SUSTAINABLE ENERGY SYSTEMS WITH POLICIES IN CHINA

EDITED BY: Pu-yan Nie, You-hua Chen, Chan Wang, Yong-cong Yang and Henry Wang

PUBLISHED IN: Frontiers in Energy Research

frontiers Research Topics

ISSN 1664-8714
ISBN 978-2-88976-612-3
DOI 10.3389/978-2-88976-612-3

About Frontiers

Frontiers is more than just an open-access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers Journal Series

The Frontiers Journal Series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the Frontiers Journal Series operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to Quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews.
Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the Frontiers Journals Series: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area! Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers Editorial Office: frontiersin.org/about/contact

SUSTAINABLE ENERGY SYSTEMS WITH POLICIES IN CHINA

Topic Editors:
Pu-yan Nie, Guangdong University of Finance and Economics, China
You-hua Chen, South China Agricultural University, China
Chan Wang, Guangdong University of Finance and Economics, China
Yong-cong Yang, Guangdong University of Foreign Studies, China
Henry Wang, University of Missouri, United States

Citation: Nie, P.-y., Chen, Y.-h., Wang, C., Yang, Y.-c., Wang, H., eds. (2022). Sustainable Energy Systems With Policies in China. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-88976-612-3

Table of Contents

frontiers | Frontiers in Energy Research
EDITORIAL
published: 28 June 2022
doi: 10.3389/fenrg.2022.943665

Check for updates

Editorial: Sustainable Energy Systems With Policies in China

You-Hua Chen[1,2]*, Pu-Yan Nie[3], Chan Wang[3], Yong-Cong Yang[4] and Henry Wang[5]

[1]College of Economic and Management, South China Agricultural University, Guangzhou, China, [2]Research Center for Green Development of Agriculture, South China Agricultural University, Guangzhou, China, [3]School of Finance, Guangdong University Finance & Economics, Guangzhou, China, [4]Institute of Studies for the Greater Bay Area, Guangdong University of Foreign Studies, Guangzhou, China, [5]Department of Economics, University of Missouri, Columbia, MO, United States

Keywords: energy efficiency, energy policy, green and sustainable development, new energy strategy, China

Editorial on the Research Topic

Sustainable Energy Systems with Policies in China

The earth has undergone tremendous changes since industrial civilization, and among these, climate change is one of the most obvious phenomena (IPCC, 2022). The average temperature of the earth has raised for nearly 1.5°C since 1900, which results in many catastrophes such as floods and droughts (Latif et al., 2022). Climate change caused by greenhouse gas emissions (GHGs) is a key issue for sustainable development all over the world (Mooney and Sjogersten, 2022). Globally, most countries are working hard to reduce carbon emissions by energy policies reform (Meys et al., 2021).

As the largest developing country, China is facing the dual constraints of economic development and environmental protection (Chen et al., 2017; Chen et al., 2020). On the one hand, China needs continuous development to improve the welfare of its residents. On the other hand, its ecology and environment have been severely damaged. A more efficient energy system is needed for China to alleviate this conflict (Rikap, 2022). So, the concern is how to maintain green and sustainable development through low-carbon energy systems. Based on the above, the journal Frontiers in Energy Research agreed to host a Research Topic about *Sustainable Energy Systems with Policies in China*. Nearly 50 papers have been submitted to this Research Topic and 22 of them are finally accepted, including 18 original research, 1 perspective, 1 policy and practice reviews and 2 policy briefs. The 22 published papers can be classified to 4 topics: industry, emission, energy and policy (See the following **Table 1**).

Edited and reviewed by:
Simone Bastianoni, University of Siena, Italy

****Correspondence:***
You-Hua Chen
yhchen214@scau.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *14 May 2022*
Accepted: *13 June 2022*
Published: *28 June 2022*

Citation:
Chen Y-H, Nie P-Y, Wang C, Yang Y-C and Wang H (2022) Editorial: Sustainable Energy Systems With Policies in China. Front. Energy Res. 10:943665. doi: 10.3389/fenrg.2022.943665

ECONOMICS EFFICIENCY AND INDUSTRIAL DEVELOPMENT

Totally five papers involve the topic of economics efficiency and industrial development. Zheng et al. surveyed the linkage development of the logistics and manufacturing industry by evaluating ecological efficiency evaluation and spatiotemporal characteristics. After classifying the carbon emissions from the logistics industry and pollution emissions from the manufacturing industry, the authors declared that the linkage ecological efficiency of the two industries will tend to be stable in the future. Jiang et al. studied the effect of market power and intertemporal permits trading (IPE) on economic efficiency. They showed that the producing and discharging behaviors of firms depend on the permits price elasticity of output price without the banking and borrowing (BB) system. The conclusions are helpful for the development of BB system. Pingkuo et al. investigated how to promote energy transition with market design by using an institution-economics-technology-behavior (IETB) analysis framework in China's electric power industry. They issued that market design should be pertinent and objective. Zhang et al. concerned on the economic impacts and challenges of Chinese mining industry (MI) by

TABLE 1 | summary of the published papers

Order	Topic	Synopsis	Papers
1	Industry	Economics efficiency and industrial development	5
2	Emission	Carbon emission and economic growth	5
3	Energy	Energy strategy and energy efficiency	6
4	Policy	Energy policy	6

Statistic based on the published articles.

employing the input-output model. Their results shown that the policy-makers should combine the MI within national economic system reform and planning. Qiu et al. prospected the development of China's renewable automotive industry (RAI) after subsidies shrinking and declared that the decrease of subsidies will have a critical impact on the development of RAI.

CARBON EMISSION AND ECONOMIC GROWTH

For the technology constraints, there is a conflict between carbon emission and economic growth. Li et al. shown compared to 2012, several provinces and cities increase their direct CO_2 emissions for the development of economy. But interestingly, several papers found that carbon emissions reducing and economic growth can be compatible. For example, using provincial panel data of China from 2000 to 2017, Zhang et al. shown that the increase of low-emission electricity increases GDP but reduces CO_2 emissions. Another study from Wang also shown that it is possible to achieve the green and sustainable economic development by stimulating green energy use. Besides, Li et al. concerned the effects of carbon emission trading market on carbon emissions of public buildings. They issued that reducing the cost of energy-conservation and emission-reduction technologies and appropriately subsidizing were effective methods to motivate public building owners to participate in carbon emission trading. Besides, Sun et al. investigated the relationships of carbon emissions and endogenous between two economic system. The marginal contribution for this study is that they consider two competitive economic system.

ENERGY STRATEGY AND ENERGY EFFICIENCY

Energy efficiency is a major topic in energy economics. Six papers published are focused on this field. Pan et al. evaluated the national new energy strategy (NNES) from the political economics perspective and, declared to design the NNES based on core technology research, innovative industry financing, cultivating professional talents, and continuous expansion of opening up. Different from Pan et al., Li et al. investigated the supply sustainability of the traditional energy, coal in China by employing a new comprehensive evaluation methodology. Two papers concerned on energy poverty. Wu et al. shown that energy poverty reduces the rural labor wages of China and so the government should to enhance the accessibility of energy consumption in rural areas to reduce energy poverty. Che et al. evaluated global energy poverty aligned with UN ADG 7 with a multidimensional assessment model. Chen et al. research the effect of urban spatial from on energy efficiency by a cross-sectional study in China and issued optimizing the urban spatial form is an important way to improve the energy efficiency. The study from Wang et al. surveyed the water-energy-food-ecology (WEFE) nexus in northwest China and their results shown the WEFE nexus in the investigated areas present a spatial convergence tread.

ENERGY POLICY

Fu et al. surveyed the support policy, such as feed-in tariff and subsidy of photovoltaic (PV) power generation in China. And they declared that the development of PV in China is aggressive, which is harmful for PV innovation. Hu examined the Coal to Clean Heating Project (CCHP) implemented in northern rural China from a policy process perspective. They claimed that beside the positive effect of CCHP, it also created mounting socio-economic and political challenges. Ma et al. investigated the effect of fiscal decentralization policy on the garbage classifications, while Chen et al. analyzed the fee-to tax reform on water resources. Li and Xiong examined the phased energy -saving and emission-reducing effects of dual-credit policy on the auto industry in China. Wu et al. assessed China's power system reform (PSR) by a comparative study on the transmission management between China and the United States. They concluded PSR ensure the timely and effective allocation of national power energy and is helpful to concentrate all kinds of resources to develop large-scale power projects.

As the largest developing country, China has carried out many beneficial reforms to its energy and development policies. The main purpose of the Research Topic was to assess the effects of China's energy policy reforms. Fortunately, it has received extensive attention and active contributions from scholars. Published articles are of high quality and cover numerous subjects in the energy economics, such as Economics efficiency and industrial development, Carbon emission and economic growth, Energy strategy and energy efficiency and, Energy policy in China. These research papers not only help people understand China's energy policy reform performance, but also help the Chinese government to further promote reform.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

FUNDING

This work was supported by the Guangdong Natural Science Foundation (2021A1515011960), the Foundation for Guangdong Province Universities and Colleges Pearl River Scholar Funded

Scheme, (GDUPS 2019), the Guangdong Natural Science Outstanding Youth Fund Project (2022B1515020034), the Key Program of the National Social Science Foundation of China (20&ZD117).

REFERENCES

Chen, Y.-H., Chen, M.-X., and Mishra, A. K. (2020). Subsidies under Uncertainty: Modeling of Input- and Output-Oriented Policies. *Econ. Model.* 85, 39–56. doi:10.1016/j.econmod.2019.05.005

Chen, Y.-H., Wen, X.-W., Wang, B., and Nie, P.-Y. (2017). Agricultural Pollution and Regulation: How to Subsidize Agriculture? *J. Clean. Prod.* 164, 258–264. doi:10.1016/j.jclepro.2017.06.216

IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the IPCC Sixth Assessment Report. Available at: https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/ (Accessed: May 11, 2022).

Latif, M., Sun, J., Visbeck, M., and Hadi Bordbar, M. (2022). Natural Variability Has Dominated Atlantic Meridional Overturning Circulation since 1900. *Nat. Clim. Chang.* 12, 455–460. doi:10.1038/s41558-022-01342-4

Meys, R., Kätelhön, A., Bachmann, M., Winter, B., Zibunas, C., Suh, S., et al. (2021). Achieving Net-Zero Greenhouse Gas Emission Plastics by a Circular Carbon Economy. *Science* 374 (6563), 71–76. doi:10.1126/science.abg9853

Mooney, S. J., and Sjogersten, S. (2022). Greenhouse Gas Emissions Rise Due to Tillage. *Nat. Food* 3, 246. doi:10.1038/s43016-022-00491-1

Rikap, C. (2022). Becoming an Intellectual Monopoly by Relying on the National Innovation System: the State Grid Corporation of China's Experience. *Res. Policy* 51 (4), 104472. doi:10.1016/j.respol.2021.104472

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 16 April 2021
doi: 10.3389/fenrg.2021.672920

Conservative or Aggressive? The Dynamic Adjustment of the Feed-in Tariff Policy for Photovoltaic Power Generation in China

Yi Fu[1], *Chang-hao Hu*[1] *and Dong-xiao Yang*[2]*

[1] School of Business, Central South University, Changsha, China, [2] Collage of Economics and Trade, Hunan University of Technology and Business, Changsha, China

With the technological progress of photovoltaic (PV) enterprises, the subsidy standard of PV power generation in China is declining. However, the conservative adjustment of feed-in tariff (FIT) policy is considered to increase the financial burden of the government, while the aggressive adjustment will have a serious impact on the PV enterprises and may reduce the research and development (R&D) investment of them. By constructing a game model between the government and PV enterprises, this article analyzes the relationship between the adjustment of government subsidy policy and R&D investment of PV enterprises. The evolution path and strategic stability of the system have been studied through evolutionary analysis and numerical simulation. Results show that three strategies may become the evolutionary stability strategy (ESS) of the system under certain conditions. Firstly, the investigation of these conditions reveals the strategy that the government chooses conservative adjustment and enterprises choose to increase R&D investment is more likely to be an ESS. Secondly, the initial preference of the government and enterprises cannot change the final result of system evolution, but only changes the speed of reaching it. Finally, the research on the interaction between government and enterprises illustrates that when the degree of influence is small, the ESS is that the government chooses aggressive adjustment and enterprises choose to increase R&D investment. But when the degree of influence is large enough, the government is more inclined to choose conservative adjustment and enterprises choose to increase R&D investment. The decision-making of the government should be focused on the interaction between the government and enterprises. The encouraging cooperation among PV enterprises, universities, and research institutions can promote the technological progress of the PV industry, so as to achieve the purpose of subsidy policies more effectively.

