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The Rebound and Fixed Effect of Technological Progress on Energy CO_2 Emissions in China

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ABSTRACT

The goal of this study is to develop a model based on panel data from 30 Chinese provinces to assess rebound and fixed effects, as well as policy implications, in order to provide a theoretical foundation for the rapid advancement of low-carbon transformation, which is a necessary result of a new stage in environmental growth. The results of primary analysis are the CO_2 emission intensity reached 15.72 kt/million yuan in 2019, which was an great decline of 21.86 kt/million yuan as compared with the intensity in 2001; the average value of technological progress reached 1.017, waved like a U shape. The findings of empirical study show that the amount of energy CO_2 emission rebound ranged widely; the average value of the rebound impact was -0.449; a 1% rise of technological progress led a 0.442% CO_2 emission decrease, notably in Central and Western China. The results lower the cost of drafting energy policies as well as the decision-making involved and increase the economic advantages and transformation rate of technical breakthroughs in practice.

1. INTRODUCTION

Governments world over are actively promoting energy conservation and emission reduction policies to address the challenges brought about by global warming, which has threatened ecosystems and human health in recent years [1]. High fossil energy use and CO_2 emissions resulting from human activities are key contributors of global warming, according to the Intergovernmental Panel on Climate Change's fourth assessment report [2]. Even though various nations have established enforceable framework agreements, such as the United Nations Framework Convention on Climate Change, the Kyoto Protocol, and the Paris Agreement, clarifying CO_2 emission reduction strategies, global CO_2 emissions increase is still uncontrollably high. According to the survey report of the United Nations Environment Programme, total global CO_2 emissions in 2019 reached 59.1 billion tons, an increase of 6.87% when compared with that of 2018. China has long been an active participant in global climate regulation as a developing country with the world's largest economy and the highest CO_2 emissions [3].The drive toward and realization of carbon peaking and carbon neutralization were the key tasks mentioned in the 2021 Central Government Work Report. Simultaneously, the State Council of the People's Republic of China has emphasized the acceleration of the green and low-carbon technological revolution, and the development of applicable low-carbon technologies in key fields. Analyzing the influence of technological progress on energy CO_2 emissions and researching China's low-carbon growth route have become crucial practical issues. We will investigate the rebound impact of energy CO_2 emissions over time, as well as the direct influence of technological progress on energy CO_2 emissions, using data from 2001 to 2019. This discussion is deemed to be of great theoretical and practical significance for energy transformation because it will provide scientific basis for Chinese governments to formulate CO_2 emission reduction policies.

The following is how the paper is organized: Section 2 examines the literature on various perspectives on the relationship between technological progress and CO_2 emissions at home and abroad; Section 3 presents the research hypotheses, methodology, and variable setting; Section 4 summarizes the performance of energy consumption and its structure, CO_2 emissions, and technological progress over time using data from China; Section 5 discusses the results of the rebound model and fixed effect model; and Section 6 concludes.

2. LITERATURE REVIEW

To explore the better low-carbon transformation methods, an increasing number of scholars have studied numerous factors involving CO_2 emissions. Technological progress is a key factor in addressing climate change and CO_2 emission reduction. The IPAT model was developed by Ehrlich and Holden [4] as a pioneering study of the impact of technology on the environment, with population, economic development, and technology as the key driving forces. Later, Dietz and Rosa [5] also propounded the STIRPAT model as a

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variant of the IPAT model. Considering the severe environmental problems, technological progress has gained proliferating importance. As a result, academics have begun to debate the impact of technical innovation on CO_2 emissions; nevertheless, most of them have yet to reach an agreement. The research conclusions can be divided into three categories.

First, technological progress aids in the decrease of CO_2 emissions. Goulder and Schneider [6] discovered that R&D efforts and technological progress can minimize the real cost of CO_2 emission reduction by studying the general equilibrium model. Cole *et al.* [7] argued that improving productivity and enhancing technical innovation may effectively cut CO_2 emissions. Kumar and Managi [8] used the static panel model to examine the link between productivity and CO_2 emissions and discovered that technological progress aided in CO_2 emission reductions, particularly in developed nations or high-income areas [9]. Wei and Yang [10] conducted a thorough analysis of the variables influencing CO_2 emissions in China, using the endogenous growth theory, and concluded that technological progress favors CO_2 emission reduction. Li and Qu [11] used total factor productivity as a metric of technological progress to see if it had any long-term influence on CO_2 emissions. Li and Niu [12] used static and dynamic panel modeling to perform an investigation and discovered that China's technological progress may greatly cut CO_2 emissions. Kim *et al.* [13] used a spatial model to examine the impact of each city's technological progress to CO_2 emission reduction. They used data from 23 cities in South Korea from 1989 to 2013. Wang and Wei [14] used the grey correlation model to examine the link between technological progress and CO_2 emission reductions in several industries in Beijing, and they testified that technological progress may increase CO_2 emission reductions. Theoretically, China’s CO2 emission reduction rate reached 5.66% by relying mainly on technological progress based on the data from 2005 to 2015 [15]. Because technological progress could improve energy efficiency [16], optimize energy consumption structures [17],which could achieve energy conservation and emission reduction.

