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Energy- and Environment-Biased Technological Progress Induced by Different Types of Environmental Regulations in China

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Abstract: With the increasing pressure of energy exhaustion and environmental degradation, environmental regulation is considered as a strategy to achieve sustainable development. This paper specifically analyzes the mechanism of multi-dimensional environmental regulations on energy- and environment-biased technological progress, and empirically detects the differentiated impacts using China's panel data from the period 2000–2016, employing the generalized method of moments (GMM) and a dynamic threshold model. The results reveal that: (1) command-and-control regulation (CCR) promotes energy-saving and pollution abatement technological progress. Market-based regulation (MBR) stimulates energy-saving technological progress, while informal regulation (IR) only accelerates environment conservation technological progress. (2) There are threshold effects on the relationship of environmental regulations and biased technological progress. With economic developments, CCR and MBR have positive effects on energy- and environment-related technological progress, whilst IR fails to promote backstop and pollution abatement technological progress. The clear diversity in the impacts of different environment regulations on biased technological progress provides new insights for the optimal future policy design.

Keywords: environmental regulation; biased technological progress; energy-saving and emission reduction; threshold effect

1. Introduction

Energy exhaustion and environmental degradation are now global issues attracting increasing attention. For high-quality development and further sustainability, China has achieved an average annual real GDP growth of 9.5% since the reform and opening up in 1978, but at the same time, it has also paid significant environmental and social costs. According to the latest Environmental Performance Index Report (2018) released by Yale University and Columbia University, China's environmental performance index ranks 120th out of 180 countries (EPI, 2018). According to "SDG Index and Dashboards Report 2018", China ranked 54th, with a score of 70.1, among all 193 UN member states. Ecological and environmental protection is a shortcoming in China's sustainable development (China's sustainable development goals (SDGs) 3, 13, and 14 are red; SDGs 7, 11, 12, and 15 are orange; and SDG 6 is yellow in the SDG Dashboard for OECD countries). In the 2015 Paris Climate Summit, China said it would cut its carbon emissions per unit of gross domestic product by 60–65% from 2005 levels by 2030. However, China is still in the stage of rapid industrialization and urbanization. The coal-based energy consumption structure has led to a high level of total energy consumption and carbon dioxide emissions in China. China is facing tremendous pressure for sustainable development.

The goals of the global climate deal in the Paris Climate Summit are achievable by fostering green growth. This, in turn, will require limiting carbon dioxide emissions and declining fossil energy consumption [1]. Energy- and environment-biased technological progress, as the generally accepted answer to the energy environment problem during economic growth, is the technical breakthrough of realizing the harmony among energy, environment, and economy—the 3E system [2,3]. Environmental regulation is one of the most direct and well received means of improving energy and environmental efficiency [4–9]. Energy–environment-oriented technological innovation directly addresses the energy and environmental issues of a sustainable economic development to achieve the SDGs proposed by the United Nations’ Sustainable Development Agenda in 2016, (mainly for SDGs 3, 6, 7, 11, 12, 13, 14, and 15), so that an ecological civilization can be constructed [10,11]. Both developed countries (e.g., American, Japan, UK, Korea, Switzerland) and developing countries (e.g., China) have historically taken environmental regulation as an answer to achieve a green economy [9,12–17]. Thus, it is vitally important to clarify the comprehensive and diversified influence of environmental regulation on energy- and environment-biased technology progress.

A series of studies has mostly been centered on the specific effect of environmental regulations on technological progress, especially on energy- and environment-biased technological progress [16,18,19]. However, more attention has been paid to the impact of environmental regulation on certain biased technologies [20–22] or total productivity efficiency [23,24] in existing studies. Only a few of these studies detected relationships between the diversity of environmental regulation and energy- and environment-biased technologies simultaneously. Environmental problems are a worldwide as well as a human problem, involving multiple stakeholders [25]. It is, thus, more targeted and practical to detect the effect of multiple environmental regulations on different types of technological progress from different perspectives [13]. In particular, under “Chinese style decentralization,” selecting appropriate environmental regulations with a subsequently induced technological progress is in line with the regional economy target [26].

Recently, scholars have started to discuss the varying influence of diverse environmental regulations on technical progress [9,20,27,28]; however, previous empirical studies were relatively vague about internal mechanisms. Moreover, few studies explore the nexus of different environmental regulations and differently biased technological progress. Thus, herein clarifies the mechanisms of how different environmental regulations act on energy- and environment-directed technological progress from the view of enterprises. Moreover, econometric models with China’s provincial data from the period 2000–2016 were constructed, and an empirical test on China’s environmental regulations was performed.

The contributions of the findings to the existing literatures are as follows. Firstly, to the best of our knowledge, this is the first study to explore the nexus of diverse environmental regulations and direct technological progress. Given the bias and differentiation of energy- and environment-related technologies, analyzing and understanding the implementation and effect of environmental regulations is of considerable importance. Secondly, the difference of technological progress bias brought about by different environmental regulations and the influence of different environmental policies on the direction of clean technology progress are analyzed, and a variety of environmental regulation combinations and technological progress options for the sustainable development of countries around the world are provided.

2. Literature Review

2.1. Directed Technical Progress

For biased/directed technical progress following from Hicks’s “Induced Innovation” [29] and Sato’s “factor-augmenting technical progress” [30], to date, studies have paid more attention to the evaluation of labor- and capital-biased technical progress [31–34], or alternatively focused on higher or lower skill (ability)-biased innovation [35–37]. In Acemoglu [38–40], the definition of “biased

technological progress” is clearly provided. If technological progress increases the marginal output of factor Z as compared to that of other factors, technological progress is directed into factor Z, i.e., a Z-biased technological progress. Acemoglu et al. [41] expanded the directed technological progress into the field of energy and environment, and a few other researchers switch into studying energy- and/or environment-biased technological progress [29,42,43].

With an increasing pressure due to energy exhaustion and environmental degradation, the number of papers focusing on energy- and environment-related technological progress has strongly increased in recent decades. These studies evaluate or measure a certain type of energy or environmental efficiency from different perspectives and analyze the influencing factors (presented in Table 1). However, a shortcoming of such studies is the focus on both energy- and environment-biased technological progress simultaneously. According to Table 1, the measurement of technological progress can be divided into three categories: input, output, and relative efficiency. Input perspective methods focus on the corresponding investment or expenditures for technological innovation. Output-focused methods focus on the application and adoption of patents about energy-saving and environmental protection. Relative efficiency methods measure technological progress from the output perspective, considering corresponding environmental factors. It is easier to distinguish the direction of technological progress via the latter method.

Table 1. The measurement of energy- and environment-biased technological progress.