Keywords: dynamic adjustment, evolutionary game, PV power generation, R&D, fit-in tariff

OPEN ACCESS

Edited by:
Chan Wang,
Guangdong University of Finance and Economics, China

Reviewed by:
Kun Wang,
University College London, United Kingdom
Zhang Haifeng,
Guangxi Normal University, China

****Correspondence:***
Dong-xiao Yang
ydx622@hutb.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies,
a section of the journal Frontiers in Energy Research

Received: *26 February 2021*
Accepted: *19 March 2021*
Published: *16 April 2021*

Citation:
Fu Y, Hu C and Yang D (2021) Conservative or Aggressive? The Dynamic Adjustment of the Feed-in Tariff Policy for Photovoltaic Power Generation in China. Front. Energy Res. 9:672920. doi: 10.3389/fenrg.2021.672920

INTRODUCTION

The shortage of fossil energy and greenhouse gas emissions caused by fossil energy combustion are increasingly a concern for people all over the world (Wei et al., 2019). Hence, renewable energy (RE) resources, such as wind, solar, biomass, and geothermal, have been developed vigorously under the promotion of technology and government support in recent decades (Chen et al., 2018).

China has already been strengthening the development and utilization of RE, which can reduce the level of carbon emissions effectively (Ming et al., 2013). Through the efforts made during the past decade, solar energy development, and its utilization in China have been in the forefront of the world, with the cumulative installed capacity of photovoltaic (PV) enterprises and annual newly installed capacity ranking first in the world. The successful development of the PV industry has greatly improved. The energy structure in China has reduced an enormous number of greenhouse gas emissions. At the same time, the implementation of subsidy policies such as feed-in tariff (FIT) has achieved good economic benefits (Ling-zhi et al., 2018). Therefore, the Chinese government has set the sustainable development goal of achieving peak of carbon emissions by 2030 and carbon emissions neutrality by 2060 (NDRC, 2017).

It is undeniable that the government's support and promotion has played an important role in the development of the PV industry (Lo, 2014; Yang D. et al., 2019). To promote the healthy development of the PV industry, the United States, Japan, Germany, China, and many other countries have formulated policies, such as FIT and renewable portfolio standard (RPS), and have adopted government subsidies, tax relief, policy support, and other methods (Chen et al., 2017). However, as the scale of the PV industry continues to expand, technology continues to improve, unit power generation cost (UPGC) continues to decline, and government subsidies need to decline. Thus, some countries implement a subsidy scheme that decreases year by year for PV projects, while some countries offer different subsidy standards for new projects in different years. In China, long-term constant FIT has not been able to adapt to the decline in the cost of PV equipment, and very broad regional pricing will hinder the development of PV generation to some extent (Yang and Ge, 2018). In 2013, the State Council of China promulgated *Several opinions on promoting the healthy development of photovoltaic industry* (NDRC, 2013a), which clearly proposed that "the policy of subsidizing distributed PV power generation according to electricity quantity" and "the implementation period of on grid electricity price and subsidy is 20 years in principle" (MF, 2013; NDRC, 2013b). In fact, the Chinese government plans to adopt a low or no subsidy policy mechanism on the RE power development in the future (Zhang et al., 2020). One of the purposes of government subsidies is to push the connection to the grid at an equal price to be achieved sooner. At present, the main PV subsidy policy in China is the regionally differentiated FIT policy. Specifically, the government divides PV projects into distributed PV (DPV) projects and concentrated PV projects and divides the country into three zones (Zone I, Zone II, and Zone III, see **Figure 1**) according to solar resources.

For each zone, the government promises to provide a certain amount of subsidy for the future electricity generated by PV projects, and the subsidy standard is usually different in different zones. Moreover, the subsidy standard is designed to be lowered once a year to adapt to the decline of PV power generation cost and the development of the PV industry (NDRC, 2016). In January 2019, the National Development and Reform Committee (NDRC) released *The Notice on Work Related to Wind Power and Photovoltaic Power Generation Connected to Grid without Subsidy* (NDRC, 2019). This Notice expresses the intention of the government to promote a low or no subsidy policy mechanism on the RE power development in the future. To achieve this goal, the current FIT price should be readjusted and redistributed (Zhang et al., 2020). **Figure 2** shows the adjustment of the PV power subsidy of China since 2013. In the past 8 years, it has been reduced eight times, with an average decrease of 60%.

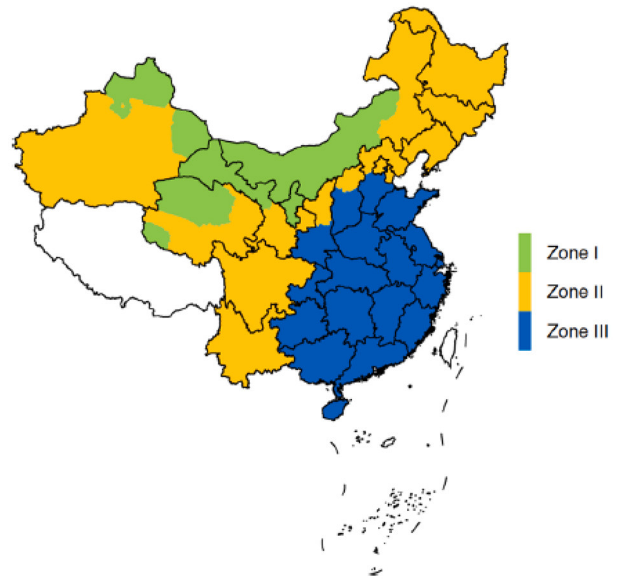

FIGURE 1 | The Chinese zonal feed-in tariff policy. Tibet was not included in the FIT policy of China (Dong et al., 2021).

Although the adjustment of government subsidy refers to the decrease of PV power generation cost and newly installed capacity, the enterprises and society have different opinions on the adjustment (Zhang and He, 2013). The actual situation shows that if the frequency and timing of subsidy decrease are unreasonable, it may have a serious impact on the profit and research and development (R&D) investment of an enterprise. For example, *The notice on matters related to photovoltaic power generation in 2018* (*531 policy*) (NEA, 2018) issued by NEA in May 2018 is considered by many PV enterprise operators that the adjustment of subsidies is too radical and will have a serious impact on the development of the enterprises. Many PV enterprises require the government to give a buffer period for policy implementation and suggest that the subsidy should not be reduced too much. This phenomenon shows that it is often difficult for the government to effectively regulate the subsidy standard. The government is not clear about the impact of the policy, resulting in the deviation between the expected goal of the government and the actual implementation effect of the policy.

Therefore, the relationship between the adjustment of government subsidies and the development of PV enterprises has become an important issue for the government to consider. How to adjust the subsidy policy to promote enterprises to increase investment in technological innovation, improve operating efficiency, and ultimately achieve the stable and

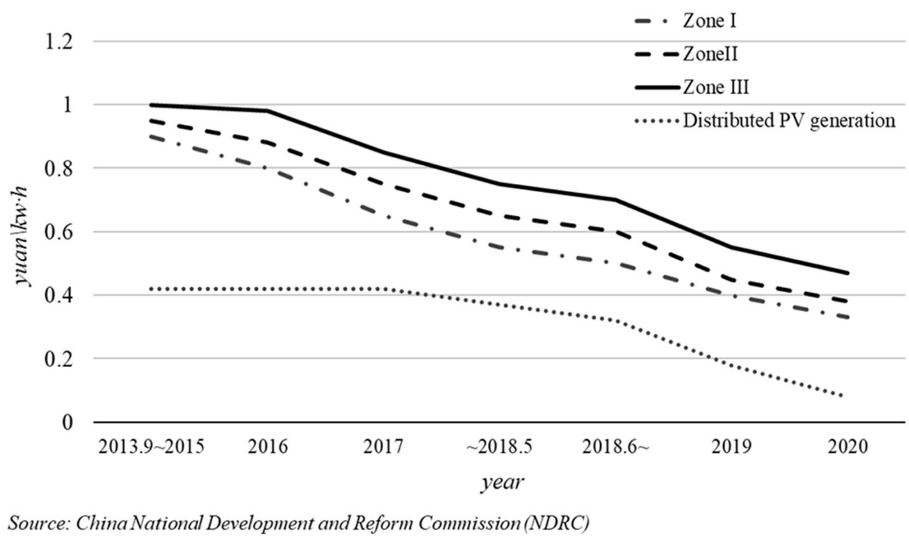

FIGURE 2 | Overview of photovoltaic subsidy (FIT) adjustment of China.

healthy development of the PV industry? What factors need to be considered in the adjustment of subsidy policy? This article constructs an evolutionary game model between the Chinese government and PV companies, and investigates the evolutionary stability strategy (ESS) of the system through numerical simulation, so as to provide a certain reference for answering the above questions. The following section discusses the literature review, introducing the relevant research on the FIT policy and PV subsidy policy of China. The "Assumptions" section consists of the hypothesis of the game model. The "Evolutionary game model" section constructs an evolutionary game model between the government and PV companies. The evolution analysis of the game model is discussed in the "Evolutionary analysis of game model" section. The "Numerical analysis" section is a numerical simulation, focusing on the influence of some important parameters on ESSs. The "Conclusion" section concludes.

LITERATURE REVIEW

Using various government subsidies to support the development of the PV industry is a common practice among countries. The FIT policies are implemented in more than 40 countries around the world. The successful development of the RE market in Germany, the United States, China, and other countries shows that the FIT policy is the most effective policy to encourage the rapid and sustainable deployment of RE (Couture and Gagnon, 2010). Therefore, a large number of studies have analyzed government subsidy policies for RE and evaluated the actual effects of them, mainly FIT and RPS (Hitaj and Löschel, 2019).

Some studies have shown that government subsidies have an important impact on the development of RE and renewable electricity generation. When the cost of RE production or the energy-negative coefficient is low, the subsidy policy generates a high electricity price (Yang and Nie, 2016). The Chinese FIT policy has played an important role in promoting the development of the PV industry. Some scholars studied the impact of the Chinese *531 policy* on the PV industry through the empirical method and estimated the effect of the Chinese FIT policy on PV-installed PV capacity. Results reveal that an increase of ¥0.1 per kWh (∼US$0.014 per kWh) in PV subsidies adds about 18 GW/year of installed capacity to the national PV market. The impact of PV subsidies on the development of PV deployment market is so great that some researchers even pointed out that if there are no subsidies, the PV industry of China would almost disappear (Dong et al., 2021). Similarly, Du and Takeuchi (2020) investigated the effectiveness of regionally differentiated FITs for the development of RE in China. A small difference in the tariff rate leads to statistically significant differences in outcome indicators among regions. Smith and Urpelainen (2014) studied the FIT policy of the United States, demonstrating that the FIT is an effective way to increase renewable electricity generation. The study finds that increasing the FIT by US$0.01 (2,000 constant prices) per kWh increases the percentage change in the share of renewable electricity of the total by 0.11% points. In the study of Italian FIT policy on the PV market, Antonelli and Desideri (2014b) also pointed out that the PV industry of Italy has developed rapidly due to adequate FIT subsidies. The overall cost of PV station construction is on the decline, which is more determined by the tariffs than by the market development and structure. But the research provided an interesting conclusion that the distribution of PV installations on the territory is not a function of solar radiation (Antonelli and Desideri, 2014a).

The influence of government subsidies on R&D input and cost reduction has also been studied by a large number of scholars. The government support policies such as subsidies and tariffs can effectively expand the market share of domestic new energy vehicles with less technology (Yang D.-X. et al., 2019). Moreover, FIT is more efficient than RPS to increase the quantity of RE (installed capacity) and to stimulate the R&D input to reduce costs (Sun and Nie, 2015). Böhringer et al. (2017) also found that the innovation impact of the German FIT scheme over the last two decades supports the positive innovation hypothesis. Zhang Y. et al. (2020) analyzed the development of dispersed wind power (DWP) and DPV in China from the perspective of technology and institutional economy. The authors believed that the subsidy policy has effectively promoted the innovation and development of new energy companies. In addition, some scholars have attempted to optimize the FIT policy. To simulate the performance of the FIT program in different situations, Kim and Lee (2012) combined cost modeling, option valuation, and consumer choice. The study tried to make recommendations for policymakers who want to expand the RE market and control the total burden of ratepayers.