Second, technological progress has been demonstrated to be favorable for CO_2 emissions [18] owing to economic growth [19] and the increase of industrial scale [20], particularly in Western China [21] and most developing nations [8], where limiting CO2 emissions was difficult [22].Gong *et al.* [23] conducted a quantitative study of energy usage in the Yangtze River Delta using the STIRPAT model and data from 1997 to 2016, demonstrating that technological progress has not yet been quick enough to cut CO_2 emissions. In fact, certain forms of technological progress, such as structural production technology [24], energy utilization technology [25] and pollution technology innovation [26]-[27] promote CO_2 emissions.

Third, it appears that technological progress has an uncertain influence on CO_2 emissions [28]. Using the ridge regression estimate model [29], the enhanced STIRPAT model [30], or the VAR model [31], some research demonstrates that the association between technological progress and CO_2 emissions is not statistically significant. Some hypothesized that technical growth would not lower CO_2 emissions in the short term [11], whilst others experimentally discovered a nonlinear connection between technological progress and CO_2 emissions [32]-[33].

The "Jevons Paradox" gave rise to the rebound effect, which was later widely utilised in the field of energy economics. In China, studies on the rebound effect began late and mostly focused on the rebound impact at the macroeconomic and residential levels. Yang and Li [34] found the carbon rebound effect was about 10-60% in Chinese provinces from 1997 to 2010. Guo *et al.* [35] indicated the carbon rebound effect existed in Yangtze River Economic Belt, utilizing data from 2003 to 2017.

A lot of study has been done on the influence of technological progress on CO_2 emissions, and several studies have been done on the carbon rebound effect from various viewpoints, data, and techniques. However, there are few research on the rebound and fixed effect in China to confirm their link; moreover, the contentious results obtained compel the conduct of more in-depth investigations on the role of technological advancement to decreasing CO_2 emissions. Technological growth invariably influences the efficiency of energy usage, which in turn affects CO_2 emissions. This work intends to build a model based on panel data from 30 Chinese provinces, quantify the impacts, and then suggest policy implications to provide a theoretical foundation for the rapid growth of low-carbon transformation.

3. RESEARCH DESIGN

3.1 Research Hypothesis

Technological progress refers to the innovation and improvement of production technology with certain resources. The specific performance is the transformation and improvement of old equipment. It also refers to the rational allocation of resources (integration and distribution of input elements), decision-making ability and management (management plan, structural adjustment, policy constraints) and the relevant professional knowledge reserves for production and technology use (new knowledge, new technologies). China's economic expansion has boosted energy consumption in recent years, resulting in significant emissions. Therefore, the Chinese government has called for the adoption of low-carbon production technologies and increased energy utilization efficiency. This will undoubtedly affect economic development and CO_2 emissions. The increase in CO_2 emissions caused by a unit increase of GDP is selected to demonstrate the quantitative changes in the economy and actual energy CO_2 emissions. Technological progress is mainly manifested in the replacement of traditional energy by renewable or innovative energy [36]. Generally, the use of new technology would not only improve energy efficiency, but also drive energy demand, resulting in a simultaneous increase in both energy production and consumption. Thus, the energy rebound effect has received high attention from policy makers and academic researchers. The energy rebound effect is related to the energy policy formulation and the resulting CO_2 emissions. Given that technological progress has the dual effect of promoting and inhibiting CO_2 emissions, this study predicts that energy CO_2 emissions based on technological progress may also have a rebound effect.

The continuous development of mechanization and technological innovation have effectively promoted economic efficiency. Thus, producers will expand their energy demand. However, extensive investment in coal and coke will induce excessive consumption of energy, which will lead to more CO_2 emissions. Governments usually formulate energy transformation policies (low energy consumption, low emissions, and high efficiency) to constrain such unfavorable situations. In addition, producers need to continuously increase their professional knowledge and management experience to improve energy utilization efficiency. In general, with economic development and technological progress, the scale of social production has been expanding. The rise in energy consumption and the improvement in efficiency will occur in stages, which may result in a rebound impact of CO_2 emissions. Because of technological progress, the introduction of new technology and resource optimization techniques helps reduce wasteful energy waste, which aids CO_2 emission reductions.

H1: The rebound impact of CO_2 emissions may arise as technology advances.

Technological progress enables the introduction and learning of sophisticated technologies, as well as the optimization of resource allocation. Production technologies can promote economic benefits and can equip advanced machines with "low energy consumption and low emissions" capabilities. Producers can acquire professional knowledge through mutual sharing to reduce the cost of technology R&D and improve marginal productivity. Operation optimization can effectively avoid the unnecessary waste of resources and make producers aware of the value of renewable energy utilization. Thus, technological progress is an effective path for CO_2 emission reduction.

