0.17, respectively. The green energy-environmental efficiency of these industries is lower than the average efficiency of heavily polluting industries, indicating that the environmental regulations of these provinces are in an ineffective state.

The moderately polluting industry shows that the average green energy-environmental efficiency is 0.32, which is lower than the heavily polluting industry. The agricultural and sideline food processing industry, cultural, educational, and sports products industry, and leather products industry's green energy-environmental efficiency is 0.60, 0.34 and 0.32, respectively. The average green energy-environment efficiency of these industries is higher than the average green energy-environmental efficiency of the moderately polluting industry. The food processing industry, pharmaceutical industry, rubber and plastics industry, metal products and garment manufacturing industry's energy environment efficiency is 0.27, 0.30, 0.18, 0.26 and 0.29, respectively. These industries' efficiencies are lower than the average green energy-environmental efficiency of the moderately polluting industry. The emission intensity of these industries are after that of the pollution-intensive industry. The reason for this phenomenon may be insufficient intensity of environmental regulation in the moderately polluting industry, resulting in waste of energy and large emissions of pollutants. Therefore, the overall green energy-environmental efficiency of the industry is lowered.

Regarding the lightly polluting industry, the overall green energy-environmental efficiency is rising. Especially for the tobacco products industry, the value of the green energy-environmental efficiency is 1, which is at the production frontier, indicating that this industry can well realize the coordinated development of energy and environment. Besides, for the communication facilities industry and the electrical machinery industry, the energy environment efficiency is 0.90 and 0.68, respectively. These are both higher than the average efficiency of the light polluting industry. The light pollution industry consists of high-tech and clean industries, and their common characteristics are low-consumption and eco-friendliness.

From the perspective of the development characteristic of the industry, the impact of environmental regulation on different industries is different, reflecting the heterogeneity of the development of the industry. At present, the focus of national environmental protection is vigorously reducing air pollution emissions from heavily polluting industries, such as the metal industry, chemicals, etc. In addition to the large investment in these heavily polluting industries, the government also adopts economic means to promote the degree of pollution control, and enterprises with high energy consumption and low productivity are gradually shut down or transferred. In theory, the green energy-environmental efficiency of the moderately polluting industry should be higher than that of the heavily polluting industry. However, from the experimental results, the green energy-environmental efficiency of the heavily polluting industry is higher than that of the moderately polluting industry. Therefore, we can conclude that environmental regulation and economic means adopted by the government play roles in coordinated development of energy and environment.

5.2. Decomposing Energy-Environmental Technical Progress Efficiency

The total factor productivity (TFP) and decomposition index are presented in Table 4. All of the results were calculated by DEAP software. In Table 4, TFP indicates the total factor productivity, and EC and TC represents the technical efficiency index and technological change index, respectively. Total factor productivity is often called the technical progress efficiency, and it is usually regarded as an indicator of technological advancement [53]. TC is an indicator of production technological change in two adjacent periods, such as innovation changes and technological advancement. EC is used to indicate whether production inputs are wasted or resource allocation is reasonable. As shown in Table 4, the average value of the heavily polluting industry EC is 0.944, which implies that resources have not been fully utilized and unreasonable distribution has occurred. The TC and TFP are 1.145 and 1.106, respectively. The values of the TC and TFP show that technology in the heavily polluting industry is constantly improving and continuing to innovate. The results show that these industries have transformed and upgraded under the guidance of environmental regulation and new technology development, hence, the energy environment efficiency has also been significantly improved. The average value of the EC of the moderately polluting industry is 1.033, and TC and TFP are 1.042 and 1.075, respectively. The results show that the resource utilization of the moderately polluting industry has been effectively utilized and rationally distributed. The moderately polluting industry has realized the transformation and upgrading of the industry under the effective regulation of the environment and the promotion of technology. The lightly polluting industry's EC is 1.019, and compared with heavily polluting industries, the resources of the lightly polluting industry have also been rationally utilized and distributed. The value of the TC is 1.019, and the TFP is 1.089. The lightly polluting industry is constantly improving its technical innovation and has begun to transform and upgrade.

From the results, we find that the heavily polluting industry's total factor productivity is higher than the other polluting industries. The state implements strict measures for heavily polluting industries and implements policies to adjust the industry structure. In the 13th Five-Year Plan, it is proposed to promote structural reforms on the supply side, to establish a mechanism for the withdrawal of heavy polluting capacity and the elimination of excess capacity, and to shut down and eliminate enterprises that have exceeded the standard for a long time. Hence, industrial enterprises with heavy pollution and high energy consumption have been forced to transfer or shut down. In addition, the government invests a large amount of funds to introduce advanced equipment and technology to ensure enterprises' development while reducing environmental pollution.