However, the government subsidy standard often needs to be adjusted according to the actual situation, and the reduction of power generation cost is one of the factors that the government needs to consider. For instance, Yang et al. (2016) found that the optimal subsidy for RE enterprises positively correlates with its cost under complete information. From the perspective of the development of the PV industry in various countries, it is true that both government subsidies and enterprise costs have declined. Xu and Ma (2021) studied FIT and tax-rebate regulation from the perspective of the members in the whole solar PV supply chain. The authors also investigated a non-linear dynamic system to study the long-term operation strategies, the stability of the equilibrium, and how the conservative and aggressive strategies impact the system. Selinger-Lutz et al. (2020) introduced a two-step tariff for the feed-in electricity with dynamic tariff switching times. From the perspective of RE enterprises, how much revenue can be obtained per kWh is one of the most important issues.

Research on FIT policy mainly includes policy effect evaluation, the relationship between the government subsidies and power generation costs, and the relationship between government subsidies and enterprise innovation input. However, there are few studies on optimizing subsidy policies from the perspective of dynamic adjustment. To provide more references for the Chinese government to rationally adjust FIT policies, this study constructs an evolutionary game model between the government and PV companies. By numerical simulation to investagate the evolution and stability strategy of the model, we obtain the conditions that should be met. The main innovation of this study is to examine the relationship between FIT policy adjustment and enterprise R&D investment from the perspective of the game between the government and PV enterprises and analyze the main factors that should be considered in policy adjustment. This research makes a certain marginal contribution to existing research.

ASSUMPTIONS

In China, the main PV subsidy policy is the regionally differentiated FIT policy. With the continuous advancement of PV technology and the decline of UPGC, subsidy standards are bound to be adjusted accordingly. At the same time, the decline in government subsidies also promotes enterprises to reduce the cost of PV power generation through technological innovation to a certain extent. Therefore, there exists an interaction mechanism between the decline of government subsidies and enterprise technological innovation (Requate, 2014). The government hopes to subsidize within a certain amount to improve the industrial technology level and PV-installed capacity, while the main goal of the company is to make a profit, and upgrading its technology will help companies reduce power generation costs and gain greater market share. Therefore, the following assumptions of the evolutionary game model are proposed:

(1) The government decides the adjustment of the subsidy policy. The decrease of the subsidy may lead to the acceleration of investment and construction of PV projects, and also the reduction of enterprise profits, thus reducing the investment of the PV projects. The interest goals of the government and enterprises are not completely consistent.
(2) The adjustment intensity of FIT policy has a direct impact on the future revenue expectation of enterprises, while the power generation cost of enterprises has a direct impact on the adjustment of the government subsidies for the next period and the overall expenditure level of the government.
(3) The game is a complete information game; the decision-making behavior of both sides is knowable; and the future income of a single participant can be predicted according to the behavior of the other one.
(4) The two strategies of enterprises are increasing innovation investment and reducing innovation investment. The two strategies of the government are to reduce the subsidies conservatively and aggressively.
(5) Increasing investment in innovation will reduce construction costs, assuming that the annual average reduction rate of generation cost per kWh is g, and the average annual decline rate of the government subsidies per kWh is h. When $h \in [0, \delta \cdot g]$, the adjustment of the government is called conservative, otherwise the government subsidy adjustment is called aggressive. The value of δ needs to be further determined by empirical research but estimated according to the actual situation, and this study assumes that $\delta = 150\%$.

EVOLUTIONARY GAME MODEL

Under the influence of the continuous reduction of the government subsidies, the technological innovation of PV enterprises may not increase the profits of enterprises, and radical policy adjustment is more likely to affect the innovation enthusiasm of enterprises. Conservative adjustment has less impact on the overall income of enterprises, but it also increases the financial burden of the government to a certain extent. There are four circumstances of the game between government and enterprise are as follows:

(1) The government chooses conservative adjustment and enterprises increase R&D investment. At this time, the government gains economic benefits R_1 from promoting the development of the PV industry. Technological innovation of enterprises makes the government gain political achievements E_1. The cost of power generation of enterprises is reduced, which in turn reduces the government expenditure αS_1(α is the extent of the impact of PV generation costs on the government expenditures,$0 \le \alpha \le 1$). The cost of the government when the government adjusts conservatively is C_{G1}. For enterprises, the subsidy they receive from the government is R_2, and the innovation incentive for enterprises is C_{E1}. The enterprises pay the innovation cost S_2, but obtain the economic benefit E_2 through technological innovation. Therefore, the revenue of the government and PV enterprises are ($R_1 + E_1 + \alpha S_1$ – C_{G1}, $R_2 + E_2$ – S_2 + C_{E1}).
(2) The government chooses conservative adjustment, and enterprises decrease R&D investment. At this time, due to the reduction of enterprise R&D investment, the government revenue also changes. The cost of technological innovation is reduced to βE_2 (β represents the intensity of investment in technological innovation,$0 \le \beta \le 1$). W_2 is the market disadvantage caused by insufficient technological innovation. Therefore, the revenues of the government and PV enterprises are ($\beta R_1 + \alpha S_1 - C_{G1}, R_2 - \beta S_2 + E_2 - W_2$).
(3) The government chooses aggressive adjustment and enterprises increase R&D investment. Under this circumstance, the government cost is C_{G2} ($C_{G2} > C_{G1}$) and the innovation incentive for enterprises is C_{E2} ($C_{E2} < C_{E1}$). Since the subsidy has fallen sharply, which has an impact on PV companies and incurs additional costs, the company subsidy is reduced to γR_2 (γ represents the extent of the impact of reduction of the subsidies on enterprises,$0 \le \gamma \le 1$). Hence, the revenues of the government and PV enterprises are ($R_1 + \alpha S_1 + \alpha E_1$-$C_{G2}$, γR_2-$S_2 + C_{\mathrm{E2}}$).
(4) The government chooses aggressive adjustment and enterprises decrease R&D investment. The economic benefits of the government from promoting the development of the PV industry are reduced to βR_1. Not only the subsidies received by enterprises are reduced to γR_2, but also the cost of technological innovation and market disadvantages are declined. Hence, the revenues of the government and PV enterprises are ($\beta R_1 - C_{G2}, \gamma R_2 - \beta S_2 - \gamma W_2$).

Suppose that the preferences of the government for choosing conservative adjustment and aggressive adjustment are $x$and $1 - x$, respectively, and the preferences of the enterprise for increasing R&D investment and reducing R&D investment are $y$and $1 - y$, which $0 \le x, y \le 1$. The payment matrix of the two participants is shown in **Table 1**, and notations and interpretations are shown in **Table 2**.

TABLE 1 | Game payment matrix.

Government	PV enterprises	
	Increase R&D investment (*y*)	**Decrease R&D investment (1 – *y*)**
Conservative Adjustment (*x*)	($R_1 + S_1 + E_1 - C_{G1}$, $R_2 - S_2 + E_2 + C_{E1}$)	($\beta R_1 + \alpha S_1 - C_{G1}$, $R_2 - \beta S_2 + E_2 - W_2$)
Aggressive Adjustment (1 – *x*)	($R_1 + \alpha S_1 + \alpha E_1 - C_{G2}$, $\gamma R_2 - S_2 + C_{E2}$)	($\beta R_1 - C_{G2}$, $\gamma R_2 - \beta S_2 - \gamma W_2$)

Therefore, the benefits (m_1, m_2) of conservative and aggressive strategies adopted by the government can be calculated. $\overline{m}$ is the average benefit.

$$\begin{cases} m_1 = y(R_1 + E_1 + S_1 - C_{G1}) + (1 - y)(\beta R_1 + \alpha S_1 - C_{G1}) = \\ (y + \beta - y\beta)R_1 + yE_1 + (y + \alpha - y\alpha)S_1 - C_{G1} \\ m_2 = y(R_1 + \alpha E_1 + \alpha S_1 - C_{G2}) + (1 - y)(\beta R_1 - C_{G2}) \\ = (y + \beta - y\beta)R_1 + y\alpha E_1 + y\alpha S_1 - C_{G2} \\ \overline{m} = xm_1 + (1 - x)m_2 \end{cases}$$

For PV enterprises, the benefits (n_1, n_2) of increasing and decreasing R&D investment can also be calculated. $\overline{n}$ is the average benefit.

$$\begin{cases} n_1 = x(R_2 + E_2 - S_2 + C_{E1}) + (1 - x)(\gamma R_2 - S_2 + C_{E2}) \\ = (x + \gamma - x\gamma)R_2 + xE_2 - S_2 + xC_{E1} + (1 - x)C_{E2} \\ n_2 = x(R_2 - \beta S_2 + E_2 - W_2) + (1 - x)(\gamma R_2 - \beta S_2 - \gamma W_2) \\ = (x + \gamma - x\gamma)(R_2 - W_2) - \beta S_2 + xE_2 \\ \overline{n} = yn_1 + (1 - y)n_2 \end{cases}$$

If $m_1 > \overline{m}$, the probability that the government chooses a conservative adjustment strategy can bring above-average benefits, and thus the probability$x = x(t)$that the government chooses conservative adjustment will increase over time; on the contrary, if $m_1 < \overline{m}$, the probability that the government chooses aggressive adjustment will increase over time. $x = x(t)$ will evolve according to the trend determined by Equation (1).

$$F(x) = \frac{dx(t)}{dt} = x(m_1 - \overline{m}) = x(1 - x)[(1 - \alpha)yE_1 + (y + \alpha - 2y\alpha)S_1 - C_{G1} + C_{G2}] \quad (1)$$

If $n_1 > \overline{n}$, the probability that enterprises increase R&D investment can bring above-average benefits, and the probability of increasing the level of technological innovation will increase with time, and anti $y = y(t)$ will evolve according to the trend determined by Equation (2).

$$G(y) = \frac{dy(t)}{dt} = y(n_1 - \overline{n}) = y(1 - y)[(x + \gamma - x\gamma)W_2 + (\beta - 1)S_2 + xC_{E1} + (1 - x)C_{E2}] \quad (2)$$

TABLE 2 | Notations and interpretations.

Participant	Notation	Interpretation
Government	R_1	The economic benefits that the government gains from promoting the development of the PV industry
	C_{G1}	The cost when the government chooses conservative adjustment
	C_{G2}	The cost when the government chooses aggressive adjustment ($C_{G2} < C_{G1}$)
	E_1	The political achievements that the government gains from technological innovation of enterprises
	S_1	The impact of power generation cost reduction on the government expenditures ($S_1 > 0$)
	α	The extent of the impact of PV generation costs on the government expenditures ($0 \le \alpha \le 1$)
	x	The probability that the government chooses conservative adjustment ($0 \le x \le 1$)
PV enterprises	R_2	The subsidies that enterprises receive from the government
	C_{E1}	The innovation incentive for enterprises when the government chooses conservative adjustment
	C_{E2}	The innovation incentive for enterprises when the government chooses aggressive adjustment ($C_{E2} < C_{E1}$)
	E_2	The economic benefit of the enterprises through technological innovation
	S_2	Innovation cost of PV enterprises ($C_{E2} > S_2$)
	W_2	The market disadvantages caused by insufficient technological innovation
	γ	The extent of the impact of the subsidies reduction on enterprises ($0 \le \gamma \le 1$)
	β	The intensity of investment in technological innovation ($0 \le \beta \le 1$)
	y	The probability that PV enterprises increase R&D investment ($0 \le y \le 1$)

The value of all notations is ≥0.

EVOLUTIONARY ANALYSIS OF THE GAME MODEL

Evolutionary Analysis of the Government Strategy

The above analysis illustrates that the probability of the government policy choice will evolve according to the path described by the dynamic differential Equation (1). Next, we will further examine the conditions for the government to achieve different ESSs.

According to $F(x) = 0$, we have $x^* = 0, x^* = 1, y^* = \frac{C_{G1}-C_{G2}-\alpha S_1}{(1-\alpha)E_1+(1-2\alpha)S_1}$. In the light of the stability principle of dynamic differential equation and the properties of ESS, when$F(x) = \frac{dx}{dt} = 0$ and$F'(x) < 0$, the value of x is ESS.

1. When $y^* = \frac{C_{G1}-C_{G2}-\alpha S_1}{(1-\alpha)E_1+(1-2\alpha)S_1}$, $\frac{dx}{dt}$will be equal to 0. In addition, x will always be stable, which means the preference of enterprises to increase technological innovation reaches, and the government strategy is stable.

2. When $y^* < \frac{C_{G1}-C_{G2}-\alpha S_1}{(1-\alpha)E_1+(1-2\alpha)S_1}$, $x^* = 0$ and $x^* = 1$are stable state of x. Further suppose that if $E_1 > \frac{(2\alpha-1)S_1}{1-\alpha}$,so $F'(0) < 0$, $x^* = 0$ will be ESS, which means the preference of enterprises to increase technological innovation less than y^*, the government will choose aggressive adjustment strategy.