While there is a significant disparity in economic strength and resource distribution across Eastern, Central, and Western China, the Chinese government pursues various energy policies. Central and Western China fall far behind in terms of technology and capital. Because each province has different resource and technical advantages, the consequences on CO_2 emissions vary.

H2: Technological progress may lower CO_2 emissions, with the effect varying by regions.

3.2 Methodology

3.2.1 DEA-Malmquist

In comparison to the Solow residual value method [37], the STIRPAT [22], and the SBM methods [38], the DEA-Malmquist method overcomes the difficulty in determining and measuring productivity growth and can measure the dynamic efficiency of multiple decision-making units over different time periods, effectively avoiding errors caused by production function selection and parameter estimation. As a result, thirty (30) Chinese provinces are chosen as decision-making units, and the DEA-Malmquist approach is used to assess the growth rate of total factor productivity (TFP). The following are the particular explanations.

Assume that the distance functions of (α_t, β_t) in period t and period t+1 are Dt (α_t, β_t) and D_{t+1}(α_t, β_t), respectively. Similarly, the distance functions of (α_{t+1}, β_{t+1}) in the t and t+1 periods are D_t (α_{t+1}, β_{t+1}) and D_{t+1} (α_{t+1}, β_{t+1}).

Therefore, the Malmquist index in period t is:

$$M_t = \frac{D_t(\alpha_{t+1},\beta_{t+1})}{D_t(\alpha_t,\beta_t)} \tag{1}$$

The Malmquist index in period t+1 is:

$$M_{t+1} = \frac{D_{t+1}(\alpha_{t+1},\beta_{t+1})}{D_{t+1}(\alpha_t,\beta_t)} \tag{2}$$

Farrel [39] defined the growth rate of TFP in period t as the geometric mean of M_t and M_{t+1} under fixed returns to scale of the decision-making unit.

$$TFP_t = \sqrt{M_t \cdot M_{t+1}} = \sqrt{\frac{D_t(\alpha_{t+1},\beta_{t+1})}{D_t(\alpha_t,\beta_t)} \cdot \frac{D_{t+1}(\alpha_{t+1},\beta_{t+1})}{D_{t+1}(\alpha_t,\beta_t)}} \tag{3}$$

3.2.2. Energy CO_2 emission rebound effect model based on technological progress

If the added economic value of a province in period t is Y_t and the energy CO_2 emission intensity is CI_t, then the energy CO_2 emission in period t is $C_t = Y_t \cdot CI_t$. If there is technological progress in period t+1, energy CO_2 emission intensity becomes CI_{t+1}; then the CO_2 emission reduction caused by technological progress is presented in formula (4).

$$C_j = Y_{t+1} \cdot (CI_t - CI_{t+1}) \tag{4}$$

Furthermore, technological progress also induces economic growth. If ξ_{t+1} stands for the contribution rate of technological progress to economic growth in period t+1, the amount of CO_2 emission rebound caused by technological progress is presented in formula (5).

$$C_k = \xi_{t+1} \cdot (Y_{t+1} - Y_t) \cdot CI_{t+1} \tag{5}$$

in which ξ_{t+1} is the ratio of the TFP growth rate (GTFP) in period t+1 to the actual economic growth rate (GY) in period t+1. ξ_{t+1} and the rebound effect (RE) in period t+1 are calculated using formula (6) and formula (7), respectively. The different values of RE are explained in Table 1.

$$\xi_{t+1} = (\frac{GTFP}{GY}) \cdot 100\% = \frac{Y_t(TFP_{t+1} - TFP_t)}{TFP_t(Y_{t+1} - Y_t)} \cdot 100\% \tag{6}$$

$$RE = \frac{C_k}{C_j} = \xi_{t+1} \cdot \frac{(Y_{t+1} - Y_t) \cdot CI_{t+1}}{Y_{t+1}(CI_t - CI_{t+1})} \quad (7)$$

3.3 Model Specification

Basic model:

$$CI_{it} = \alpha_0 + \alpha_1 TP_{it} + \gamma X_{it} + \lambda_i + \lambda_t + \varepsilon_{it} \quad (8)$$

Where CIit means the intensity of CO_2 emissions in the ith province in year t; TPit denotes technological progress in the tth year; and Xit signifies a vector consisting of a number of control factors comprising energy consumption structure, industrial structure, and environmental regulation. Year fixed effect, province fixed effect, and random disturbance are represented by λi, λt and εit, respectively. Each model coefficient and its relevance should, of course, be examined, since this assists in the analysis of the link between technological progress and CO_2 emissions.

3.4 Variable Setting and Data Processing

Explained variable: The intensity of CO_2 emissions (CI) reflects the efficiency of CO_2 emissions [40]. In reality, the quantity of CO_2 emissions created by the GDP unit might indicate CO_2 emission intensity, which is an important prerequisite for achieving economic sustainability and low-carbon environmental development. CO_2 emissions are calculated from the coefficients of nine energy materials from IPCC Carbon Emissions Guidelines in Table 2.