Table 4. Results of total factor productivity and decomposition index.

Classification	Industries	EC	TC	TFP
Heavily polluting industry	Paper products industry	0.926	1.173	1.086
	Oil processing industry	0.924	1.195	1.104
	Non-metallic products industry	1.000	1.271	1.271
	Chemical industry	0.900	1.150	1.035
	Chemical fiber manufacturing industry	0.957	1.142	1.093
	Ferrous metal industry	0.869	1.227	1.066
	Beverage manufacturing industry	1.027	1.089	1.119
	Textiles industry	0.929	1.091	1.014
	Non-ferrous metal industry	0.963	1.208	1.163
	Average	0.944	1.145	1.106
Moderately polluting industry	Food processing industry	1.044	1.083	1.130
	Pharmaceutical industry	1.040	1.095	1.138
	Agricultural and sideline food processing industry	0.975	1.107	1.079
	Cultural, educational, and sports products industry	1.143	0.957	1.094
	Leather products industry	0.998	0.954	0.952
	Rubber and plastics industry	0.990	1.076	1.066
	Metal products	1.054	1.054	1.111
	Garment manufacturing industry	1.018	1.010	1.028
	Average	1.033	1.042	1.075
Lightly polluting industry	Tobacco products industry	1.000	1.188	1.188
	Special-purpose equipment industry	1.016	1.074	1.091
	Instrument and meter industry	1.033	1.012	1.046
	General-purpose equipment manufacturing industry	1.001	1.081	1.083
	Furniture industry	1.100	0.972	1.069
	Wood processing industry	1.041	1.076	1.120
	Printing media industry	1.054	1.067	1.124
	Communication facilities industry	1.000	1.018	1.018
	Electrical machinery industry	1.041	1.045	1.087
	Cardboard manufacturing	0.900	1.176	1.059
	Average	1.019	1.071	1.089

Notes: TFP: Total factor productivity; EC: Technical efficiency; TC: Technological change.

5.3. Influencing of Environmental Regulation on Technical Progress Efficiency

If environmental regulation is biased towards technical innovation that leads to green development efficiency through R&D investment, it can be tested by introducing interactions between environmental regulation and R&D investment [54]. When the sign of the interaction term coefficient is positive, it indicates that environmental regulation can guide the R&D investment to the green technical innovation [55]. Similarly, when the sign of the coefficient of interaction between R&D investment and governance transformation is positive, it has a positive effect on green development of industry. To avoid heteroscedasticity, we took the natural logarithm of the variable. Panel Tobit regression was used in this study, and the results are shown in Table 5. Besides, in order to reduce the influence of multicollinearity on the stability of the model, this paper first decentralized the interaction items of variables. Also, taking into account the lagging effects of environmental regulation and technological innovation, we took a year lag. The regression results calculated by Stata software and the results are shown in Table 5.

Table 5. Manufacturing sub-sectors regression results.

	Variables	Coefficients		Variables	Coefficients		Variables	Coefficients
Lightly polluting industry	Ln(er)	−0.031 * (0.060)	Moderately polluting industry	Ln(er)	−0.194 *** (0.135)	Heavily polluting industry	Ln(er)	0.204 *** (0.146)
	Ln(gtrd)	0.020 ** (0.094)		Ln(gtrd)	0.359 ** (0.043)		Ln(gtrd)	0.171 ** (0.140)
	Ln(gt)	0.003 ** (0.040)		Ln(gt)	0.138 ** (0.056)		Ln(gt)	0.021 *** (0.049)
	Ln(errd)	−0.003 * (0.031)		Ln(errd)	0.065 ** (0.068)		Ln(errd)	0.061 ** (0.081)
	Ln(rd)	0.054 * (0.760)		Ln(rd)	0.352 * (0.333)		Ln(rd)	0.212 * (0.356)
	Ln(fdi)	−0.247 *** (0.074)		Ln(fdi)	0.244 ** (0.098)		Ln(fdi)	−0.306 * (0.100)
	_cons	−0.009 ** (0.420)		_cons	−0.547 * (0.906)		_cons	−0.812 ** (1.058)
	Log likelihood	211.82		Log likelihood	312.54		Log likelihood	−214.03

Note: ***, **, * indicate significance levels at 1%, 5%, and 10%, respectively. Standard errors in parentheses.