3. When $y^* > \frac{C_{G1}-C_{G2}-\alpha S_1}{(1-\alpha)E_1+(1-2\alpha)S_1}$,$x^* = 0$ and $x^* = 1$ are stable state of x. Further suppose that if $E_1 > \frac{(2\alpha-1)S_1}{1-\alpha}$, so, $x^* = 1$ will be ESS, which means the preference of enterprises to increase technological innovation more than y^*, the government will choose conservative adjustment strategy. The replication dynamic phase diagram of the above three cases is shown in **Figure 3**.

Evolutionary Analysis of PV Enterprise Strategy

Similarly, the evolution path of PV enterprises is described by dynamic differential Equation (2). When $G(y) = 0$, we have$y^* = 0, y^* = 1, x^* = -\frac{\gamma W_2-(\beta-1)S_2-C_{E2}}{(1-\gamma)W_2+C_{E1}-C_{E2}}$. When$G(x) = \frac{dy}{dt} = 0$and $G'(x) < 0$, the value of y is ESS.

1. When $x^* = -\frac{\gamma W_2-(\beta-1)S_2-C_{E2}}{(1-\gamma)W_2+C_{E1}-C_{E2}}$, $\frac{dy}{dt}$ will be equal to 0,And y will always be stable, which means the preference of the government chooses conservative adjustment strategy reaches x^*, the enterprise strategy is stable.

2. When $x^* < -\frac{\gamma W_2-(\beta-1)S_2-C_{E2}}{(1-\gamma)W_2+C_{E1}-C_{E2}}$, $y^* = 0$ and $y^* = 1$ are stable state of y. Further suppose that if $W_2 < \frac{C_{E2}-C_{E1}}{1-\gamma}$, so $G'(1) < 0, y^* = 1$ will be ESS, which means the preference of the government chooses conservative adjustment strategy less than x^*, the PV enterprise will increase R&D investment.

3. When $x^* > -\frac{\gamma W_2-(\beta-1)S_2-C_{E2}}{(1-\gamma)W_2+C_{E1}-C_{E2}}$ and $W_2 < \frac{C_{E2}-C_{E1}}{1-\gamma}$,so $G'(0) < 0, y^* = 0$will be ESS, which means the preference of the government chooses conservative adjustment strategy more than x^*, the PV enterprise will decrease R&D investment.

Figure 4 is the replication dynamic phase diagram of PV enterprise strategy.

Evolutionary Analysis of System Stability

When the system is in a stable state, the proportion of the government and the enterprise to choose their own strategies remain unchanged, and their stable values are. x^* y^*. The five possible equilibrium points in the system are. (x,y):(0,0),(0,1),(1,0),(1,1), $\left(-\frac{\gamma w_2-(\beta-1)s_2-C_{E2}}{(1-\gamma)w_2+C_{E1}-C_{E2}}\ \frac{C_{G1}-C_{G2}-\alpha S_1}{(1-\alpha)E_1+(1-2\alpha)S_1}\right)$ Different from the analysis from the perspective of a single participant, the ESS of the system may have different results. The evolutionary strategy analysis of a single participant

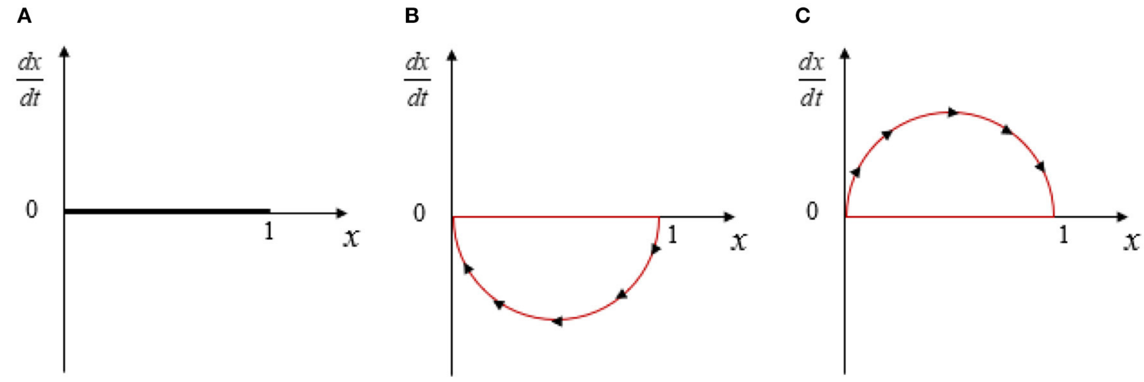

FIGURE 3 | Replication dynamic phase diagram of the government strategy. **(A)** $y^* = \frac{C_{G1}-C_{G2}-\alpha S_1}{(1-\alpha)E_1+(1-2\alpha)S_1}$, **(B)** $y^* < \frac{C_{G1}-C_{G2}-\alpha S_1}{(1-\alpha)E_1+(1-2\alpha)S_1}$, and **(C)** $y^* > \frac{C_{G1}-C_{G2}-\alpha S_1}{(1-\alpha)E_1+(1-2\alpha)S_1}$.

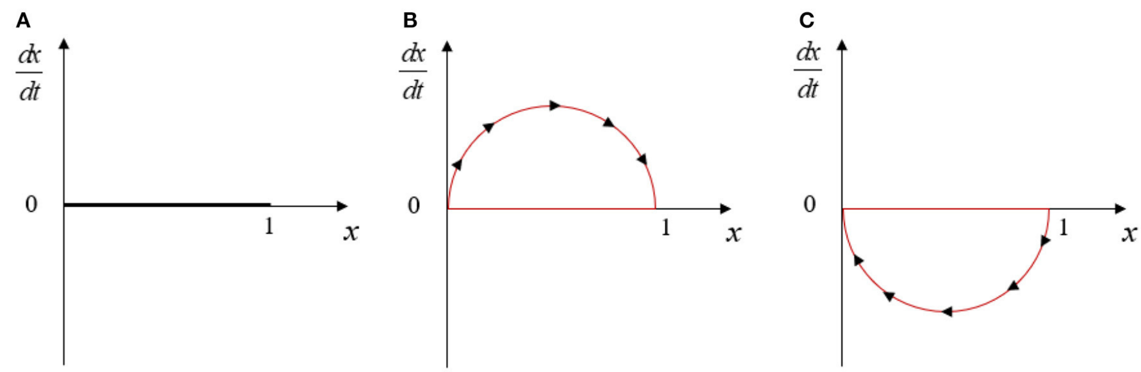

FIGURE 4 | Replication dynamic phase diagram of enterprise strategy. **(A)** $x^* = -\frac{\gamma W_2-(\beta-1)S_2-C_{E2}}{(1-\gamma)W_2+C_{E1}-C_{E2}}$, **(B)** $x^* < -\frac{\gamma W_2-(\beta-1)S_2-C_{E2}}{(1-\gamma)W_2+C_{E1}-C_{E2}}$, and **(C)** $x^* > -\frac{\gamma W_2-(\beta-1)S_2-C_{E2}}{(1-\gamma)W_2+C_{E1}-C_{E2}}$.

is based on the initial preference of another participant, while the ESS of the whole system considers the interaction between the government and enterprises. By analyzing the local stability of the Jacobian matrix of the equilibrium point (x, y), the stability of the system at the equilibrium point can be judged. The Jacobian matrix of the system is:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial G(y)}{\partial x} & \frac{\partial G(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)[(1-\alpha)yE_1+(y+\alpha-2y\alpha)S_1-C_{G1}+C_{G2}] & x(1-x)[(1-2\alpha)S_1] \\ y(1-y)[(1-\gamma)W_2+C_{E1}] & (1-2y)[(x+\gamma-x\gamma)W_2+(\beta-1)S_2+xC_{E1}+(1-x)C_{E2}] \end{bmatrix}$$

According to *Lyapunov's* first method, if a point is ESS, then this point corresponds to the optimal strategy of each participant under certain initial conditions. The local stability of five equilibrium points can be judged by analyzing the Jacobian matrix, as shown in **Table 3**.

(1) (1,0)

According to the assumptions, we can obtain $(-1)[\alpha S_1 - C_{G1} + C_{G2}] < 0$ and $W_2 + (\beta-1)S_2 + C_{E1} > 0$, so $\mathrm{Det}(J) < 0$. If $\alpha < \frac{W_2-(1-\beta)S_2+C_{G1}-C_{G2}+C_{E1}}{S_1}$ (Condition 1), then we can obtain $Tr(J) > 0$ and point (1,0) is an ESS.

(2) (0,1)

According to the assumptions, we can obtain $(1-\alpha)(S_1+E_1) - C_{G1} + C_{G2} > 0$ and $(-1)[\gamma W_2 + (\beta-1)S_2 + C_{E2}] < 0$, so $\mathrm{Det}(J) < 0$. If $\alpha < 1 - \frac{\gamma W_2-(1-\beta)S_2-C_{G2}+C_{G1}+C_{E2}}{E_1+S_1}$ (Condition 2), then we have $Tr(J) > 0$ and point (0,1) is an ESS.

(3) (1,1)

Similarly, we can obtain$(-1)[(1-\alpha)(E_1+S_1) - C_{G1} + C_{G2} <$ 0and$(-1)[\gamma W_2 + (\beta-1)S_2 + C_{E2}] < 0$, so $\mathrm{Det}(J) > 0$. If $\alpha < 1 + \frac{W_2-(1-\beta)S_2+C_{G2}-C_{G1}+C_{E1}}{E_1+S_1}$ (Condition 3), then we have $Tr(J) < 0$ and point (1,1) is an ESS. Moreover, if the condition $W_2 - (1-\beta)S_2 + C_{G2} - C_{G1} + C_{E1} > 0$ is satisfied, Condition 3 will be satisfied as well. In this case, (1,1) is always an ESS.

In conclusion, the three equilibrium points (0,1), (1,0), (0,1) of the system have local stability under certain conditions, and

TABLE 3 | Local stability of five points.

Point	Det(*J*)	Tr(*J*)	Local stability
(0,0)	+	+	Unstable
(1,0)	−	+(Condition 1)	ESS
(0,1)	−	+(Condition 2)	ESS
(1,1)	+	−(Condition 3)	ESS
(x^*, y^*)	0	0	Saddle point

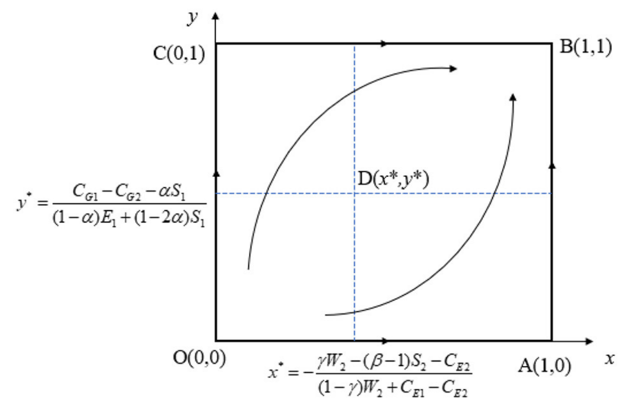

FIGURE 5 | System replication dynamic phase diagram.

(x^*, y^*) is a saddle point. **Figure 5** shows the evolution of the system stable strategy.

The above analysis shows that the equilibrium points (1,0), (0,1) and (1,1) may become the ESS of the system under general circumstances. However, by comparing each condition, it can be seen that Condition 3 is easier to meet, which means that point (1,1) is more likely to become an ESS point. The point (1,1) indicates that the government chooses a conservative adjustment strategy while the enterprise chooses to increase investment in technological innovation. In this case, the government strategy allows companies to have more time to innovate; a conservative adjustment policy also means that the government subsidizes more companies; and therefore companies may invest more in innovation. Although the choice of a conservative adjustment strategy of the government often means more expenditure than an aggressive strategy, the more adequate technological research and development of enterprises also bring relatively more economic benefits and performance benefits to the government, so the system shows a stable situation at point (1,1).