Explanatory variable: Technological progress (TP) can be expressed by TFP and can be measured through the DEA-Malmquist method, which organically combines the traditional DEA model with the Malmquist index model [41-42]. This study focuses on input and output as the foundation for the DEA-Malmquist evaluation system. GDP influences economic production, and the value of GDP reflects output capability and competitiveness. Employment, capital investment, and total energy consumption are some of the inputs (Table 2). Capital investment would be made using each province's capital stock from 2001 to 2019.

Control variables: The fraction of coal usage in overall energy consumption yields the energy consumption structure (ECS) [43]. With varying energy demand, industrial structure (IS) influences the ultimate CO_2 emission intensity. Because the secondary industry consumes a significant amount of energy, it must be included in the analysis. The authors used the share of secondary industry production in GDP as a representation of industrial structure[36]. The share of local environmental protection expenditures in GDP[44] shows that environmental regulation (ER) has a considerable influence on CO_2 emissions.

From 2000 to 2019, statistics were gathered from the China Statistical Yearbook, the China Energy Statistical Yearbook, the China Statistical Yearbook on Environment, and the statistical yearbooks of 30 provinces (excluding Tibet, Hong Kong, Taiwan, and Macao). To avoid the influence of price variations, all statistics are adjusted at a constant price in the year 2000. Table 3 depicts the descriptive statistics for each variable.

Table 1. Classification of RE and its description.

RE	Effect	Energy policy
$(1, +\infty)$	Reverse effect	detrimental
1	Full-rebound effect	ineffective
(0, 1)	Partial-rebound effect	effective
0	Zero-rebound effect	effective
$(-\infty, 0)$	Over-storage effect	sustainable effective

Table 2. Coefficients of each energy material.

	Standard coal conversion coefficient	CO_2 emissions coefficient
Coal	0.7143	0.7559
Coke	0.9714	0.8556
Crude	1.4286	0.5538
Fuel-oil	1.4286	0.5857
Gasoline	1.4714	0.5921
Kerosene	1.4714	0.5714
Diesel	1.4571	0.6185
Natural gas	1.33	0.4483
Electricity	1.229	2.2132

Table 3. Descriptive statistics of each variable.

Variable	Obs	Mean	Std. Dev.	Min	Max
CI	570	2.039	1.742	0.296	9.516
TP	570	1.017	0.058	0.753	1.222
ECS	570	0.553	0.151	0.025	0.856
IS	570	0.456	0.082	0.162	0.615
ER	570	0.010	0.006	0.001	0.078

4. PRIMARY ANALYSIS

4.1 Energy Consumption and CO_2 Emissions

The total quantity of energy used is the sum of all types of energy consumed by various industries and households in a specific location over a specific time period. According to Figure 1, China's total energy consumption increased from 1.48 billion tons of standard coal equivalent (tce) to 4.48 billion tce in 19 years, demonstrating significant energy development in China. The total energy consumption in 2019 was 4.48 billion tce, which shows an increase of 2.7% over the previous year. The growth rate of energy consumption has slowed down since 2012 (3.1%), which has aided the rapid development of the national economy.

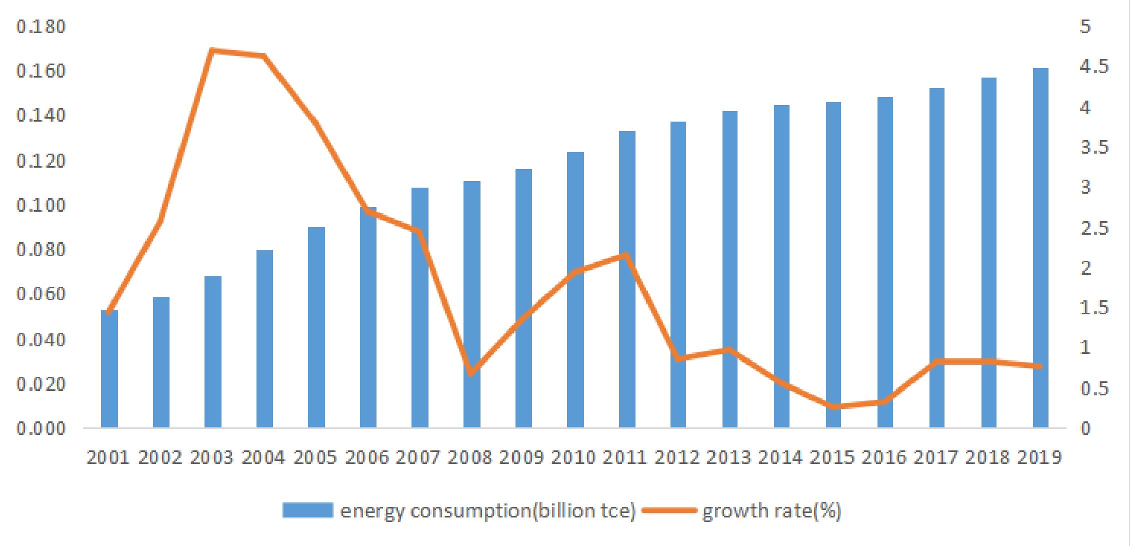

Fig. 1. Total energy consumption and its growth rate.