In order to explore the compound effects of environmental regulation and governance transition on green development and study the industry heterogeneity of the Porter hypothesis transmission mechanism, this paper conducted group tests about the heavily polluting industry, the moderately polluting industry, and the lightly polluting industry. The regression results are shown in Table 5. Regarding the lightly polluting industry, the coefficients of the Ln(er), Ln(errd), and Ln(fdi) are negative at the 10%, 10% and 1% significant levels, respectively. This results indicate that the environmental regulation intensity is weak for the lightly polluting industry, and the environmental intensity is not enough to stimulate innovation in lightly polluting industries. The coefficients of the Ln(gtrd), Ln(gt), and Ln(rd) are positive at the5%, 5% and 10% significant levels, respectively, which indicates that R&D investment can directly promote TFP, and governance transition could promote green technology or green product development. In addition, governance transition could stimulate light pollution industries to increase R&D investment, and further promote the TFP.

About the moderately polluting industry, the coefficient of the Ln(er) is negative at the 1% significant level. The results show that environmental regulation cannot directly promote the progress of the TFP. The coefficient of interaction between environmental regulation and R&D, as well as governance transition and R&D, are both positive. Thus, the environmental regulation and governance transition could induce companies to increase investment in research and development, and achieve innovation to promote TFP. The coefficients of Ln(rd) and Ln(fdi) are both positive at the 10% and 5% significance levels, respectively. The above results show that for the moderately polluting industry, the intensity of environmental regulation needs to be enhanced.

The regression results of the heavily polluting industry show that the coefficients of Ln(er) and Ln(rd) are positive. However, the coefficient of Ln(fdi) is negative, which indicates that for the heavily polluting industry, in the context of China's economic transition, the inflow of FDI does not play an important role to promote the TFP. The coefficient of the Ln(errd) and Ln(gtrd) are both positive, indicating that environmental regulation and governance transition can promote the growth of TFP by investing in research and development. The above results show that the heavy pollution industry, in order to achieve green transformation and upgrading, needs to rely on technological progress.

6. Conclusions and Recommendations

In this paper, we first divided manufacturing, according to the environmental pollution intensity, into heavily polluting industry, moderately polluting industry, and lightly polluting industry. Then, we employed the SBM-undesirable to evaluate the green energy-environmental efficiency of manufacturing to understand the coordinated development of energy and environment in sub-industries. We then used the Malmquist index to evaluate and decompose the technical progress efficiency to analyze the dynamic changes of technical efficiency and innovation in sub-industries. Lastly, considering that China has entered a new era and the economy is in a period of governance transition, we analyzed the relationship between characteristics of industry, environmental regulation, governance transition, and technical innovation to explore the compound effects on green development and study the industry heterogeneity of the Porter hypothesis transmission mechanism during the period of 2006 to 2015. The following conclusions can be drawn.

The manufacturing industry with the highest green energy-environmental efficiency is the lightly polluting industry with 0.52, followed by the heavily polluting industry with 0.40. The moderately polluting industry has the lowest efficiency with 0.32. The measures and treatment methods adopted by the government's policies in heavily polluting industries are effective in improving environmental quality. From the perspective of the development characteristics of the industry, the impact of environmental regulation on different industries is different, which reflects the industry's heterogeneity.

During the 10 years, under the environmental regulations, the total factor productivity shows an upward trend. Regarding the heavily polluting industry, the average value of the TFP is 1.106, and the EC and TC are 0.944 and 1.145, respectively. The government has strengthened the control of pollution in heavily polluting industries, and uses economic means to promote the marketization of pollution control. Technical innovation has promoted industrial transformation and upgrading. However, the results show that resources are not effectively utilized or reasonably allocated. The average value of the moderately polluting industry and lightly polluting industry's TFP, EC, and TC are more than 1, which suggests that the resources have been rationally utilized and distributed, and the industry has continued to innovate. The above results show that under environmental regulation and constant technical innovation, the manufacturing industry is undergoing transformation and upgrading.

In order to explore the compound effects on green development and study the industry heterogeneity of the Porter hypothesis transmission mechanism, this paper conducted group tests between the heavily polluting industry, the moderately polluting industry, and the lightly polluting industry. The results suggest that for the lightly polluting industry, the moderately polluting industry, and the heavily polluting industry, R&D investment and governance transition can directly promote technical progress efficiency. Based on the above experimental results, we give the following recommendations.