NUMERICAL ANALYSIS

The dynamic evolution process of the game under different initial states is simulated by numerical simulation for further analysis. First of all, it is necessary to discuss the values of parameters in the model. The cost of PV power generation is an important reference for the government to adjust the subsidy standard, so the impact of the decline of power generation cost on government expenditure (S_1, α) should be greater. The technological innovation of enterprises mainly improves the profit of enterprises (so E_2 is comparatively larger) while the government may get less benefit from the improvement of technological level (E_1 is comparatively smaller). When the government chooses aggressive adjustment, it will have a greater impact on enterprises, resulting in more unexpected losses, so $\gamma_{aggressive} > \gamma_{conservative}$. In addition, the R&D investment of enterprises is often small, assuming that the innovation incentive of the government to the enterprises is greater than the cost of technological innovation, so $C_{E2} > S_2$. The PV industry has relatively higher technical requirements, and the technological level of an enterprise largely determines the income of PV projects. The market disadvantage caused by the insufficient innovation makes the relative loss of the enterprise greater, so the impact of W_2 cannot be ignored. Based on the above analysis and using numerical simulation, it is possible to more intuitively analyze the evolution trajectory of the strategies of the two participants in the game model under different assumptions.

The horizontal axis represents the evolution time t, the simulation period is set as 2 or 3, and the time step is set as 0.01 to reflect the evolution trajectory of the system more accurately. The vertical axis indicates the probability that the government chooses conservative adjustment strategy or the enterprise increases the investment of technological innovation, and the range is [0,1]. The values of parameters are strictly limited in the range of constraints. Assuming that $S_1 = 5$, $S_2 = 1$, $E_1 = 0.5$, $E_2 = 2$, $C_{G1} = 10$,$C_{G2} = 6$, $C_{E2} = 2$, $C_{E1} = 4$, $\alpha = 0.7$, $\beta = 0.5$, $\gamma = 0.5$, $W_2 = 5$, and initial preferences are $x = 0.8$, $y = 0.2$, and $x = y = 0.5$, then the evolution path obtained for the two participants is shown in **Figure 6**.

It can be obtained that under the assumption of the above parameters, the final stable strategy of the system is (0,1), which means that the government chooses an aggressive adjustment strategy while the enterprise chooses to increase R&D investment. When analyzing the ESS of the system, we have discussed the conditions of this situation. In fact, the purpose of an aggressive adjustment is to promote enterprises to accelerate R&D while reducing the burden of government subsidies. If the innovation level of enterprises cannot be effectively improved, and the government subsidies decline rapidly, the operation of enterprises will face serious difficulties. Therefore, the optimal strategy for enterprises is to increase the investment in innovation.

Evolution Analysis of the Strategy of a Single Participant

The initial value of the preference of a single participant is fixed, and the probability of the evolution of the preference of the other participant is investigated. Based on the above parameter assumption, **Figures 7A,B** show the evolution trajectory of x when $y = 0.1$ and $y = 0.9$, respectively; **Figures 7C,D** show the evolution trajectory of y when $x = 0.1$ and $x = 0.9$, respectively.

Figure 7 shows that the initial preference of the participants cannot change the ESS, but only change the speed of reaching it. For instance, when $x_0 = 0.1$, y reaches a stable state ($y = 1$) approximately at $t = 1.6$. But when $x_0 = 0.9$, y

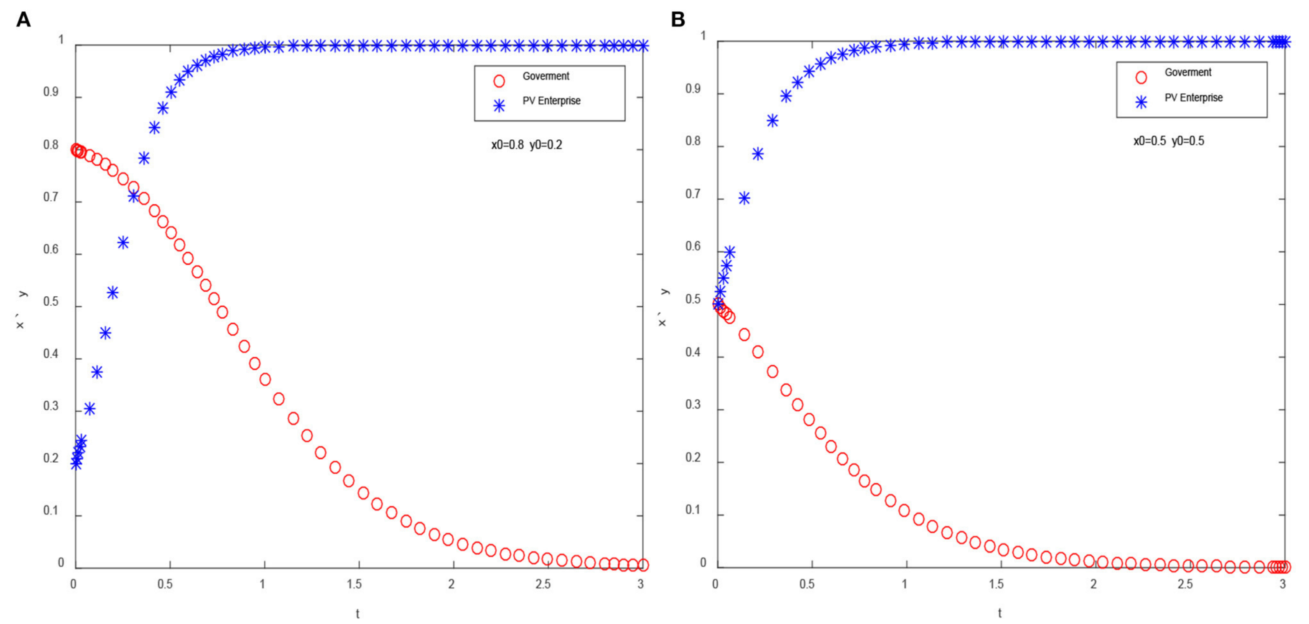

FIGURE 6 | Evolution path of dual participant system. **(A)** Initial state: $x = 0.8$, $y = 0.2$ and **(B)** Initial state: $x = 0.5$, $y = 0.5$.

reaches ESS ($y = 1$) approximately at $t = 1.8$. It is worth noting that when analyzing the ESS of government strategy (see "Evolutionary analysis of the government strategy" section), we have proved that when $x^* < -\frac{\gamma W_2-(\beta-1)S_2-C_{E2}}{(1-\gamma)W_2+C_{E1}-C_{E2}}$ and $W_2 < \frac{C_{E2}-C_{E1}}{1-\gamma}$, $y^* = 1$will be the ESS of government strategy. But if $-\frac{\gamma W_2-(\beta-1)S_2-C_{E2}}{(1-\gamma)W_2+C_{E1}-C_{E2}} > 1$, we can obtain $y^* = 1, \forall x \in [0,1]$. Therefore, there will be a situation that the initial preference (x_0, y_0) will not change the final ESS of the two game participants. The ESS of the system is mainly affected by the interaction between the two participants. It also shows that it is necessary to study the influence of the degree parameters (α, γ) of the interaction between the government and enterprises on the ESS.

The Influence of α *and* γ on ESS

In the evolutionary game model, α represents the extent of the impact of PV generation costs on government expenditures and γ represents the extent of the impact of subsidies reduction on enterprise. α and γ are the main parameters to measure the degree of interaction between the government and enterprises, so we examine the impact on the ESS. Assuming that $\alpha = 0.02$, $\gamma = 0.02$; $\alpha = 0.1$, $\gamma = 0.1$; $\alpha = 0.3$, $\gamma = 0.3$; $\alpha = 0.6$, $\gamma = 0.6$, respectively, then we can obtain the evolution path of the system (as shown in **Figure 8**).

From the above analysis, it can be concluded that the degree of influence between the enterprise and the government determines the final ESS of the system. When the influence degree is small (as shown in **Figures 8A,B**), the ESS of the system is (0,1). In addition, the speed of the government strategy to reach a stable state (aggressive strategy) decreases with the increase of α and γ, which means that the greater the influence between the government and enterprises, the slower the government strategy to reach a stable state. Otherwise, when the impact is large enough, the ESS of the system becomes (1,1) (as shown in **Figures 8C,D**). During this period, the government will choose the conservative adjustment strategy, and the enterprises will increase the investment in technological innovation. In fact, the ESS of (1,1) may be optimal for the government and enterprises. For the government, the conservative adjustment strategy makes the government spend more on subsidies and is more likely to cause overcapacity, but it may be more beneficial to the technological innovation of enterprises. The aggressive adjustment strategy has a serious impact on enterprises, which can be proved by the implementation of *531 policy*. From the perspective of enterprises, the conservative adjustment strategy enables enterprises to have more time and funds for technological R&D, and the application scope of PV industry technology innovation will also be wider. All of these will promote the healthy development of PV enterprises and industries.

CONCLUSIONS

The development of the PV industry is often strongly supported by the government, and the Chinese government has formulated many subsidy policies to promote the development of the PV industry. However, with the development of the PV industry, the government subsidies are bound to continue to decline. The subsidy standard of Chinese FIT policy for PV power generation has been adjusted once a year. Therefore, the impact of the government subsidy adjustment on enterprises has become an important issue.

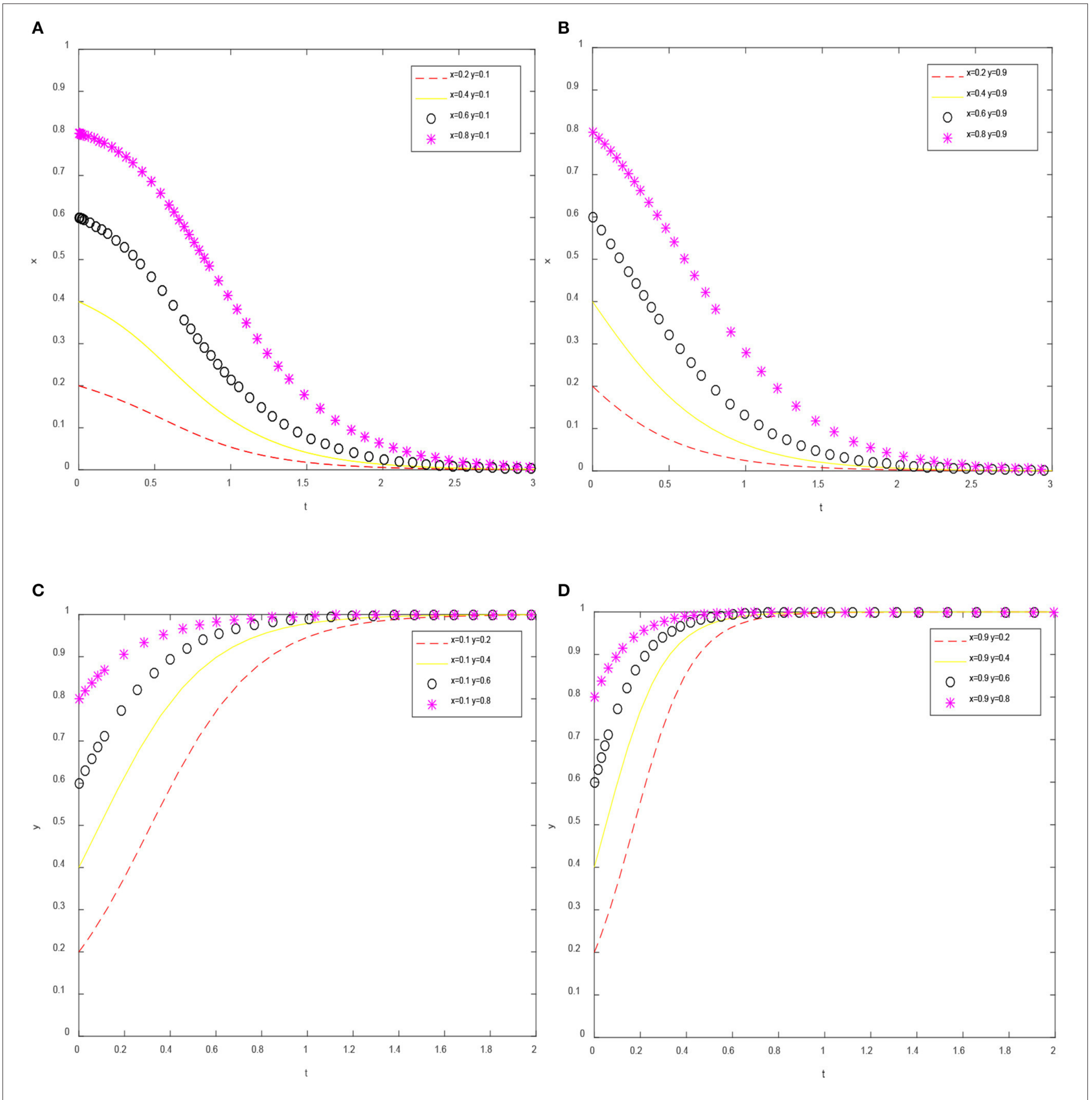

FIGURE 7 | Evolution path of the strategy of a single participant. **(A)** $y = 0.1$, **(B)** $y = 0.9$, **(C)** $x = 0.1$, and **(D)** $x = 0.9$.