Category	Biased Technological Progress	Typical Tools	References
Input perspective	Green innovation practices	Factorial analysis based on GRI (Global Reporting Initiative) variables and ISO (International Organization for Standardization) 14001 certification: UN Global Compact, DJSI (Dow Jones Sustainability Index) and environmental investments	Borsatto and Amui [44]
	Eco-innovation: eco-investment + eco-planning innovation	Firms’ eco-investment, including the expenditure for sewage, environmental protection facility, environmental protection technology, preventive, etc. Eco-planning innovation: sustainable development, strategy, planning and assessment of the environment	You et al. [45]
	Input ability of green technological innovation	The ratio of green R&D expenditure to the operating income The ratio of green R&D personnel to total employees	Li et al. [46]
Output perspective	Green technological innovation’s output ability	Green patents granted per green R&D personnel; this year’s increased profit of green products divided by last year’s gross profit of green products	
	Energy efficiency innovation	Quantity of patented energy efficiency inventions	Girod et al. [47]
	Energy efficiency technologies	Selected patents	Costantini et al. [48]
	Green innovation	Patent counts; citation-weighted patent counts	Zhang et al. [49]
	Renewable energy technological innovation	Renewable energy patents	Lin and Zhu [50]
Relative efficiency perspective	Environment-biased technical progress	A super-efficiency SBM model	Song and Wang [10]
	Energy conservation technological progress	SFA based on the translog production function	Yang et al. [51]
	Green total factor productivity	SFA based on the translog production function	Shao et al. [52]
	Energy-biased technical change	A three-factor nested CES function	Zha et al. [53]
	Green-biased technological progress	DEA model	Li et al. [46]
	Green total factor efficiency	Super SBM model containing undesired output	Jin et al. [54]
	Green technology innovation	Malmquist index and DEA	Luo et al. [55]

Note: SBM = slack-based measure; SFA = stochastic frontier analysis; DEA = data envelopment analysis; CES = constant elasticity of substitution.

Considering the fact that a technological advancement, caused by the symbiosis of pollution emission and fossil energy consumption [56] and the substitutability between new energy and fossil fuels often improves both energy and environmental efficiency, comparing and discussing the technological progress of various energy environments is more consistent with the actual technological progress and can focus on the structural problems of technological progress. Hence, herein we identified three kinds of energy- and environment-biased technological advances, namely energy-saving technical progress, pollution-abatement technical progress, and backstop technical progress (new energy technical progress).

The driving forces or influencing factors of energy- and environment-biased technological progress, innovation policy, foreign direct investment (FDI), trade, employment structure, relevant investment, environmental regulation, etc., have been frequently investigated in recent decades [51,57–61]. Meanwhile, with the internalization of environmental externalities, environmental regulation has become a significant factor that affects technology choice [62] as well as an institutional factor that results in the emergence of energy- and environment-directed technological progress. Therefore, a discussion about the influence from environmental regulations on energy- and environment-directed technological progress through a comparative analysis of different modes of energy- and environment-directed technological advances is presented.

2.2. Diversity of Environmental Regulations

Environmental regulations are meant to mitigate pollution emission and energy consumption. In a large sense, this should be a comprehensive system, which is comprised of laws, regulations, industry norms, suggestions, supervision, punishment, rewards, environmental protection publicity, education, and other means adopted by multiple subjects to provide feedback on various aspects of environmental problems. With the complexity of environmental policy systems and the diversity of tools, it is more targeted and practical to measure the implementation effectiveness of different types of environmental regulations systematically.

To date, environmental regulations have been classified into different types from different perspectives (Table 2). For example, according to the type of environmental regulation, relevant policy instruments are conventionally classified into the two broad categories of formal regulation and informal regulation [63]; alternatively, explicit regulation and implicit regulation. Among these classifications, formal environmental regulation (FR) generally deals with the direct intervention of the government on the utilization of environmental resources mainly by administrative orders, which include clearly stipulated emission and production standards, environmental taxes and fees, resource taxes, pollution permits, and subsidy policies [20]. Informal environmental regulation (IR) not only contains the behavior of social groups—who basically consider their own interests, seeking to improve environmental quality when the original formal regulation fails [64]—but also includes external manifestations of the residents' environmental awareness, such as public petitions and complaints about environmental damage, exposure to pollution, green products of choice, and voluntary environmental programs [12,65]. Considering the coerciveness of tools, some researches divided environmental regulation into command-and-control regulation (CCR), market-based regulation (MBR), and voluntary environmental regulation [20,27,66]. Alternatively, environmental regulation can be divided into expense type and investment type environmental regulation, or quantity-based and price-based environmental regulation [67], and trust-based environmental regulation [68] due to the heterogeneity of environmental capital utilization.

Specifically, CCR refers to an environmental intervention, which does not rely on financial incentives but on regulations, including permission, prohibition, standard setting, and enforcement. The main characteristic of CCR is coerciveness, which depends on administrative measures [27]. Based on market mechanisms, environmental protection tools, such as environmental taxes, subsidies, and carbon emission rights, are classified as MBR. Non-profit environmental regulations, such as environmental supervision, environmental protection publicity, and education—provided by residents,

social organizations, and so on—are generally considered to be voluntary environmental regulation (VR) [24], so-called IR. It is the public environmental awareness rather than the government regulation that is effective.

Based on Table 2, the nexus between environmental regulation and energy conservation and emission reduction can be concluded as follows. (1) The crow-out effect: the compliance cost caused by environmental regulation decreases the profit of enterprises and crowds-out technological innovation investments, thus weakening the corresponding enterprises' competitiveness [69–72]. (2) The “Porter Hypothesis” claims that confronted with environmental regulations and shrinking profits, some enterprises may try to accelerate innovation to solve the current dilemma, so as to achieve an efficiency improvement and even technological renovation (viz. the corresponding weak and strong Porter hypothesis); finally, the benefit of innovation compensates the compliance costs of environmental regulations and realizes the innovation compensation effect [15,73–75]. (3) The non-linear relationship: in the beginning, low environmental regulations fail to stimulate innovation. As the strength of regulations increases, enterprises need to improve technological progress to seek a subsequent innovation compensation. Once the environmental regulation is so high that the innovation compensation fails, the enterprises may transfer or find other ways to deal with environmental pressures, thus no longer significantly promoting technological innovation. These results may be presented as subsequent U-shaped [76], inverted U-shaped [77], or other more complex threshold relationships [78]. (4) Non-relationship: enterprises can also choose other ways to deal with environmental regulations, such as rent seeking/corruption [79], seeking political connections [80], or enterprise transfer [81,82]. Correspondingly, there is no significant relationship, as shown by empirical results, between environmental regulation and technological progress [83–86]. To summarize, there is a lack of accordant statements about the nexus of environmental regulations and technological progress in the present literature due to the different perspectives, measurements, samples, etc.

Table 2 lists the different categories and corresponding indicators of environmental regulations and the impact on the energy- and environment-related technology innovation. Combined with the above theoretical analysis, both theory and empirical evidence demonstrate that different environmental regulations have different comparative advantages, but numerous factors, jointly, decide which strategy to choose. Clarifying the mechanism behind these relationships from the view of enterprises and testing the specific impact of diversified environmental regulations within economic transition are important for guiding technological progress in China. In addition, different categories or measures of innovation/technological progress can also influence the effect of environmental regulation [83,87,88]. Therefore, it is more practical and comprehensive to analyze how effectively different environmental regulations impact biased technological progress. Considering that energy- and environment-biased technological progress is an adoptive answer to resolve urgent energy and environmental issues, and eventually, realize China's green growth, there is a necessity to detect the consequences of environmental policies on energy- and environment-directed technological progress.

Table 2. Diversity of environmental regulations and the impacts on the energy- and/or environment-related technological progress.