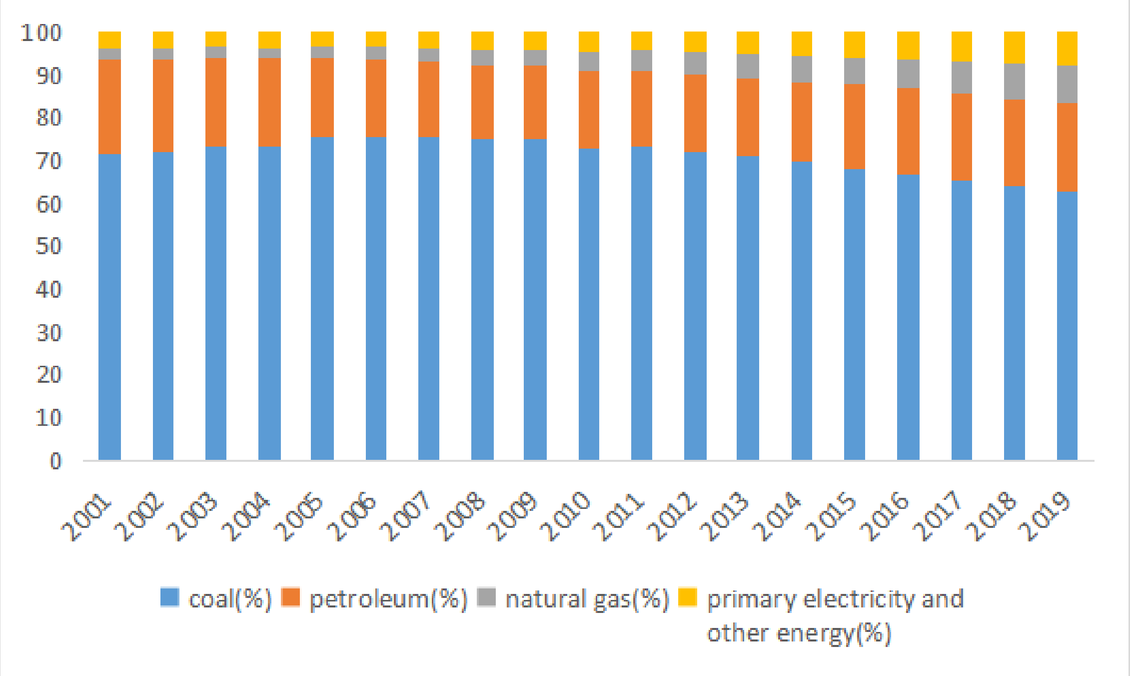

Fig. 2. Changes of consumption structure.

As seen in Figure 2, consumption of coal, petroleum, and natural gas, as well as primary power and other energy, has reached 2.811 billion tce, 0.927 billion tce, 0.389 billion tce, and 0.349 billion tce, respectively. Coal usage accounted for 62.8% of total energy consumption in 2019, a 1.1% decrease from 2018, but coal remained the primary energy source throughout 2001 and 2019. Petroleum, natural gas, primary electricity, and other energy use have grown in proportion to total energy consumption through time, illustrating China's ongoing optimization of the energy consumption structure.

The intensity of CO_2 emissions is a measure of a country's environmental quality. According to Figure 3, CO_2 emission reduction has made a great breakthrough in recent years. In 2019, the intensity was 15.72 kt/million yuan, a considerable decline from 2001 (21.86 kt/million yuan). It was evidence that the Chinese government had made sound judgments on the country's energy policy. Because of the relative weakness of the economy and resources, the intensity of CO_2 emissions in Central and Western China was around double that of Eastern China. CO_2 emissions intensity in Central and Western China and Eastern China had decreased by 23.76% and 42.04 %, respectively, when compared to 2001, exhibiting great policy accomplishment. However, China's energy CO_2 emissions in 2019 were 9.826 billion tons, accounting for 28.8% of total CO_2 emissions worldwide. As a result, CO_2 emission reductions in China must be hastened and expanded

4.2 Analysis of Technological Progress

Technological progress could be measured by the DEA-Malmquist method. As shown in Figure 4, technological progress declined from 2001 to 2009 and recovered during the next nine-year period. The average value of technological progress was 1.017, with half the years falling below average, illustrating technological progress in China being U-shaped. Central and Western China had a lower rating of technological progress (1.01) than Eastern China (1.029). Central and Western China's technological progress was below the national average; consequently, a bigger technological change is necessary.