By constructing an evolutionary game model between the government and PV enterprises, this article studies the relationship between the government subsidy adjustment and the R&D investment of PV enterprises, aiming to provide more suggestions for the government to adjust the subsidy standard reasonably.

The analysis of the ESS shows that (0,1), (1,0), and (1,1) could become the final ESS of the system, which is further proved by the simulation analysis. The initial preference of the government and enterprises (x_0, y_0) cannot change the ESS, but only change the speed of reaching it. Most importantly, this article focuses on the impact of the degree of interaction between the enterprises and the government (mainly expressed by α and γ) on the final ESS. Results show that when the influence degree is small, the ESS of the system is (0,1). But if the influence degree is large enough, the ESS of the system will become (1,1), which means that the

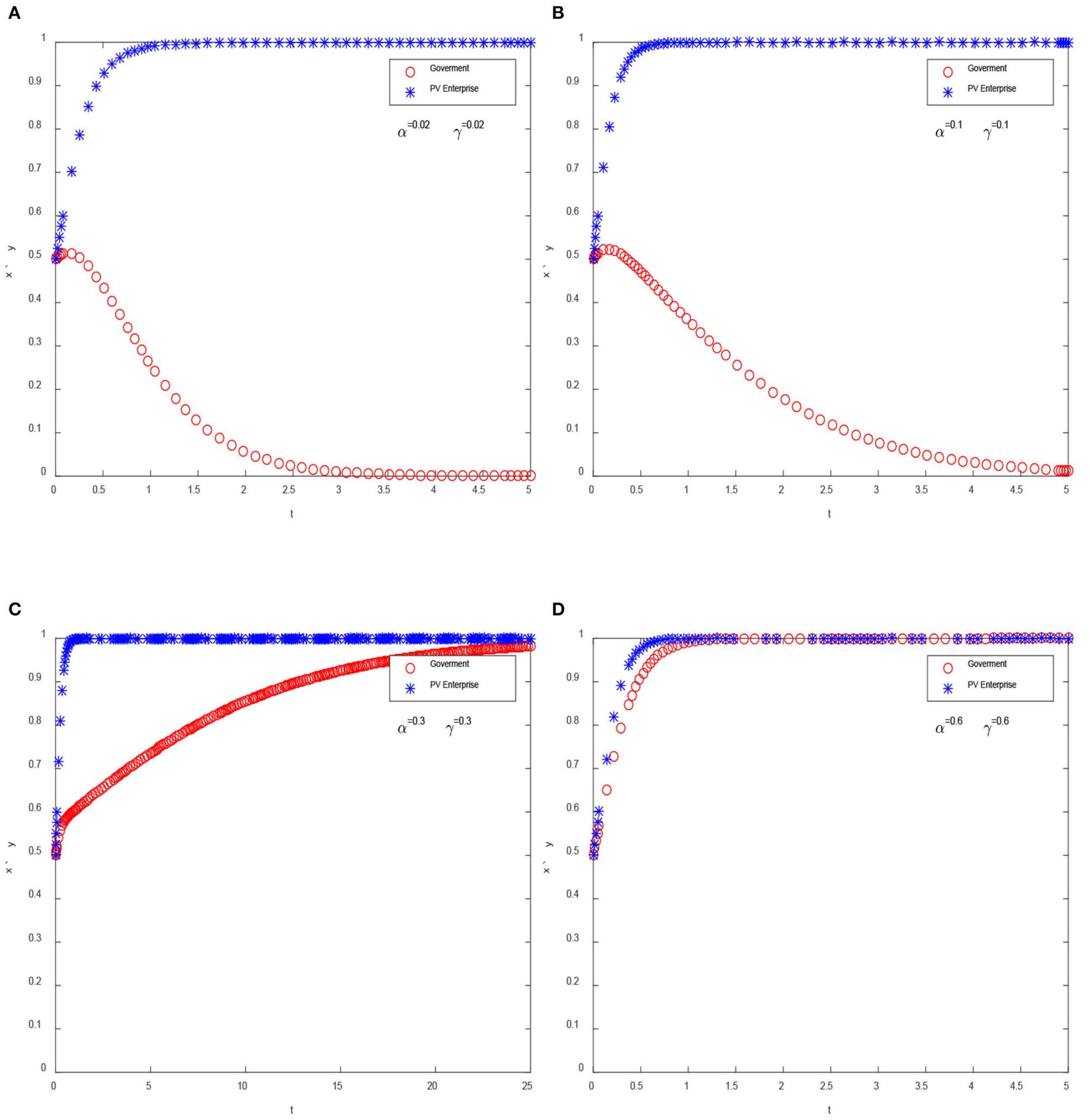

FIGURE 8 | The influence of α and γ on ESS. **(A)** $\alpha = 0.02$, $\gamma = 0.02$, **(B)** $\alpha = 0.1$, $\gamma = 0.1$, **(C)** $\alpha = 0.3$, $\gamma = 0.3$, and **(D)** $\alpha = 0.6$, $\gamma = 0.6$.

government will choose a conservative adjustment strategy and the enterprises will increase R&D investment.

In China, the degree of interaction between government and enterprises is usually large, but it needs to be further confirmed by empirical research. The adjustment policies of the Chinese government will indeed have an important impact on the operation of PV enterprises and the development of the PV industry, which can be verified from the results of previous policy adjustments made by China. Under the influence of various factors, the choice of conservative adjustment strategy of the government and enterprises to increasing R&D investment is more likely to become the ESS of the game, which can also be considered as the optimal result. From the perspective of promoting the improvement of technology, the conservative adjustment policy enables enterprises to have more funds and time to

R&D and fully reduce the PV power generation cost, while the reduction of cost makes it possible for the government to further reduce the subsidy standard. However, the government should carefully adjust the subsidy standard, and the value of h should not be too high relative to the value of g, otherwise, it may not be conducive to enterprises to improve the level of technological innovation. Based on the comprehensive consideration of technological progress and subsidy expenditure, the Chinese government needs to further improve the subsidy retrogression mechanism. The government and PV enterprises should also strengthen cooperation in the field of technological innovation, including promoting cooperation among enterprises, universities, and R&D institutions, so as to further improve the level of technological innovation.

However, there are still many issues that need to be studied. In this article, 150% × g (g is the annual average reduction rate of generation cost per kWh) is regarded as the dividing line between the conservative and aggressive adjustments. This is because the decline of the power generation cost is the main basis for the government to formulate policies. However, the specific value of δ needs to be further determined through empirical research. In addition, as the focus of this article, the specific values of α and γ should also be estimated through the actual data. Only after understanding the degree of influence between the government policies and R&D of PV enterprises, we can provide more valuable references for the government policy adjustments.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found at: https://www.ndrc.gov.cn/fgsj/.

AUTHOR CONTRIBUTIONS

YF: formal analysis, writing—review and editing, and funding acquisition. CH: formal analysis, investigation, methodology, writing—review and editing, and software. DY: formal analysis, funding acquisition, and investigation. All authors contributed to the article and approved the submitted version.

FUNDING

This work was partially supported by Natural Science Foundation of Hunan Province (2020JJ5111), Project of Hunan Social Science Achievement Appraisal Committee (XSP20YBZ081), Young Teacher Innovation Drive Project of Hunan University Technology and Business (19QD04), and the Project of Humanities and Social Sciences (17YJC790035), an initiative of the Ministry of Education of the People's Republic of China.

REFERENCES

Antonelli, M., and Desideri, U. (2014a). Do feed-in tariffs drive PV cost or viceversa? *Appl. Energy* 135, 721–729. doi: 10.1016/j.apenergy.2014.06.059

Antonelli, M., and Desideri, U. (2014b). The doping effect of Italian feed-in tariffs on the PV market. *Energy Policy* 67, 583–594. doi: 10.1016/j.enpol.2013.12.025

Böhringer, C., Cuntz, A., Harhoff, D., and Asane-Otoo, E. (2017). The impact of the German feed-in tariff scheme on innovation: evidence based on patent filings in renewable energy technologies. *Energy Econ.* 67, 545–553. doi: 10.1016/j.eneco.2017.09.001

Chen, Y. H., Nie, P. Y., and Yang, Y. C. (2017). Energy management contract with subsidy. *J. Renew. Sustain. Energy* 9:055903. doi: 10.1063/1.5004549

Chen, Z. Y., Huang, Z. H., and Nie, P. Y. (2018). Industrial characteristics and consumption efficiency from a nexus perspective – based on Anhui's Empirical Statistics. *Energy Policy* 115, 281–290. doi: 10.1016/j.enpol.2018.01.031

Couture, T., and Gagnon, Y. (2010). An analysis of feed-in tariff remuneration models: Implications for renewable energy investment. *Energy Policy* 38, 955–965. doi: 10.1016/j.enpol.2009.10.047

Dong, C., Zhou, R., and Li, J. (2021). Rushing for subsidies: the impact of feed-in tariffs on solar photovoltaic capacity development in China. *Appl. Energy* 281:116007. doi: 10.1016/j.apenergy.2020.116007

Du, Y., and Takeuchi, K. (2020). Does a small difference make a difference? Impact of feed-in tariff on renewable power generation in China. *Energy Econ.* 87:104710. doi: 10.1016/j.eneco.2020.104710

Hitaj, C., and Löschel, A. (2019). The impact of a feed-in tariff on wind power development in Germany. *Resour. Energy Econ.* 57, 18–35. doi: 10.1016/j.reseneeco.2018.12.001

Kim, K.-K., and Lee, C.-G. (2012). Evaluation and optimization of feed-in tariffs. *Energy Policy* 49, 192–203. doi: 10.1016/j.enpol.2012.05.070

Ling-zhi, R., Xin-gang, Z., Yu-zhuo, Z., and Yan-bin, L. (2018). The economic performance of concentrated solar power industry in China. *J. Clean. Product.* 205, 799–813. doi: 10.1016/j.jclepro.2018.09.110

Lo, K. (2014). A critical review of China's rapidly developing renewable energy and energy efficiency policies. *Renew. Sustain. Energy Rev.* 29, 508–516. doi: 10.1016/j.rser.2013.09.006

MF (2013). *Notice on Issues in the Exemption of the Government Funds and Surcharges for Self-Use of DPV* (Beijing).

Ming, Z., Ximei, L., Na, L., and Song, X. (2013). Overall review of renewable energy tariff policy in China: evolution, implementation, problems and countermeasures. *Renew. Sustain. Energy Rev.* 25, 260–271. doi: 10.1016/j.rser.2013.04.026

NDRC (2013a). *12th Five-Year Plan for Renewable Energy Development* (Beijing).

NDRC (2013b). *Notice on Promoting the Healthy Development of Photovoltaic Industry by Playing the Role of Price Leverage* (Beijing).

NDRC (2017). *National Carbon Emissions Trading Market Development Plan (Power Generation Industry)* (Beijing), 1–7.

NDRC (2019). *Notice on Work Related to Wind Power and Photovoltaic Power Generation Connected to Grid without Subsidy [WWW Document]* (Beijing).

NDRC, N. (2016). *13th Five-Year Plan for Renewable Energy Development* (Beijing).

NEA (2018). *Guidance of Energy Work in 2018* (Beijing).