References	Typical Tools	Object (Technology)	Sample and Methods	Result			
Zhang et al., 2012	Regulatory policies: central and regional governmental, exports, countries' regulations in energy conservations/saving (EC) and CO ₂ reduction/abatement (CR)	Innovation (IN): R&D investment on EC and CR technology, remold the process of production for EC and CR, energy-efficient equipment substitution Residue recycling (RR): recycling residual energy, scrap materials, by-products Carbon crediting mechanism's implementation (IC) CO ₂ abatement strategy (CA)	203 iron or steel companies. Questionnaires and a regression model	IN	RR	IC	CA
	0			0	0	+	
	+			+	+	0	
	0			0	+	0	
Lamperti et al., 2015	MBR: carbon taxes and subsidies for clean sectors CCR: dirty inputs (and greenhouse gas emissions)	Redirect technical progress to green technology	An extension of the model developed by Acemoglu et al. [41]	Not always successful Successful			
Zhao et al., 2015	CCR: comprehensive index from questionnaires, including emission standards, fines, supervision measures, etc.	Technological innovation (TE) constructed by different kinds of technologies, for example, end-of-pipe abatement, new processes.	Chinese electric power and iron and steel firms; Questionnaires and structural equation model	TE	EM		
	MBR: comprehensive index from questionnaires, including tax credits, clean development mechanisms, and emissions trading systems	Environmental management (EM) constructed by different actions, such as reducing pollutant emissions, environmental protection investment.		+	+		
Xie et al., 2017	CCR: environmental investments in new construction projects	“Green” productivity evaluated by an SBM model and the Luenberger productivity index, taking undesirable outputs into consideration	China's provincial panel data (2000–2012); a panel threshold model	Double thresholds: 0, +, +			
	MBR: pollutant discharge fees			Single threshold: +, 0			
	IR: public complaints for pollution events			Double thresholds: 0, 0, 0			
	employees' education level			Single threshold: +, +			

Table 2. Cont.

References	Typical Tools	Object (Technology)	Sample and Methods	Result		
Naqvi and Stockhammer, 2018	MBR: a market-based one-off and a continuous resource of (or carbon) tax's increase	Resource-saving technologies	Policy simulations with a demand-driven post-Keynesian ecological macromodel	+		
	CCR: autonomous increase in the share of R&D toward resources			+		
Ren et al., 2018	CCR: constructed index by wastewater discharge's standard-achieving rate, removal rate of SO ₂ and soot and dust, solid wastes' comprehensive utilization rate	Eco-efficiency evaluated by directional distance function	China's provincial panel data (2000–2013); STochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) model	Eastern	Central	Western
	MBR: total amount of pollutant discharge fee			0	+	+
	VR: constructed index by environment labels, disclosure of environment events, and public's voluntary participation			+	+	0
Cai and Li, 2018	CCR: questionnaires on the requirements of international environmental regulations	Eco-innovation behaviors: low energy consumption, recycling, use of cleaner technology, manufacturing process optimization	442 Chinese firms; structural equation model	-		
	MBR: questionnaires on preferential tax policy, propagation of environmental protection, preferential subsidies			+		
Li and Ramanathan, 2018	CCR: quantity of environmental administrative penalty cases	Environmental performance (EP): a comprehensive index concluding main environmental pollutants (air, water, land)	China's provincial data (2004–2014); linear and quadratic functional form of regression model	No lag	1-year lag	2-year lag
	MBR: pollutant discharge fees			U	U	-
	IR: quantity of complaint letters about the problems of pollution and environment			U	0	0
Liu et al., 2018	Economical environmental regulation (ER) = environmental pollution treatment investment/added industrial value	Technological innovation = R&D input/GDP Total energy consumption	China 1997–2015; feasible generalized least squares method	Total	Eastern	Other
	Legal ER: quantity of environmental administrative penalty cases			0	-	+
	Supervised ER: quantity of year-end environmental protection institutions			+	+	+

Table 2. Cont.

References	Typical Tools	Object (Technology)	Sample and Methods	Result		
Wang and Shao, 2019	FR: market-based Environmental Policy Stringency Index	Green growth level measured by Global Malmquist–Luenberger index	Group 20 countries during the period 2001–2015; a panel threshold regression	+ in high level		
	FR: non-market-based Environmental Policy Stringency Index			Non-linear		
	IR: share of environment-related technological patents and the ratio of total enrollment at tertiary education levels			+ in low level		
Shen et al., 2019	CCR: comprehensive index agreeing with Ren et al. [20]	Environmental total factor productivity calculated by Metafrontier Malmquist–Luenberger method	Panel data of Chinese industry (2000–2016); the threshold model	Pollution industries		
	Heavy			Moderate	Slightly	
	0, 0, +			–, 0	–, +	
	MBR: constructed index by the discharge fee of wastewater pollutant and exhaust pollutant			0, 0, +, 0	–, 0, 0, 0	–, +, 0, +
Pan et al., 2019	CCR = industrial pollution control investment/added industrial value	Energy efficiency (EE) = energy consumption/GDP Technical innovation (TI): patent applications	China’s provincial data (2006–2015); directed acyclic graph (DAG) and structure vector autoregression (SVAR)	EE	TI	
	+			0		
	MBR: sewage charge			+	+	
Curtis and Lee, 2019	CCR: the early 1990s’ regulations for NOx	Energy efficiency = total output of the plant/energy consumption	US manufacturing plants (1992–1997); Difference-in-Difference (DID)	-		
	MBR: cap-and-trade			+		

Note: FR = formal environmental regulation; IR = informal environmental regulation; CCR = command-and-control regulation; MBR = market-based regulation; VR = voluntary regulation; 0 = non-significant relationship; − = significantly negative relationship; + = significantly positive relationship.

3. Theoretical Mechanisms

The environmental regulation process can be broken down into three stages: policy making and implications, impact on enterprises, and strategy adjustment and reaction, as depicted in Figure 1. In the following paragraphs, a detailed explanation of the mechanisms behind the effect of environmental regulations on biased technological progress is provided.

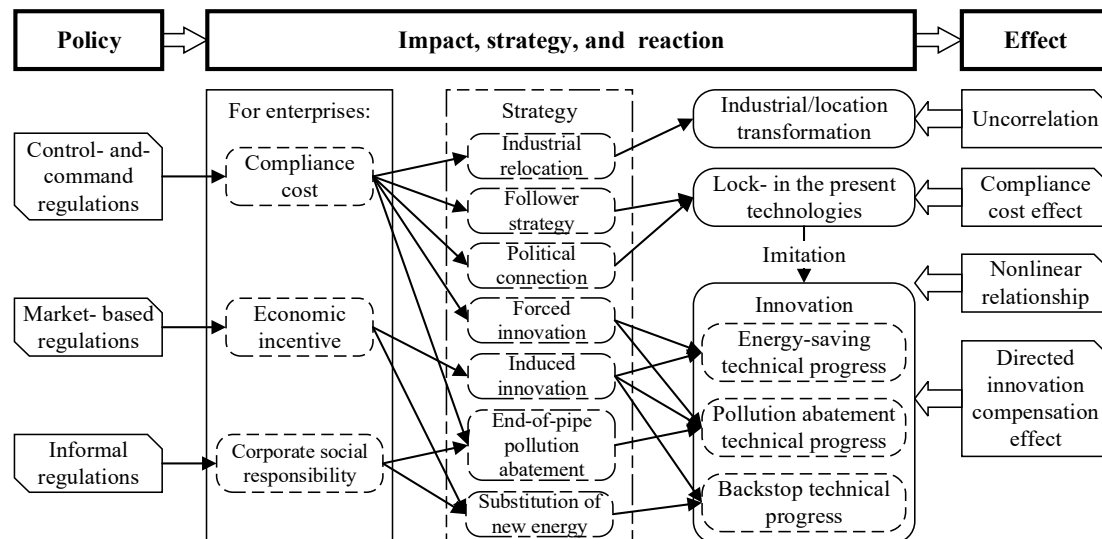


Figure 1. The theoretical routes and effects of environmental policy on innovation in China from the perspective of enterprises.