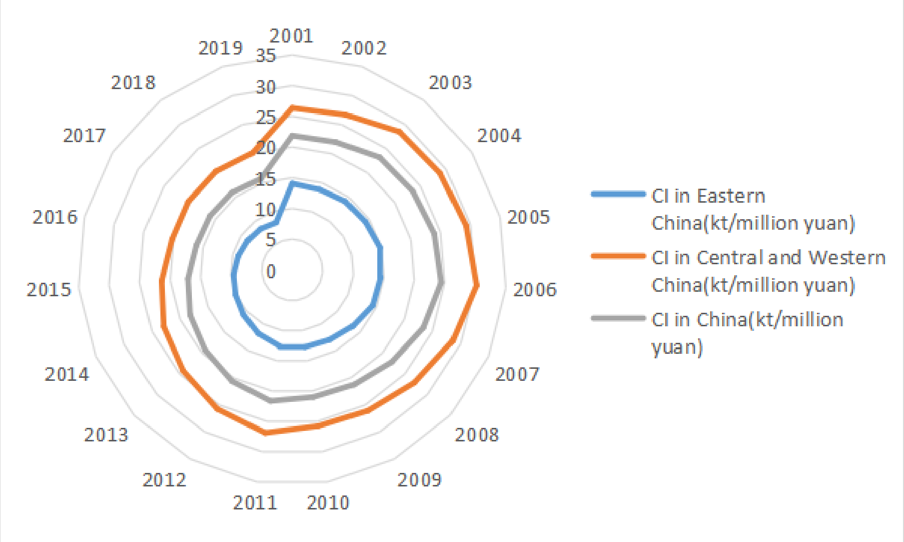

Fig. 3. CO_2 emission intensity in China.

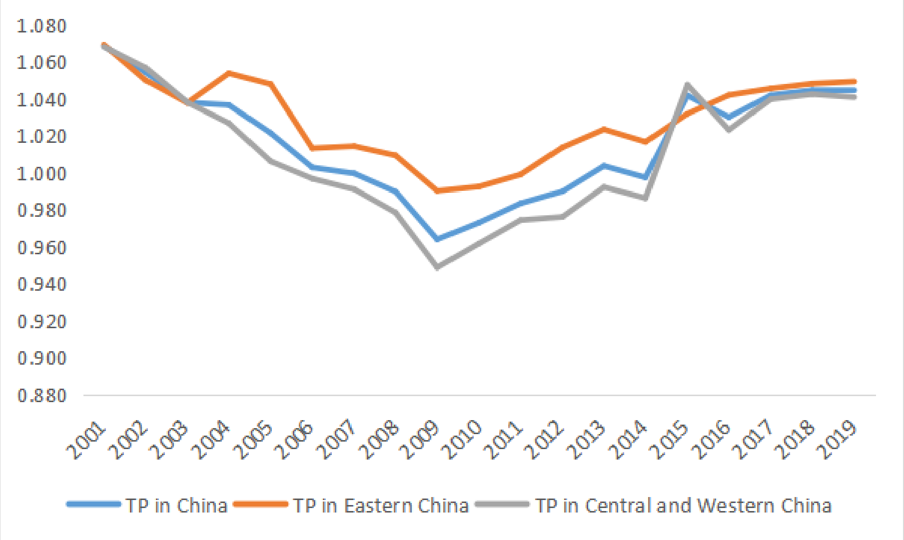

Fig. 4. Changes of technological progress in China.

5. EMPIRICAL ANALYSIS

5.1 Analysis of CO_2 Emission Rebound Effect Based on Technological Progress

Table 4 shows the amount of CO_2 emission reduction, rebound, and rebound effect in China from 2001 to 2019. The sample periods are divided into 2001–2007, 2008–2013, and 2014–2019. Table 4 shows that the quantity of CO_2 emission decrease, rebound, and rebound effect caused by technological progress varied substantially throughout time. With the exception of 2003–2006, there was an overall increase in CO_2 emission reduction over the years, from 1.908 million tons in 2001 to 5.44 million tons in 2019, with a cumulative increase of 185.313%. As for CO_2 emission rebound, there were large fluctuations in each year, with the lowest in 2009 reaching -5.522 million tons, and the highest in 2018 reaching 11.251 million tons. The overall average rebound effect was -0.449 and it was 0.924, 0.262 and -2.761 in 2001–2007, 2008–2013, and 2014–2019, respectively, reflecting the relatively strong performance of Chinese energy polices. Taking different years as an example, the partial-rebound effect was evident in six years; the over-storage effect was present in seven years and the reverse effect appeared in six years. Technological advances resulted in more CO_2 reductions than rebounds in most years, suggesting that energy-efficient policies worked positively. Table 4 strongly supports H1. Technological progress has led to a large investment in productive materials, allowing for the improvement of production and energy efficiency. Hence, energy CO_2 emissions have been gradually suppressed after a slight rebound. Technological progress and the extensive use of energy have promoted the rapid development of the national economy.

Table 4. The amount of CO_2 emission reduction, rebound and rebound effect by year.