Requate, T. (2014). Green tradable certificates versus feed-in tariffs in the promotion of renewable energy shares. *Environ. Econ. Policy Stud.* 17, 211–239. doi: 10.1007/s10018-014-0096-8

Selinger-Lutz, O., Groß, A., Wille-Haussmann, B., and Wittwer, C. (2020). Dynamic feed-in tariffs with reduced complexity and their impact on the optimal operation of a combined heat and power plant. *Int. J. Electr. Power Energy Syst.* 118:1–9. doi: 10.1016/j.ijepes.2019.105770

Smith, M. G., and Urpelainen, J. (2014). The effect of feed-in tariffs on renewable electricity generation: an instrumental variables approach. *Environ. Resour. Econ.* 57, 367–392. doi: 10.1007/s10640-013-9684-5

Sun, P., and Nie, P.-Y. (2015). A comparative study of feed-in tariff and renewable portfolio standard policy in renewable energy industry. *Renew. Energy* 74, 255–262. doi: 10.1016/j.renene.2014.08.027

Wei, W., Zhao, Y., Wang, J., and Song, M. (2019). The environmental benefits and economic impacts of Fit-in-Tariff in China. *Renewable Energy* 133, 401–410. doi: 10.1016/j.renene.2018.10.064

Xu, T., and Ma, J. (2021). Feed-in tariff or tax-rebate regulation? Dynamic decision model for the solar photovoltaic supply chain. *Appl. Math. Modell.* 89, 1106–1123. doi: 10.1016/j.apm.2020.08.007

Yang, C., and Ge, Z. (2018). Dynamic feed-in tariff pricing model of distributed photovoltaic generation in China. *Energy Proced.* 152, 27–32. doi: 10.1016/j.egypro.2018.09.054

Yang, D., Jiang, M., Chen, Z., and Nie, P. (2019). Analysis on one-off subsidy for renewable energy projects based on time value of money. *J. Renew. Sustain. Energy* 11:025901. doi: 10.1063/1.5050059

Yang, D.-X., Chen, Z.-Y., and Nie, P.-Y. (2016). Output subsidy of renewable energy power industry under asymmetric information. *Energy* 117, 291–299. doi: 10.1016/j.energy.2016.10.089

Yang, D.-X., Qiu, L.-S., Yan, J.-J., Chen, Z.-Y., and Jiang, M. (2019). The government regulation and market behavior of the new energy automotive industry. *J. Clean. Product.* 210, 1281–1288. doi: 10.1016/j.jclepro.2018.11.124

Yang, D. X., and Nie, P. Y. (2016). Influence of optimal government subsidies for renewable energy enterprises. *IET Renew. Power Generat.* 10, 1413–1421. doi: 10.1049/iet-rpg.2015.0307

Zhang, R., Shimada, K., Ni, M., Shen, G. Q. P., and Wong, J. K. W. (2020). Low or No subsidy? Proposing a regional power grid based wind power feed-in tariff benchmark price mechanism in China. *Energy Policy* 146:111758. doi: 10.1016/j.enpol.2020.111758

Zhang, S., and He, Y. (2013). Analysis on the development and policy of solar PV power in China. *Renew. Sustain. Energy Rev.* 21, 393–401. doi: 10.1016/j.rser.2013.01.002

Zhang, Y., Yuan, J., Zhao, C., and Lyu, L. (2020). Can dispersed wind power take off in China: a technical & institutional economics analysis. *J. Clean. Product.* 256: 120475. doi: 10.1016/j.jclepro.2020.120475

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 21 April 2021
doi: 10.3389/fenrg.2021.670026

Does Energy Poverty Reduce Rural Labor Wages? Evidence From China's Rural Household Survey

*Wei-ping Wu[1,2], Wei-kang Zeng[1], Si-wen Gong[3] and Zi-gui Chen[1,4]**

[1] Key Laboratory of Digital Economy and High Quality Development, Hunan University of Technology and Business, Changsha, China, [2] School of Economy and Trade, Hunan University, Changsha, China, [3] School of Finance, Shanghai University of Finance and Economics, Shanghai, China, [4] Design and Art Institute, Hunan University of Technology and Business, Changsha, China

OPEN ACCESS

Edited by:
*Chan Wang,
Guangdong University of Finance and Economics, China*

Reviewed by:
*Huihui Wang,
Cleveland State University, United States*
*Yongran Lin,
Henan Administration Institute, China*

***Correspondence:**
*Zi-gui Chen
chenzigui0213@163.com*

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: 20 February 2021
Accepted: 31 March 2021
Published: 21 April 2021

Citation:
Wu W-p, Zeng W-k, Gong S-w and Chen Z-g (2021) Does Energy Poverty Reduce Rural Labor Wages? Evidence From China's Rural Household Survey. Front. Energy Res. 9:670026. doi: 10.3389/fenrg.2021.670026

Eliminating energy poverty is helpful to get rid of the vicious circle between the lack of adequate and affordable energy services and low income in rural areas. We deconstruct energy poverty into extensive energy poverty and intensive energy poverty and analyze the net effect and its heterogeneity of energy poverty on rural labor wages with micrometric methods, as well as further investigate the impact mechanism from education effect and health effect. The results show that both extensive energy poverty and intensive energy poverty have a significant negative effect on the wages of rural workers, and the marginal effect of extensive energy poverty on the wages of rural workers is lower than that of intensive energy poverty. In addition, the net effect of energy poverty on the wages of rural workers shows labor heterogeneity and regional heterogeneity, and the inhibition effect to low skilled workers and workers with middle wage and in the Western region is the most obvious. Furthermore, energy poverty will limit the access of rural workers to education and damage their health, and then inhibit their productivity and wage. Our results suggest that enhancing the accessibility of energy consumption in rural areas and reducing the incidence of energy poverty are critically essential, and the implementation and optimization of energy poverty alleviation policy should give full consideration to labor force heterogeneity and regional heterogeneity.

Keywords: energy poverty, wages, labor heterogeneity, rural workers, education effect, health effect

INTRODUCTION

Energy poverty is one of the three major challenges facing the energy system of the world and an important symbol of poverty in developing countries, which has been plagued by the development of some countries and regions (Che et al., 2021). On the one hand, the energy structure of rural households based on fossil energy and traditional biomass energy has not been broken. The extensive use of energy has caused certain environmental pollution and restricted the improvement of the quality of life of rural families (Gupta et al., 2020). According to the third agricultural census report of China in 2017, the proportion of electricity used in the surveyed households was 58.6%; the proportion of gas, natural gas, and liquefied petroleum gas used was 49.3%; the proportion of firewood used was 44.2%; the proportion of coal used was 23.9%; the proportion of biogas and solar energy used was 0.9%; and the proportion of other energy used was 0.5%. On the other hand, energy poverty has widened the life quality gap among residents of different income classes and become a "stumbling block" for low-income rural families to pursue a happy life. According to the National Bureau of Statistics of China, the per capita disposable income of rural households in 2019 was 16,020.7 yuan, which is only 37.8% of the per capita disposable income of urban residents. And the housing expenditure of rural households (including water, electricity, gas, and heating expenditure) was 2,871.3 yuan, which is only 42.3% of the housing expenditure of urban residents. Rural household energy supply is insufficient, and the utilization structure is unreasonable, which make it difficult to get rid of the low-income dilemma.

Eliminating energy poverty and promoting the balanced development between urban and rural areas have become the common goals in developing countries (Bardazzi et al., 2021; Faiella and Lavecchia, 2021). The Chinese government attaches great importance to the problem of rural families getting rid of energy poverty and increasing their income and has issued a series of policies, which have achieved certain results. In 2018, the National Energy Administration of China issued the notice of the action plan for further supporting energy development in poor areas and boosting poverty alleviation (2018–2020), which clearly put forward the strategic goal of "orderly and effective promotion of energy development in poor areas and significant improvement of energy universal service level." The data released by the National Energy Administration of China in 2020 show that in the past 8 years, the accumulated investment in major energy projects in poor areas has exceeded 2.7 trillion yuan, which has effectively driven the local economic development and played an important role in poverty alleviation. So, whether and how energy poverty reduces rural labor wages at the micro level has become the focus of this study. The main marginal contributions of this study are shown in two aspects. First, we deconstruct energy poverty into extensive energy poverty and intensive energy poverty and implement a more comprehensive measurement using the Foster–Greer–Thorbecke (FGT) index and the micro-survey data of the rural household of China. Second, we empirically study the net effect and its heterogeneity of energy poverty on rural labor wages with micrometric methods and further investigate the impact mechanism of energy poverty on rural labor wages from education effect and health effect, which provides a new explanation for energy poverty alleviation.

LITERATURE REVIEW AND HYPOTHESIS

Energy is the material basis for the survival and development of human society (Fabbri and Gaspari, 2021). Energy poverty will not only restrict economic development but also affect the physical and mental health and labor productivity. British scholar Bradshaw and Hutton (1983) is the first to pay attention to the problem of energy poverty. According to the International Energy Agency (IEA), 2010 the energy-poor group is defined as the group that cannot obtain electricity or other modern clean energy services, but mainly relies on traditional biomass energy or other solid fuels for cooking and heating. In the existing research, energy poverty is mainly manifested as extensive energy poverty and intensive energy poverty (Chang et al., 2020). Among them, extensive energy poverty refers to the incidence of energy poverty in a country or region, that is, the proportion of households whose energy consumption is lower than the energy poverty line. Intensive energy poverty refers to the relative gap between the energy consumption of energy-poor families and the energy poverty line. From the existing literature, most studies have verified the negative correlation between comprehensive energy poverty and the income of rural residents (Liu et al., 2020) and believe that the key to poverty alleviation in rural areas lies in the realization of electrification (Dijk, 2012). However, it is rare to explore the impact of energy poverty on rural labor wage from the perspective of extensive energy poverty and intensive energy poverty. Specifically, the extensive energy poverty reflects the loss of modern energy resources and services to a large extent, which can not only create more employment opportunities (Dinkelman, 2011) but also improve labor productivity by driving modern tools (Ifeoluwa and Richard, 2021). Therefore, we infer that extensive energy poverty will have a negative impact on the wages of rural workers. In addition, intensive energy poverty reflects the difficulty of energy-poor families in obtaining modern energy resources and services (Apergis, 2015). Therefore, there is a negative correlation between intensive energy poverty and the wages of rural workers. At last, although the positive effects of electricity and clean energy use on the employment opportunities of women and labor productivity have reached consensus in academic circles, there are still differences in the effects of the use of electricity and clean energy on the productivity and wages of male workers (Grogan and Sadand, 2013; Topcu and Tugcu, 2019). This means that energy poverty will have a differential impact on the wages of different workers. Therefore, this article proposes proposition 1.

> Proposition 1. Energy poverty will have a negative effect on the wages of rural workers from both extensive and intensive energy poverty, and this effect will be different for different workers.

So, how can energy poverty restrain the wages of rural workers? What researchers have discussed is that energy poverty limits the educational attainment and health of individual workers. And the positive correlation between education and health level and individual labor productivity has been supported by existing studies (Lucas, 1988, 2004). From the perspective of education, family energy poverty will lead school-age children to spend more time on collecting firewood and other resources, and the access to education will be limited (Sothea, 2019). Moreover, this inhibitory effect is more obvious for rural female children, because they need to spend more time on household energy collection (Nankhuni and Findeis, 2004; Ndiritu and Nyangena, 2011). In addition, the research of Martins (2005); Khandker et al. (2012), and Aguirre (2014) show that the promotion of electrification has a positive effect on the enrollment rate and home study time of school-age children and significantly improves the average education level in this region. From the perspective of health, energy poverty will damage the health of residents and then limit their productivity and wages (Gordon et al., 2014; Sadath and Acharya, 2017; Zhang et al., 2019). For example, Barreca et al. (2014) found that reducing the use of coal in heating resulted in a decrease of about 1.25% in the mortality rate of the whole age population and 3.27% in the infant mortality rate in the United States between 1945 and 1960. Based on Turkish data, Cesur et al. (2018) found that replacing coal with natural gas significantly reduced the risk of death for adults and the elderly, and every 1% increase in household natural gas ordering rate resulted in a decrease of about 1.4% in the overall mortality rate for adults and the elderly. Maji et al. (2021) found that electrification can reduce the probability of cough by about 35–50%. In short, energy poverty not only limits the possibility of rural workers obtaining education resources but also damages their health, resulting in the loss of human capital and labor productivity. Therefore, this article proposes the second and third theoretical hypotheses:

Proposition 2. Energy poverty will limit the access of rural workers to education during school age, resulting in loss of human capital and labor productivity.

Proposition 3. Energy poverty will damage the health of rural workers, resulting in the damage of labor productivity and wages.

MATERIALS AND METHODS

Data

The data used in this article are derived from the Chinese General Social Survey (CGSS) in 2015, which includes six modules, such as "Core Module," "Ten Years Review," "EASS Module," "ISSP Module," "Energy Module," and "Legal Module," The contents of the survey involve the basic personal information of the subjects, family information, social attitudes, energy use, and knowledge of laws and regulations. The reason why we choose CGSS 2015 as research data is based on two considerations: first, the "Energy Module" only exists in CGSS 2015, and the data can meet the demand of this article for the index data of extensive energy poverty and intensive energy poverty measurement. Second, CGSS is the earliest national, comprehensive, and continuous academic investigation project in China, which adopted multi-order stratified probability proportionate to size (PPS) random sampling method and covered more than 10,000 households in 25 provinces across the country.