To begin with, energy saving and emission reduction is a matter which needs joint efforts of multiple stakeholders, including a leading role from the government, the participation of market entities, and the supervision of the public. With the work of multiple stakeholders, the development of tools for environmental regulation has been accelerated. The influence of environmental regulation systems, including CCR, MBR, and TR, on economic subjects includes three aspects: pressure, incentive, and voluntariness. As the holder of technological improvement and innovation, enterprises play a core and leading role in the advancement of energy-saving and emission reduction technology. CCR, MBR, and IR cause three kinds of pressures (or powers) on enterprises through increasing the cost of energy conservation and emission reduction, forming economic incentives, and increasing social responsibility pressure. Among them, mainly proposed by the government, CCR is typically associated with coercive pressure [76] and changes the total factor production cost by internalizing environment and energy costs. Using marketization tools, MBR creates comparative advantages for low-emission enterprises and forms economic incentives for high-efficiency enterprises through the market transmission mechanism. Formed by social organizations and residents, IR represents people's expectations for a better living environment, affects the social reputation of the enterprises, and exerts social responsibility pressure on the enterprises.

Thus, confronted with the changed environment and passion/motivation, enterprises have to take corresponding strategies. First, regarding the increasing cost caused by CCR, enterprises may employ strategies such as industrial relocation, industrial transfer, follower strategy, political connection, forced innovation, or end-of-pipe pollution abatement. Generally, leading enterprises have fairly comprehensive abilities and long-term development planning. Their pessimistic anticipation of stricter environmental regulations in the future leads to a higher endeavor to improve the existing production technology and develop new energy technology. When the emissions from regulated firms (e.g., large automobile companies, oil companies, or electric power generators) account for a giant rate of the gross emissions, such strategic revolution can occur. With internationalization, foreign-funded and small enterprises are more inclined to adopt industrial relocation (environmental regulations affect

the location of enterprises) or industrial transfer strategies to avoid the rising energy-saving and emission reduction costs. As market followers, small enterprises may also “wait-and-see” due to the strong uncertainty of environmental regulations. In the short term, they will be locked in existing technologies and even crowding out innovation investments, thus presenting a negative correlation, the so-called “compliance cost effect.” In the long-term, however, such enterprises will employ mature and optimal technology for a higher productivity by imitation or introduction. For state-owned enterprises with strong market power, it is highly tempting to gain larger emission space by seeking political connections [80], especially in the context of Chinese-style decentralization. It is a remarkable fact that stringent environmental standards, which bring inefficiency to the firms, can push the firms to look for measures in pollution abatement, including the renewal of end-of-pipe technologies, enhancing resource utilization, and substitution by new energies. In case such standards are satisfied, enterprises, however, will have no further incentives to aim for research and innovation, specifically relating to policies on technical standards [27].

Second, the economic incentives caused by government subsidies preferential policies (e.g., Green credit) and taxes, on the one hand, stimulate enterprises to develop energy conservation and emissions reduction technology, i.e., induced innovation, and on the other hand, promote enterprises to adopt backstop technology, i.e., new energy substitutions. Confronted with larger incentives and the urgency for long-term development, leading enterprises have a greater incentive to develop energy conservation and emission reduction technologies. High-tech enterprises also struggle to develop new energy technology due to seizing development opportunities. With the deepening of market-based policies, the comparative advantages of new energies have become more and more prominent, which provides a proper market for the development and application of renewable energy technology. Backstop technology becomes one of the alternative strategies for enterprises to realize the substitution of new energy.

Third, IR, such as social regulation, exerts pressure on the enterprises’ social responsibility. Facing social pressure, enterprises take an end-of-pipe pollution abatement strategy to deal with environmental issues, promoting the company’s social image. Especially under the circumstances of information asymmetry and imperfect social supervision systems, enterprises tend to adopt mature end-of-pipe pollution abatement technology to deal with such social pressure, and once the pressure is relieved, they may not increase such innovation investment, ultimately leading to the failure of the “strong Porter hypothesis” in environment-biased technological progress. Leading enterprises, which pay more attention to social responsibility, prefer to take new energy as the substitution of traditional energy for long-term development. Thus, new energy technology plays a vital role in driving the future sustainable development of enterprises.

For several reasons, to address various types of environmental problems, different types of environmental regulations are adopted that put different pressures on enterprises. Thereafter, considering the internal and external environment and conditions, enterprises may adopt differentiated strategies and promote diversified energy- and environment-biased technological progress for complex stress, brought by diversified environmental regulations. Finally, there are the heterogeneous effects of diverse environmental regulations on biased technological progress. Additionally, from a dynamic perspective, environmental regulations vary in time and are uncertain, thus leading to more complex effects on biased technological progress. The above theoretical conclusions generally favor the three following hypotheses:

Hypotheses 1 (H1). *Environmental regulation exerts influences on technological progress, but the specific effects are uncertain.*

Hypotheses 2 (H2). *Different kinds of environmental regulations have different impacts on biased technological progress.*

Hypotheses 3 (H3). *The influence of a certain environmental regulation on different biased technological progress are heterogeneous.*

4. Model and Data

4.1. Model

Based on the aforementioned analysis, a basic model was established to detect the nexus between different environmental regulations and directed technical progress [89,90]:

$$Tech_{it} = \alpha + \beta ER_{it} + \beta_j Control_{it} + year_t + region_i + \varepsilon_{it}, \quad (1)$$

where $Tech_{it}$ indicates biased technological progress, namely, energy-saving technological progress (ES), backstop technological progress (BT), and pollution abatement technological progress (PA). ER_{it} indicates environmental regulation, specifically referring to CCR, MBR, and IR. $Control_{it}$ represents control variables. $year_t$ and $region_i$ are the year and region fixed effects, and ε_{it} is a random error term.

Allowing for the path dependence of technological development, the so-called “inertial technology” [91], a dynamic model was constructed based on (1):

$$Tech_{i,t} = \alpha + \beta_1 Tech_{i,t-1} + \beta_2 ER_{i,t} + \theta_j Contral_{i,t} + year_t + region_i + \varepsilon_{i,t}. \quad (2)$$

Additionally, due to the regional heterogeneity in the Chinese economy, a model with an economic threshold was established [92–94]. In line with model (2), a dynamic panel threshold model was established as follows:

$$Tech_{i,t} = X'_{it} + (1, X'_{i,t})\delta_1 \{q_{i,t} > \gamma\} + \mu_{i,t} + \varepsilon_{i,t} \quad (3)$$

X_{it} contains the lag term $Tech_{i,t-1}$, grp_{it} estimates the development of a region's economy and is set as the threshold variable. Thus, the incidental parameter $\theta = (\beta', \delta', \gamma)'$ is removed through the generalized method of moments (GMM). The presence of the threshold is tested by a fast bootstrap algorithm. The null hypothesis and the alternative hypothesis are displayed as (4) and (5), respectively:

$$H_0 : \delta_0 = 0, \text{ for any } \gamma \in \Gamma \quad (4)$$

$$H_1 : \delta_0 \neq 0, \text{ for any } \gamma \in \Gamma \quad (5)$$

Herein, Γ is the parameter space of γ .