Year	Reduction	Rebound	RE	Effect
2001	1.908	4.056	4.826	Reverse
2002	0.822	3.93.	0.422	Partial-rebound
2003	-2.235	2.832	2.100	Reverse
2004	-0.313	1.166	-0.041	Over-storage
2005	-4.130	1.241	0.323	Partial-rebound
2006	-0.266	0.616	-1.221	Over-storage
2007	5.857	-0.338	0.042	Partial-rebound
2008	8.131	-2.323	0.230	Partial-rebound
2009	6.873	-5.522	-3.328	Over-storage
2010	2.850	-4.360	2.907	Reverse
2011	0.014	-3.12	2.318	Reverse
2012	11.983	-2.461	-0.797	Over-storage
2013	15.327	-0.718	0.245	Partial-rebound
2014	11.584	-0.893	-0.997	Over-storage
2015	11.931	3.414	1.096	Reverse
2016	9.948	3.859	0.176	Partial-rebound
2017	6.966	9.196	1.454	Reverse
2018	4.693	11.251	-17.686	Over-storage
2019	5.445	10.200	-0.608	Over-storage
2001-2007	0.235	1.929	0.921	Partial-rebound
2008-2013	7.530	-3.084	0.262	Partial-rebound
2014-2019	8.428	6.171	-2.761	Over-storage
2001-2019	5.126	1.686	-0.449	Over-storage

The average value of rebound effect in Eastern, Central and Western China varied from 1.076, 6.997 in 2001 to 0.483, -1.239 in 2019. The evolution of rebound effect in China within 19 years showed various energy-saving and emission-reduction technologies have been gradually upgraded, and the growth of energy CO_2 emissions has been effectively restrained. The value of rebound effect in eight provinces were less than 0 in 2019, showing the over-storage effect happened and good energy polices formulation. Partial-rebound effect presented in fifteen provinces, such as Beijing, Shanghai, Chongqing. The value of rebound effect in Shanxi and Hubei reached 4.424 and 3.278, expressing bad energy policy implement with reverse effect.

5.2 Empirical Analysis

5.2.1 Basic regression model

Table 5 displays the regression outcomes. Model (I) and Model (II) report the result by Pooled OLS and FE model, and the coefficients were significantly negative. But Model (II) fit better for the higher value of R2. Therefore, FE model was selected for this study. The result was still likely to be endogenous because the causality would not be confirmed or important variables maybe omitted. Thus, the explanatory variable and control variables were lagged one year to get Model(III), which indicating that there was no serious endogenous problem in the basic regression model. The results demonstrated that technological progress had a direct influence on CO_2 emissions since the coefficient of CO_2 emissions was notably negative. That is, technological progress increased by 1%, CO_2 emission intensity dropped by 0.442%. H2 is supported and new technology and knowledge benefit innovation capacity and performance, which achieves clean and efficient use of energy. Environmental regulation has effectively promoted CO_2 emission reduction, while the proportion of the output of secondary industry in GDP and the proportion of coal consumption in total energy consumption have led to an increase in energy CO_2 emissions.

Table 5. Results of Pooled OLS and FE model.

	(I)	(II)		(III)
	CI	CI		CI
TP	-1.809***	-0.442***	L.TP	-0.652***
	(0.332)	(0.139)		(0.141)
ER	-2.53***	-2.132*	L.GR	-0.968
	(3.005)	(1.347)		(1.359)
ECS	2.483***	1.301***	L.ECS	1.097***
	(0.142)	(0.114)		(0.120)
IS	0.808***	1.060***	L.IS	0.876***
	(0.256)	(0.168)		(0.171)
_cons	-1.540***	-0.775***	_cons	-0.722***
	(0.114)	(0.0745)		(0.0765)
Year	Y	Y		Y
Province	Y	Y		Y
N	570	570	N	540
R2	0.5562	0.9547	R2	0.9562

5.2.2 *Robustness Test*

A robustness test was also performed to increase the credibility of the results. There are several ways for assessing robustness, including alternative variables, supplemental variables, sub-sample regression, and model replacement. For the robustness test, we replaced technology progress with R&D intensity[44], the number of patent [45] ,and spatial Durbin model(SDM) was selected, and Real GDP per capita was added in the model for robustness tests (Table 6). Real GDP per capita (pgdp) is a mirror of the living standard of people and economic growth in a country, which relates to CO_2 emissions greatly[46]. We see the direction of each model was consistent with Model II. The coefficients of technological progress in Model IV, Model V, Model VI and Model VII were significantly different from each other. Spatial rhos in Model(VII) was significant showing a strong spatial spillover effect between technological progress and CO_2 emissions. Due to the spillover effect of local excellent technology, professional knowledge and management experience by mutual learning and communication, energy conservation and CO_2 emission reduction were achieved in surrounding regions. The significance and coefficients of control variables were in line with the differences among model settings. Hence, the results of Model II are robust.

5.2.3 *Regional Heterogeneity*

Table 7 demonstrates the above-mentioned direct effect in Eastern China (model VIII), Central and Western China (model IX) as a result of varying regional economic growth and urban building. As we can see, technological progress had a negative effect on CO_2 emissions in Central and Western China. Even if Eastern China's economic development, innovation, and energy environment were superior to those of Central and Western China, technological progress and environmental control could not be effective in reducing CO_2 emissions there. While technical innovation and environmental regulation were beneficial to CO_2 emission decrease in Central and Western China. Finally, the expansion of secondary industries and the rise in coal usage boosted energy CO_2 emissions.