According to the regression results of the panel model, governance transition and R&D investment can promote TFP. Besides, the interaction between governance transition and R&D intensity has a deep compound effect on the improvement of TFP, which is consistent with the conclusion of Du et al. [33]. Therefore, the government should vigorously develop the private economy and improve the supply-side main structure, which can effectively promote the improvement of China's industrial green competitiveness. Although the current environmental regulations and governance transition have promoted green energy-environmental efficiency of the manufacturing industry, it is not possible to fully encourage manufacturing to carry out technical innovation and achieve coordinated development of energy and environment. Therefore, due to the heterogeneity of the industry, the intensity of environmental regulation should be diversified under the context of governance transition. For heavily polluting industries, the government should moderately weaken the environmental supervision of these industries, reduce the compliance costs of enterprises, and avoid the crowding effect. The heavily polluting industry is dominated by pollution-intensive industries and heavy chemical industries. From the results, the environmental regulations have a positive impact on the total factor productivity of heavy polluting industries. However, if the environmental regulation intensity of heavily polluting industries is further strengthened on this basis, the burden on enterprises will be increased. If the intensity of environmental regulation exceeds the bearing capacity of enterprises, environmental regulation will have an adverse impact on enterprises' technological innovation activities, thus the win–win situation between economy and environment cannot be achieved. Especially for those small and inefficient SMEs with poor technical equipment, they cannot meet environmental standards in the short term, thus avoiding the pollution reduction behavior. This will not increase the investment in environmental protection technology, but will further lead to enterprises willing to sacrifice the environment to gain profits. Therefore, for the heavily polluting industry, on the basis of maintaining the current intensity of environmental regulation, the direction of energy-saving and emission reduction should be shifted from the environmental regulation of enterprises to technological innovation and structural adjustment. First, increasing investment in the research and development of green technology. The government should support the research and development and promotion of special technologies for heavily polluting enterprises, such as water conservation and pollution control, recycling, etc., so that enterprises can carry out green innovation and management innovation in the production process to achieve energy conservation and emission reduction. Second, continue to integrate resources and optimize resource allocation. For companies with low technical capacity and particularly serious pollution, enterprises will be shut down or reorganized. Third, change the policy implementation concept and explore the multiple complementary ways of green innovation policy. For heavily polluting industries, achieving green development efficiency could depend on a combination of policies: Environmental regulation, foreign investment and government support, and the availability of scientific researchers.

The moderate pollution industry is mainly based on the living materials manufacturing industry and some heavy industries. Based on the analysis of experimental results, it can be seen that environmental regulation has a negative correlation with moderately polluting industries. The development of the moderately polluting industry has had a great impact on the environment, but it has not been governed, and a large amount of pollutants are discharged in an untreated manner. The weaker environmental regulations account for a small proportion of the total cost of the enterprise due to lower costs. Therefore, it cannot stimulate the company to carry out technological innovation and management innovation. For instance, the rubber and plastic products and metal products industry with high pollution emission intensity, but the environmental regulation intensity is relatively weak, thus resulting in relatively low environmental pollution costs. Therefore, for the moderate pollution industry, on the one hand, the government should strengthen the intensity of environmental regulation, adjust the cost structure, and control pollution discharge. On the other hand, there is a positive correlation between R&D and total factor productivity. Therefore, strengthening R&D investment is conducive to the improvement of green development efficiency. For the lightly polluting industry, although it is mainly a technology-intensive and clean industry, in its development process, some industries still pose a threat to green development of the environment—such as the special-purpose equipment industry, printing media industry, wood processing industry, and cardboard manufacturing, which have a very low green energy-environmental efficiency. The environmental regulation of lightly polluting industries is weak and fails to stimulate technological innovation and growth of total factor productivity. Therefore, the government should appropriately strengthen the intensity of environmental regulation for the lightly polluting industry. Moreover, strengthen the investment intensity of R&D and improve the efficiency of green energy-environmental efficiency through technical innovation.

This study explores the energy-environmental efficiency and decomposes total factor productivity under the environmental regulation from the perspective of industry heterogeneity, and opens the black box of the Porter's hypothesis to explore the transmission mechanism of environmental regulation in different industries. Environmental regulation can be divided into policy-type environmental regulation and market-oriented environmental regulation. Different types of environmental regulations have different effects on the productivity of manufacturing industries; however, this study does not analyze the impact of the environment on manufacturing productivity by different policy types. This is an important direction that we will continue to study in the future.

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