4.2. Data

4.2.1. Dependent Variables

Based on the aforementioned studies (Table 1), the method of relative efficiency is more applicable in evaluating diversely directed technological progress. Herein, energy- and environment-directed technological progress was measured by a super-efficiency model. Following Zhou and Feng [95], the “energy–environment efficiency” super-efficiency model is given as follows:

$$\left\{ \begin{array}{l} \text{Min} \beta + \gamma + \varphi \\ \text{s.t. } \sum_{t=1}^T \sum_{k=1, k \neq k'}^K z_k^t x_{kn}^t \leq x_{k'n}^t, \forall n; \sum_{t=1}^T \sum_{k=1, k \neq k'}^K z_k^t e^{-t}_k \leq \beta e^{-t}_{k'}; \\ \sum_{t=1}^T \sum_{k=1, k \neq k'}^K z_k^t e^t_k \leq \gamma e^t_{k'}; \sum_{t=1}^T \sum_{k=1, k \neq k'}^K z_k^t y^t_k \geq y^t_{k'} \\ \sum_{t=1}^T \sum_{k=1, k \neq k'}^K z_k^t b^t_k = \varphi b^t_{k'}; z_k^t \geq 0, \forall k, t \end{array} \right. \quad (6)$$

Here, (x, e^-, e, y, b) denote the non-energy, non-fossil energy (or renewable energy) and fossil energy inputs, and desirable and undesired outputs, respectively. T is the number of periods, and K is the number of decision units. (β, γ, φ) represent non-fossil energy (or renewable energy) efficiency, fossil energy efficiency, and environmental efficiency, respectively, measuring the backstop technological progress (BT), energy-saving technological progress (ES), and pollution abatement technological

progress (PA). The input includes fossil energy, renewable energy, capital stock, and labor. The desired output indicator is the regional GDP, and the undesired output is carbon dioxide (CO₂) emissions.

4.2.2. Independent Variables

There are many metrics for environmental regulation, which were analyzed in Section 2.2. Herein, the indicator for environmental regulations were selected based on the following considerations: (1) the coverage of the tools, considering that the Chinese government often pilots some regulation tools in several provinces [20]; (2) the representativeness of indicators, assuring that synthetic indicators are more representative; and (3) the uniformity, completeness, and availability of data, given that some indicators feature inconformity or vanish in the statistics in the long term. Figure 2 shows the commonly used indicators of environmental regulation in many studies. Among them, CCR1 was constructed by calculating the proportion of basic keywords including “environment”, “pollution”, “ecology”, “control”, “energy saving”, and “emission reduction” to total government work reports [96]; CCR2 is the acceptance of environmental administrative punishment cases; CCR3 is the implementation rate of the environmental assessment institution; CCR4 is the industrial solid wastes’ comprehensive utilization rate; and CCR5 is a newly implemented environmental law and regulation. MBR1 is the gross pollutant discharge fee; and MBR2 is the complete investment amount for industrial pollution control. IR2, IR3, and IR4 are the total number of letters, visitors, and visiting batches, respectively, of the environmental petition letter of each province in the current year. IR1 is a comprehensive indicator calculated by the entropy method based on IR2, IR3, and IR4. Allowing for the context of China’s environment protection, CCR1, MBR1, and IR1 were chosen as the indexes for CCR, MBR, and IR, respectively. According to Figure 2, these three indicators showed a general upward trend during the sample year, which was in line with China’s real-time emphasis on environmental protection and the strengthening of regulatory efforts in recent years.

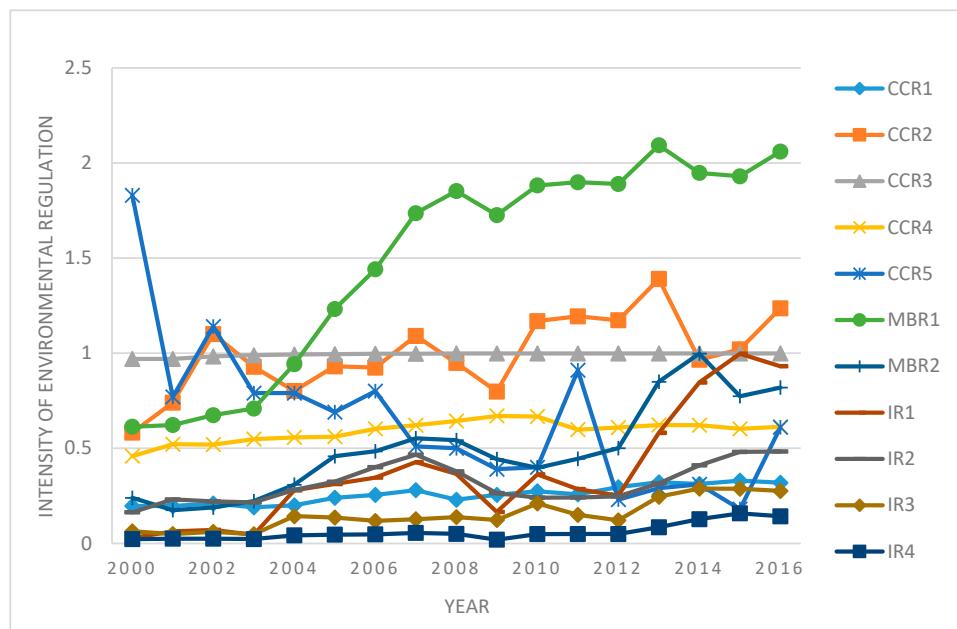


Figure 2. Indicators of environmental regulation and its trend in China from 2000 to 2016. **Note:** CCR1–5 indicate the corresponding control and command regulations, MBR1 and 2 indicate the market-based regulations, and IR1 to 4 indicate the informal regulations. Details about the indicators are provided in the paragraphs above. Data were sourced from calculations by the authors based on China’s Statistical Yearbooks from 2001 to 2017, the China Statistical Yearbook on Environment from 2001 to 2017, and the Statistical Communiqué of the People’s Republic of China from 2001 to 2017. Allowing for the comparability of indexes, the units of the indicators were dealt with.

4.2.3. Control Variables

Bias in technological progress results from various sources [61]. Control variables in this paper included human capital (edu), R&D expenditure (rd), FDI, openness (open), public budget (gov), information level (post), and the structure of energy consumption (ecs) [16,91,97,98]. In detail, as the supporter of innovation, human capital (edu) is measured by the weighted average assignment of classified different levels of education. R&D activities measured by the proportion of R&D expenditure to the GDP play the core role and a strong guiding role in technological innovation. Calculated by the ratio of FDI to the GDP, FDI's spillover effect on technological progress under environmental regulations may show the effect of the "pollution halo" or "pollution heaven". Calculated by the proportion of total import and export volume to the GDP, the openness of the economy (open) determines the introduction and exchange of international advanced technology and directly impacts technological progress. The public budget (gov) was calculated via the proportion of government fiscal expenditure to the GDP, reflecting the government's dominance of an economy and positively affecting technological innovation, especially for technologies with positive externalities. The level of informatization (email), measured by the total amount of postal and telecommunication services, evaluates the level of development of information technology and can promote technology spillovers by reducing the transaction cost of information. Energy consumption structure (ECS), calculated via the proportion of coal use to the gross energy consumption, directly affects energy efficiency due to the fact that different energies have different calorificity and emissions.