Table 6. The robustness test results.

	(IV) CI	(V) CI	(VI) CI	(VII) CI
TP	-0.515***			-0.499***
	(0.139)			(0.130)
RD		-0.001**		
		(0.000)		
Patent			-0.176***	
			(0.0621)	
lnPGDP	-0.211***			
	(0.0621)			
ER	-2.535*	-1.832	-2.080	-1.441*
	(1.339)	(1.349)	(1.349)	(1.186)
ECS	1.353***	1.265***	1.340***	1.129***
	(0.114)	(0.116)	(0.116)	(0.109)
IS	1.574***	0.984***	1.425***	1.354***
	(0.225)	(0.168)	(0.224)	(0.147)
_cons	1.196**	-0.522***	0.814	
	(0.586)	(0.152)	(0.584)	
Year	Y	Y	Y	
Province	Y	Y	Y	
Spatial rho				0.583***
				(0.0362)
sigma2_e				0.0170***
				(0.001)
Log-L				392.1329
N	570	570	570	570
R2	0.9556	0.9542	0.9545	0.3040

Table 7. Results of FE model in regions.

	(VIII) CI	(IX) CI
TP	0.0751	-0.619***
	(0.196)	(0.193)
ER	3.703	-3.758**
	(3.029)	(1.533)
ECS	1.073***	1.465***
	(0.212)	(0.149)
IS	2.757***	0.843***
	(0.301)	(0.232)
_cons	-1.364***	0.568***
	(0.127)	(0.194)
Year	Y	Y
Province	Y	Y
N	209	361
R2	0.9352	0.9509

6. CONCLUSIONS AND POLICY IMPLICATIONS

Using panel data from China, this study employs the rebound effect and fixed effect models to analyze the effects of technological progress on energy CO_2 emissions. The following are the study's findings. First, while total energy consumption in China increased rapidly, the pace of rise in energy consumption has slowed since 2012.The proportion of petroleum, natural gas, primary electricity, and other energy has risen over time, reflecting the gradual optimization of the energy consumption structure in China. CO_2 emissions intensity in 2019 was 15.72 kt/million yuan, a significant decrease from 2001, with Central and Western China emitting around twice as much as Eastern China. The average value of technological progress reached 1.017, forming a U shape. The value of technological progress in Central and Western China (1.01) was lower than in Eastern China (1.029). Second, China's energy CO_2 emission reduction rose from 1.908 in 2001 million tons to 5.44 million tons in 2019, while the amount of CO_2 emission rebound fluctuated greatly. The overall CO_2 emissions had a partial rebound effect, with an average value of -0.449. There were six years with partial-rebound effect, seven years with over-storage effect, and six years with reverse effect in the 19 years analyzed. The average value of the rebound effect in Eastern, Central, and Western China ranged from 1.076, 6.997 in 2001 to 0.483, -1.239 in 2019, indicating that numerous energy-saving and emission-reduction technologies have been continuously enhanced. Third, the regression findings of the fixed effect model suggest that technological progress may successfully support energy CO_2 emission reduction as well as environmental control, particularly in Central and Western China. Secondary industrial expansion and coal usage increase energy CO_2 emissions across China.

It is imperative that the Chinese government actively cut CO_2 emissions. First, improving technical efficiency is an essential strategy to achieve CO_2 emission reduction. The government should strive to provide financial support and human capital investment for local technological innovation and green R&D with low cost and easy operation and evaluate its practical performance; encourage industry-university-research cooperation to utilize clean energy and renewable energy into low-carbon fields; learn advanced energy-saving technologies from other provinces. Second, the Chinese government has designed and implemented a number of energy and environmental regulations during the previous few decades. It is important to strengthen the reasonable guidance of these policies and help the transition to "low-carbon fossil energy and renewable energy". When formulating relevant energy policies, the government, from its negative experience of the reverse effect, should act to create the over-storage effect. As for the actual carbon emission intensity of each province, the government should formulate differentiated environmental regulation policies and shut down high-polluting enterprises, to avoid pollution agglomeration in Central and Western China. Finally, the government should improve both energy consumption structures and industrial structures through the introduction of renewable energy consumption(like electricity, wind, nuclear), strengthening the development of advanced manufacturing(like chips, integrated circuits, new energy vehicles) and service industries.

There are certain significant limitations that need to be addressed in future study. For starters, there is much of potential for further research into the influence of technological progress on CO_2 emissions during the COVID-19 pandemic and in some specialized industries (such as mining and manufacturing), which may provide surprising results and discoveries. Second, alternative methodologies or models, such as SFA, GS2SLS, MLE,GMM, and dynamic spatial model, might be used to validate this result. Third, mediating factors and the nonlinear connection might be investigated to better understand how they interact with one another. All of these things might be done to discover new breakthroughs for ideas in the next stage.

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