The 2000–2016 panel data of 30 provinces (cities) in mainland China were selected, and the data sources included the China Statistical Yearbook, China City Statistical Yearbook, and the Statistical Communiqué of the People's Republic of China. Table 3 displays the corresponding summary statistics for all variables. In contrast to BT and FDI, the mean value of the other variables was greater than the standard deviation, indicating that the data do not include extreme values and the overall dispersion of the data is not high; therefore, further model analysis could be performed with the data.

Table 3. Descriptive statistics of the main variables.

Variable	Description	Symbol	Sample	Mean	Std. Dev.	Min	Max
Explained variable	Energy-saving technological progress	ES	510	0.6936	0.2597	0.2188	1.9350
	Backstop technological progress	BT	510	0.2560	0.3748	0.0000	1.9519
	Pollution abatement technological progress	PA	510	0.5322	0.2855	0.1135	2.8316
Core explanatory variable	Command-and-control regulation	CCR	510	0.8548	0.2242	0.1893	1.8152
	Market-based regulation	MBR	510	0.0782	0.0656	0.00016	0.6899
	Informal regulation	IR	510	0.1387	0.1196	4.25×10^{-5}	0.7728
Threshold variable	Economic development level	gdp	510	2.1022	1.5123	0.2645	8.5954
Control variable	Human capital	edu	510	8.4035	1.0559	5.4383	12.3891
	R&D expenditure	rd	510	0.0127	0.0104	0.0015	0.0628
	FDI	fdi	510	0.0270	0.0295	0.0000	0.2074
	Openness	open	510	0.3415	0.4399	0.0133	1.8910
	Public budget	gov	510	0.1989	0.0933	0.0262	0.6269
	The level of informatization	post	510	5.8691	1.0537	1.5933	8.8382
	Energy consumption structure	ecs	510	0.6426	0.4306	0.0981	7.8600

Note: data were sourced from calculations by the authors based on China's Statistical Yearbooks from 2001 to 2017 [99], China Statistical Yearbook on Environment from 2001 to 2017 [100], and the Statistical Communiqué of the People's Republic of China from 2001 to 2017 [101].

5. Results and Analysis

5.1. Basic Analysis of the Nexus between Environmental Regulations and Technical Progress

Due to endogeneity problems, the GMM method was adopted for regression. According to Table 4, the Autocorrelation (AR) test, Sargen test, and Hansen test showed that the GMM was suitable and robust for the regression.

Firstly, CCR has promoted progress in energy-saving and pollution abatement technologies but had a negative effect on backstop technological progress. CCR was the core of China's environmental regulation system for a long time, until the market economy development brought about an increased application of MBR and IR [102]. Meanwhile, fossil energy and environmental protection technologies are relatively mature and have always been used for sustainable development in China. The existing administrative regulation and information system is capable of sufficiently implementing CCR. Thus, the implementation and promotion of CCR can stimulate the fossil energy-saving and pollution abatement technological progress. However, to date, the utilization of new energies is insufficient in China. New energies have an indistinct scope, and new energy technology is relatively lagged and appears immature. Therefore, there is a higher possibility of "government failure" on CCR for accelerating backstop technological progress. That is, improper governance environmental regulation may increase intervention costs, hinder innovation and resource utilization, and entail undesired results [23].

Secondly, MBR has a positive effect on the progress of pollution abatement technology, but a negative impact on that of fossil and non-fossil energy technologies. The main reason may be that frequent environmental disasters and a changing climate make it urgent to internalize environmental costs. Moreover, market-based environmental regulations result in the environment becoming the more expensive factor for sustainable economic development. Aiming to save more costs, enterprises would prefer to develop environmental conservation technology. Additionally, the current tools of MBR in China mainly include emission fees, emission permits, and environmental taxes [20]. Both emission fees and emission permits focus on the environment and directly stimulate enterprises to adapt cleaner technology, reduce pollution emissions, and subsequently promote environmental efficiency. Environmental taxes, which focus on both pollution emissions and energy consumption, aim at influencing environmental inputs and outputs. Unfortunately, China's MBR system is not perfect. The fact that China officially levied environmental protection taxes from 1 January 2018, has led to MBR that positively impacts progress in pollution abatement technologies, but fails to promote energy-related technological progress.

Finally, IR, the so-called voluntary environmental regulation, promotes the progress of fossil energy and non-fossil energy technologies but fails to promote pollution abatement technological progress. IR depends on the residents' environmental awareness and is devoted to overcoming the information asymmetry between government regulations and corporate pollution emissions. First, information-based regulations (namely IR) mainly positively stimulate progress in energy technology from the view of household consumption choice. China has established a comprehensive product energy labeling system since 2004. With an increasing environmental awareness, residents are more inclined to consume low-energy and new energy products. The residents' consumption choices promote a new energy utilization and energy efficiency [24]. In contrast, such regulations fail to effectively identify the consumer market for pollution abatement technological progress. Furthermore, China's lack of non-governmental environmental organizations and social groups makes it almost impossible to express the environmental demands of residents. Under Chinese-style decentralization, the information asymmetry between central and local governments on environmental issues led to a lack in feedback related to the residents' environmental complaints [103,104]. As per the aforementioned analysis, enterprises can develop end-of-pipe pollution abatement to cope with informal environmental regulations. Once the residents' environmental complaints are met, enterprises will lose the motivation to make further environmental protection efforts [27].

Table 4. Regression results of environmental regulation affecting technological progress.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	ES	ES	ES	BT	BT	BT	PA	PA	PA
L.Y	0.9376 *** (40.33)	0.9093 *** (63.83)	0.9295 *** (54.69)	0.7627 *** (37.50)	0.7352 *** (42.07)	0.7840 *** (62.14)	0.8299 *** (18.96)	0.7828 *** (20.07)	0.4387 *** (10.44)
CCR	0.1150 *** (8.14)			−0.2794 *** (−9.33)			0.0570 ** (2.31)		
MBR		−0.0563 *** (−3.34)			−1.0358 *** (−8.65)			0.3323 *** (3.16)	
IR			0.0909 *** (2.94)			−0.1639 *** (−3.43)			−0.2434 *** (−4.58)
edu	0.0372 *** (7.44)	0.0138 *** (3.56)	0.0461 *** (14.06)	0.0151 (1.08)	−0.0016 (−0.20)	0.0215 ** (2.49)	0.0467 *** (5.65)	0.0560 *** (7.73)	0.0976 *** (6.26)
rd	−1.6045 (−1.29)	7.5705 *** (5.42)	5.6047 ** (2.19)	10.4415 *** (2.79)	7.3721 *** (5.09)	3.7107 ** (2.01)	0.7324 (0.28)	1.6818 (0.91)	−4.2678 (−1.25)
open	−0.0390 (−1.19)	−0.1524 *** (−5.10)	0.0146 (0.67)	−0.1122 *** (−4.04)	−0.0620 *** (−3.13)	−0.0432 ** (−1.99)	−0.0403 (−0.48)	−0.2280 *** (−3.60)	−0.1341 *** (−4.45)
post	0.0049 (1.23)	0.0017 (0.44)	0.0432 *** (16.02)	0.0827 *** (18.99)	0.0577 *** (12.15)	0.0782 *** (13.39)	0.0143 *** (3.85)	0.0345 *** (17.13)	0.0294 ** (2.55)
gov	0.1291 * (1.87)	0.2296 *** (3.77)	0.2393 ** (2.54)	1.6899 *** (18.20)	1.5136 *** (15.90)	0.2256 ** (2.15)	−0.1240 (−0.84)	0.1046 (0.94)	−0.8151 *** (−3.17)
ecs	0.0152 (1.01)	0.0621 *** (5.29)	0.0664 *** (2.73)	0.0139 (0.35)	0.0709 (1.04)	0.0272 *** (3.93)	−0.0219 *** (−5.98)	−0.0063 * (−1.88)	−0.0029 (−0.65)
fdi	−0.1115 (−0.41)	0.6438 (1.11)	0.5508 * (1.72)	1.5191 *** (2.66)	0.3292 (0.96)	1.2435 *** (3.09)	−0.6136 (−1.03)	3.4121 *** (4.85)	1.6529 ** (2.52)
Constant	−0.3946 *** (−10.34)	−0.1984 *** (−4.70)	−0.8056 *** (−17.63)	−0.7940 *** (−7.02)	−0.6047 *** (−5.35)	−0.6724 *** (−9.76)	−0.3953 *** (−8.27)	−0.6486 *** (−15.72)	−0.4152 *** (−3.69)
Observations	480	480	480	480	480	480	480	480	480
Number of ids	30	30	30	30	30	30	30	30	30
Sargan	143.1	44.38	26.37	51.18	49.59	38.58	55.84	40.10	41.87
P–Sargen	[0.142]	[0.133]	[0.147]	[0.111]	[0.142]	[0.302]	[1.000]	[0.639]	[0.538]
Hansen	25.09	23.59	24.40	23.42	17.24	11.81	19.70	18.04	27.15
P–Hansen	[1.000]	[0.929]	[1.000]	[0.983]	[0.999]	[1.000]	[1.000]	[1.000]	[0.940]
AR(1)	−2.588	−2.517	−2.430	−2.264	−2.252	−2.250	−1.951	−1.861	−1.842
P–AR(1)	[0.010]	[0.012]	[0.015]	[0.024]	[0.024]	[0.025]	[0.051]	[0.063]	[0.066]
AR(2)	0.519	−0.0108	−0.107	0.666	0.758	0.464	1.708	1.698	1.781
P–AR(2)	[0.604]	[0.991]	[0.915]	[0.505]	[0.448]	[0.643]	[0.088]	[0.089]	[0.075]

Note: the 1%, 5%, and 10% level significances are indicated by ***, **, and *, respectively; the T value in () and the *p*-Value in []. Data were sourced from calculations by the authors based on China's Statistical Yearbooks from 2001 to 2017, China Statistical Yearbook on Environment from 2001 to 2017, and the Statistical Communiqué of the People's Republic of China from 2001 to 2017. L.Y indicates a lack of the corresponding dependent variables. The full definitions of abbreviations can be found in Table 1. AR(1): first-order sequence autocorrelation, AR(2): second-order sequence autocorrelation. Sargan and Hansen statistics to test whether the model was overidentified.

With respect to the control variables, their influence on the three technological advancements is consistent and robust, except for the fact that the degree of openness (open) has a negative influence on the three types of technological progress, while other factors have contributed to the development of energy- and environment-biased technological progress. The main reason is that most of China's industries still belong to the mid- and downstream of the global value chain, and export products are still dominated by labor-intensive products. For a long time, the problem of "capture" has not been removed in developed countries. Therefore, openness failed to effectively promote technological progress. Education (edu) and R&D investments (rdgdp) are the main drivers of technological progress. The higher the government fiscal expenditures (govgdp), the higher the support of innovation. The postal and telecommunications business volume (post) indicates the contribution of infrastructure levels to innovation. FDI brings advanced technologies, and the resulting knowledge spillovers and industrial driving effects have contributed to technological advances.

5.2. *Nolinear Relationship of Environmental Regulation and Directed Technological Progress*

The aforementioned discussion indicated that different environmental regulations have different impacts on China's energy and environment-related technological progress. There are regional heterogeneities both in the type of environmental regulations and the direction of technological progress. These heterogeneities result from various sources, for example, resource endowment, technology input, industrial structure, and economic development. During China's economic transition, economic development is the basic factor to promote an increase in the technology input and upgrades to industrial structures, and to make the gap in regional resource endowments. In essence, there are considerable gaps across regional economies in China. Moreover, the regional economic heterogeneity may be the main factor that led to the differentiation in the impact of environmental regulations on directed technological progress. That is, with economic development, the nexus between environmental regulations and technological progress may not be a simple linear but a nonlinear relationship [60]. Hence, detecting the threshold effect of environmental regulations on technological progress is highly relevant. Previous studies describe this nonlinear relationship primarily through the environmental Kuznets curve and set watersheds, which divided pollution generation and treatment, by the inflection point on the curve [105,106]. This led people to mistakenly believe that environmental governance and technological progress will automatically improve with economic growth [107,108] and ignore the relevance of environmental regulations. Herein, the threshold model was adopted to detect the nonlinear nexus between the corresponding environmental regulations and directed technological progress.

In line with the above results of the GMM, the threshold model with the per capita GDP as the threshold was established [93,94]. According to the results shown in Table 5, there was a threshold effect between environmental regulations and biased technological progress.

The threshold effects of the three environmental regulations on energy-saving technological progress are consistent. When a region's per capita GDP was below the threshold value, all environment regulations showed a negative impact on fossil energy efficiency. Once the per capita GDP was over the threshold value, local environmental regulations significantly promoted fossil energy efficiency. Considering the traditional high-input and high-energy economic growth, energy input is a driving force behind local economic developments in China, especially in under-developed and/or resource-rich regions. Additionally, Chinese resource endowments led to coal being the main energy source. Generally, with Chinese style decentralization, under-developed regions often had less and incompletely implemented environmental regulations because of their aim to catch up economically. Therefore, facing the environmental costs compelled by corresponding regulations, enterprises in these regions preferred to relocate or transfer in response to stronger environmental regulations [95]. Thus, environmental regulations have a negative influence on fossil energy-saving technological progress. Along with a rapid economic development, technology-intensive industry booms and becomes the core force to economic growth. Meanwhile, stronger environmental regulations have been set and implemented to further a green economy. Because of the accumulation of capital and technology, enterprises pay lower

costs to switch to alternative energies and prefer technological innovations to deal with more stringent environmental regulations in the future. Therefore, environmental regulations successfully induce technological progress on energy savings.

Table 5. Dynamic threshold regression results.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	ES	ES	ES	BT	BT	BT	PA	PA	PA
CCR_b	−1.7568 *** (−3.44)			2.0403 * (1.66)			−0.4294 * (−1.77)		
MBR_b		−4.1950 * (−1.73)			−2.3696 ** (−2.06)			−2.5984 * (−1.77)	
IR_b			−6.1511 ** (−2.03)			−2.0228 ** (−2.49)			3.7032 ** (1.96)
CCR_d	2.3141 *** (5.42)			−1.8669 * (−1.78)			0.6493 * (1.89)		
MBR_d		7.2414 ** (2.09)			3.7368 ** (2.21)			4.4569 ** (2.28)	
IR_d			1.0837 * (1.92)			2.3625 (1.53)			−3.9611 ** (−2.16)
γ	1.0169 ** (2.13)	2.6402 *** (3.12)	0.8591 ** (2.36)	2.6853 ** (2.24)	2.6628 *** (10.56)	2.3697 *** (7.75)	2.3471 ** (2.19)	2.5050 ** (2.00)	0.9718 *** (3.16)
Bootstrap p-Value for linearity test	300	300	300	300	300	300	300	300	300
Observations	480	480	480	480	480	480	480	480	480
Number of ids	30	30	30	30	30	30	30	30	30

Note: the 1%, 5%, and 10% level significances are noted by ***, **, and *, respectively; the T value in (). Data were sourced from calculations by the authors based on China's Statistical Yearbooks from 2001 to 2017, China Statistical Yearbook on Environment from 2001 to 2017, and the Statistical Communiqué of the People's Republic of China from 2001–2017.

Within the regression on backstop technology, below the threshold, CCR and MBR had a significant positive and negative coefficient, respectively; once above the threshold value, they had opposite coefficients. This indicates that, with economic development, environmental regulations should switch from CCR to MBR to accelerate non-fossil energy technological progress. This is in agreement with the results of Xie et al. [27]. In less developed regions, a lagged marketization and government competition with “Chinese style decentralization” lead to market segmentation, so that the market cannot optimize the allocation of non-fossil energy [108]. Moreover, because of a backward economic development, non-fossil energy consumption is relatively small, and residents have a low acceptance and recognition of non-fossil energy [86]. There is a need that the government drives backstop technological progress by CCR. With economic development, the residents' demands for the non-fossil energy and consumption of new energy have increased. Furthermore, the role of marketization in resource allocation has been strengthened. Therefore, MBR promotes new energy efficiency. Meanwhile, CCR increases the environmental costs of enterprises, which extrudes backstop technological innovation, and ultimately fails to promote the efficiency of new energies.

For pollution abatement technological progress, below the threshold, CCR and MBR had a negative impact on pollution abatement technological progress; once above the threshold, they significantly promoted environmental efficiency. By contrast, IR had the exact opposite effect. In the initial stages of an economy, the production technology of enterprises was generally backward, and it is difficult for such industries to invest in clean technology innovation. Both government and market regulations force enterprises to accept increased emission reduction costs and crowding out investments in environmental technology innovation. Stringent environmental regulations may cause enterprises to migrate, but as the local economy develops, enterprises would have a tendency to stay local due to the home market effect [66]. With economic growth, the industrial transfer brought about by environmental regulations is reduced, and the resulting economic losses are reduced correspondingly. With the development of clean technology and a clean economy, enterprises have accumulated sufficient capital and technology, and the marginal costs of environmental protection are reduced. Thus, CCR and MBR

can force the advancement of pollution abatement technology [109,110]. In China, social supervision does not constitute a direct constraint on enterprises, and the current public supervision fails to solve the environmental pollution problem. The main reason is that the companies' emissions are determined by the government, and the public's demands for the environment are difficult to reflect. IR, which is maintained by public supervision, has not become the incentive of the enterprises' environmental technological progress.

6. Conclusions

Based on China's 2000–2016 data, the impact of environmental regulations on biased technological progress from theoretical and empirical aspects was analyzed. Environmental regulations were divided into command-and-control regulations (CCR), market-based regulations (MBR), and informal regulations (IR), and the different effects of environmental regulations on environmental- and energy-biased technological progress were analyzed. Based on this, the heterogeneous influence of environmental regulations on biased technological progress at different stages of economic development was discussed. Clean technology progress is the effect of technology development efficiency and environmental policy accumulation. Policy intervention will change the direction of technological progress by affecting compliance costs and changing economic incentives and social responsibility pressure. Different environmental regulation policies have different focuses and biases. CCR has a promoting effect on the progress of fossil energy and environmental technologies. Because of the lack of information and the high costs of decision-making in CCR, government intervention has increased the costs of progress in non-fossil energy technology. Due to the current restrictions on China's energy consumption structure and market regulation system based on emission fees and emission permits, MBR can effectively promote environmental technology progress, but there is a crowding out effect on energy technology progress. The improvement of IR is conducive to the progress of environmental technology, but not conducive to the progress of energy technology. Research also shows that the impact of environmental regulations on technological progress depends on the level of regional economic development. In regions with a low level of economic development, the degree of marketization is low, and CCR plays an important role in the progress of energy and environmental technology. With the development of the economy, shortcomings of CCR have emerged. At this time, CCR and MBR are required to complement each other. In economic developed areas, MBR is the main environmental regulatory force. However, the role of IR in China's biased technological progress is not prominent.

At this stage, China is facing the dual pressure of a slowed economic growth and a deteriorating environmental quality. Completely relying on market forces may lead to insufficient clean technology innovation, and economic growth will be locked on an unsustainable path, leading to unsustainable development. Policy interventions can change the direction of environmental technological progress and achieve a compatible development of economic growth and environmental quality. To achieve a sustainable development and promote progress in clean technology, China needs to make environmental regulation an important regulatory means. Adopting targeted environmental regulation means is an effective way to promote progress in clean technology and solve environmental pollution. In the long run, the fundamental driving force for economic development is technological progress. Clean technology is the main driving force for a green economic growth, which considers the sustainable development of the economy and environmental protection. Different types of environmental regulations have different effects on technological progress with various biases; furthermore, to change the direction of technological progress and reduce the costs of environmental degradation, the most controllable environmental regulations have to be determined. By driving clean technologies, effective environmental regulations will and be a win-win situation for China to deal with environmental pollution and improve energy efficiency, and make the commitments that its carbon emissions would peak no later than 2030 a possibility. At the same time, system and management innovations of environmental regulation policy designs should be strengthened, and full play should be given to the

incentive effect of MBR and IR on progress in green technology. The formulation of environmental regulatory policies must be tailored to local conditions and fully consider the actual local conditions. Different types of regulatory tools should be used rationally to give full play to their respective advantages. In addition, to prevent the transfer of polluting industries brought about by regional regulatory policies of different economic development levels, the joint governance capabilities between regions should be improved, the regional ecological environment should be promoted to form a virtuous cycle system, and a regional joint governance should be implemented.

Because of the technical and data limitations, there are still many problems that need to be further studied. Firstly, the analysis of the comparative advantages of biased technologies among regions. Due to the differences in resource endowments between regions, the appropriate economic development paths differ. In the future, in the process of the coordinated economic development between regions, the use of advantages of each region to achieve complementary advantages in favored technological progress, thereby reducing the costs of technological progress and realizing a sustainable development, is one of the important directions of technological progress research. Secondly, herein we preliminarily analyzed the threshold of regional environmental regulation policies based on the heterogeneity of economic development levels. However, there are differences in resource endowments, historical conditions, and institutional arrangements among regions. Therefore, in the process of implementing environmental regulations, it is necessary to comprehensively utilize the policy combination of CCR, MBR, and IR, and implement environmental governance according to local conditions to avoid the “one size fits all” environmental governance crowding out of technological innovations.

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