Due to the inseparable relationship between the energy access capacity and the overall resource endowment of households (Pachaul et al., 2004), we calculated the comprehensive energy consumption in households and then obtained the county-level rural household energy poverty index by calculating the arithmetic mean. However, in CGSS, the units of fuel consumption such as electric power, pipeline natural gas, bottled liquefied gas, diesel, firewood, charcoal, and coal are different. So, we first converted them into kgce and then calculated the comprehensive energy consumption.

Identification of Energy Poverty

At present, the FGT index constructed by Foster and Thorbecke (1984) is widely used to measure energy poverty in academic circles. Since this study focuses on the extensive energy poverty and intensive energy poverty, we expand the FGT index to identify two different types of energy poverty index. The formula is as follows:

$$P_a = \frac{1}{n}\sum_{i=1}^{q}(\frac{z - x_i}{z})^a \tag{1}$$

In this formula, n is the total number of rural households in the sample area; q is the number of rural households whose energy consumption is lower than the energy poverty line; $z$represents the energy poverty line; and $x_i$is the energy consumption of household. In addition, we set the value of parameter a to 0 or 1. When a is equal to 0, P_0 represents the incidence of energy poverty, which is used to measure the extensive energy poverty index. When a is equal to 1, P_1 reflects the relative distance between the energy consumption of energy-poor households and the energy poverty line, which is used to measure the intensive energy poverty index.

As for the calculation of the energy poverty line, we first calculated the rural household energy consumption based on the rural per capita energy consumption and household population. According to *China Statistical Yearbook* 2016, the average number of people in each household in 2015 is 3.1. Combined with the 514.04 kgce per capita domestic energy consumption of Chinese rural households calculated by Qiu et al. (2015), we further calculated that the average domestic energy consumption of rural households in China is 1,593.52 kgce. Then, referring to the practice of Chang et al. (2020), the energy poverty line of rural households in China is 414 kgce by multiplying the average domestic energy consumption of rural households by the proportion coefficient of the national poverty line and the per capita net income of rural households.

Model Specification

Theoretical studies show that the impact path of extensive energy poverty and intensive energy poverty on the wages of rural workers is different, which means that there will be a gap between the two effects on rural labor wages. In order to identify this different effect, this article constructs a wage decision model at the individual level to test the net effect of extensive energy poverty and intensive energy poverty on the wages of rural workers, as follows:

$$\ln(wage_{ijt}) = \alpha + \beta_1 ex\_poverty_{jt} + \gamma_1 ind\_control_{ijt} + \gamma_2 fam\_control_{jt} + \varepsilon_{ijt} \tag{2}$$

$$\ln(wage_{ijt}) = \alpha + \beta_2 in\_poverty_{jt} + \gamma_1 ind\_control_{ijt} + \gamma_2 fam\_control_{jt} + \varepsilon_{ijt} \tag{3}$$

In Equations 2, 3, i represents the rural individuals, j represents the county, t is the time, $\ln(wage)$is the natural logarithm of the wages of rural workers, and *ex_poverty* and *in_poverty* represent the extensive energy poverty and the intensive energy poverty, respectively. *ind_control* and *fam_control* are used to control the individual attribute factors and family factors affecting the wages of rural workers, respectively. The coefficient β represents the net effect of energy poverty on the wages of rural workers, and γ represents the estimated coefficient of each control variable. ε is a random disturbance term.

The individual attributes and family factors controlled in this article are gender, age, marriage, education, experience, total household income (*h_income*), and number of household real estate (*real_estate*). Specifically, for measures of gender, the female is assigned 0 and the male is assigned 1. For marital status, the value of unmarried is 0, and the value of first marriage, remarriage, divorce, and widowed is 1. For education level, the value of not having attended school is 1, the value of primary school (including literacy class) is 2, the value of junior high school is 3, the value of senior high school (including technical secondary school) is 4, the value of junior college is 5, the value of undergraduate college is 6, and the value of graduate school is 7. As for work experience, it is obtained by the time that the interviewees have been engaged in their first non-agricultural work so far. In addition, we also control the age squared term according to the general practice of existing literature (Wu et al., 2020).

RESULTS

Baseline Regression

Table 1 represents the baseline estimates for models (2) and (3). The net effect of extensive energy poverty on rural labor wages is reported in columns 1–3, and the net effect of intensive energy poverty on rural labor wages is reported in columns 4–6. We gradually increased the control variables in the estimation equations, so as to reduce the multicollinearity problem and enhance the robustness of the estimation results. Among them, columns 1 and 4 do not include control variables; columns 2 and 5 include individual attribute factors; and columns 3 and 6 include both individual attribute factors and family factors. The results show that both extensive energy poverty and intensive energy poverty have a significant negative effect on the wages of rural workers, no matter whether the control variable is added or not. Specifically, the marginal effect of extensive energy poverty on the wages of rural workers is −0.21, which is lower than that of the intensive energy poverty by −0.36. It shows that even though the incidence of energy poverty will reduce the wages of rural workers, the inhibitory effect on the wages of rural workers is less than that of the intensive energy poverty. Therefore, to expand the effect of energy on economic poverty alleviation, in addition to enhancing the accessibility of energy consumption in rural areas and reducing the incidence of energy poverty, narrowing the gap between the energy consumption of rural low-income families and the energy poverty line is even more important.

From the estimation results of control variables, the estimation coefficient of gender is significantly positive, and the marginal coefficient is 0.30, indicating that the average wage of rural male workers is 30% higher than that of female workers. This is because in Chinese tradition, in addition to more domestic activities, rural women also take care of the elderly and children, which affects their labor supply and productivity. The estimation coefficient of age is significantly positive and that of the age square term is significantly negative, which indicates that there is an inverted U-shaped relationship between the wages and age of the rural workers, and the inflection point is about 38 years old. The estimated coefficient of marriage variable is significantly positive and 0.14, which means that the average wage of married rural workers is 14% higher than that of unmarried individuals. Education and work experience are positively correlated with the wages of rural workers, and the marginal coefficients are 0.08 and 0.005, respectively. In addition, the total household income also has a positive effect on the wages of rural individual workers, and every 1% increase in the total household income will lead to an increase of 0.69% in the average wages of individual workers. However, there is a significant negative correlation between the number of household real estate and the wages of rural workers, and each increase in household real estate will reduce the wages of rural workers by 1.42%. This is because the increase in the number of household real estate will reduce the employment participation and labor time supply of individual workers and then pull down their wages.

Heterogeneity Analysis

Quantile Regression Estimation

According to the statistical data, there are differences in the employment industry and occupation distribution of rural workers with different wage levels, which means that rural workers with different wage levels may be affected differently by energy poverty. In order to verify this inference, we use the Quantile regression model (QR) to further investigate the differentiated effect of energy poverty on the wages of rural workers at different quantiles. **Table 2** reports the response of the wages of rural workers to the extensive energy poverty and intensive energy poverty at the 25th, 50th, and 75th quantile. Among them, no matter in the estimation equation of extensive energy poverty or intensive energy poverty, energy poverty has a significant inhibitory effect on the wages of rural workers at all quantiles. Furthermore, compared with the rural workers with higher and lower wage income, the middle wage group is more negatively affected by the extensive energy poverty and intensive energy poverty. In summary, proposition 1 has been proved.

Labor Force Heterogeneity

In reality, rural workers are not homogeneous individuals, but have obvious heterogeneity of human capital. The differences in human capital will not only lead to the emergence of labor stratification but also promote different types of workers to show different identities and labor productivity in the labor market. Therefore, this part will focus on the net effect of energy poverty on the wages of rural workers with different skills. By reference to Borjas (1999), we divide the rural workers into two types: high-skilled workers and low-skilled workers according to their education or work experience. Among them, the workers with university degree or above are divided into high-skilled workers, and the workers with high school degrees or below are

TABLE 1 | Baseline regression estimation results.

	Dependent variable: ln(*wage*)					
	(1)	(2)	(3)	(4)	(5)	(6)
Ex_poverty	−0.3066** (0.1326)	−0.2270** (0.1577)	−0.2106*** (0.1169)			
In_poverty				−0.4684*** (0.1608)	−0.4574*** (0.1565)	−0.3670*** (0.1162)
Gender		0.2798*** (0.0276)	0.2971*** (0.0206)		0.2809*** (0.0276)	0.2976*** (0.0206)
Age		0.0352*** (0.0081)	0.0283*** (0.0061)		0.0352*** (0.0081)	0.0283*** (0.0062)
Age^2		−0.0006*** (0.0001)	−0.0004*** (0.0001)		−0.0006*** (0.0001)	−0.0004*** (0.0001)
Marriage		0.1025** (0.0467)	0.1369** (0.0534)		0.1046** (0.0467)	0.1379*** (0.0354)
Education		0.2653*** (0.0104)	0.0826*** (0.0084)		0.2645*** (0.0104)	0.0822*** (0.0084)
Experience		0.0163*** (0.0017)	0.0055*** (0.0013)		0.0163*** (0.0017)	0.0051*** (0.0013)
Ln(h_income)			0.6885*** (0.0126)			0.6880*** (0.0125)
Real_estate			−0.0142*** (0.0053)			−0.0141*** (0.0053)
F Stats.	13.550***	169.100***	567.070***	18.480***	169.910***	567.640***
R^2	0.4004	0.5221	0.6034	0.3605	0.5230	0.6037
Obs.	4,651	3,519	3,364	4,651	3,519	3,364

****P* < 0.01 and ***P* < 0.05, robust standard errors in parentheses.*

TABLE 2 | Quantile regression estimation results.

	Dependent variable: ln(*wage*)					
	25 points		50 points		75 points	
	(1)	(2)	(3)	(4)	(5)	(6)
Ex_poverty	−0.1839* (0.1033)		−0.3947*** (0.1207)		−0.2119*** (0.1231)	
In_poverty		−0.2072** (0.1026)		−0.4260*** (0.0033)		−0.2378** (0.1143)
Ind_control	Yes	Yes	Yes	Yes	Yes	Yes
Fam_control	Yes	Yes	Yes	Yes	Yes	Yes
Pseudo R2	0.3981	0.3982	0.4164	0.4167	0.4395	0.4397
Obs.	3,364	3,364	3,364	3,364	3,364	3,364

****P* < 0.01, ***P* < 0.05, and **P* < 0.1, robust standard errors in parentheses.*

divided into low-skilled workers. In addition, workers above the average value of work experience are classified as high-skilled workers, and workers below the average value are classified as low-skilled workers.

Table 3 reports the net effects of extensive energy poverty and intensive energy poverty on the wages of rural workers with different skills. The results show that whether grouped by education or work experience, extensive energy poverty and intensive energy poverty have a significant inhibitory effect on the wages of rural workers with different skills. Comparatively speaking, the wage of low-skilled workers is more restrained by two types of energy poverty. In addition, whether in the sample of low-skilled workers or high-skilled workers, the results of labor heterogeneity analysis further verify that the inhibitory effect of extensive energy poverty on the wages of rural workers is greater than that of intensive energy poverty. These findings further support proposition 1.

Region Heterogeneity

Due to the large gap in economic development and the obvious difference of energy resource endowment in Eastern, Central, and Western China, there will be differences in the energy resource supply and labor employment policies. Based on the above considerations, we also examined the net effect of extensive energy poverty and intensive energy poverty on the wages of rural workers in different regions (**Table 3**). The results show that extensive energy poverty and intensive energy poverty only have significant negative effects on the wages of rural workers in the central and western regions, but not in the eastern region. Specifically, the estimated coefficients of extensive energy poverty in central and western regions are −0.15 and −0.41, and the estimated coefficients of intensive energy poverty in central and western regions are −0.29 and −0.40, respectively. This means that the restraining effect of extensive energy poverty and intensive energy poverty on the wages of rural workers is more prominent in the western regions. Therefore, the implementation and optimization of energy poverty alleviation policy should also give full consideration to regional heterogeneity.

Mechanism Analysis

Education Effect

Theoretical research shows that the negative impact of energy poverty on the academic education and non-academic education of rural workers will further affect their labor productivity and wages, which will be more prominent for rural female workers. Due to the heavy labor cost of solid fuel collection, female workers have to reduce their opportunities to participate in education and training, employment, and other productive activities with income (Cooke, 1998). In developing countries, female workers spend seven times as much time collecting fuel as adult male workers and 3.5 times as much time as male workers of the same age. This is no exception in China. A survey on the time distribution of "indoor" activities of farmers in poor areas of China shows that female workers spend an average of 26 h a week collecting firewood and cooking activities, which is much higher than that of male workers who spend 9 h a week (Ding and Chen, 2002).

In order to verify the negative effect of energy poverty on the education of rural workers, we empirically test the education effect of energy poverty on rural workers with mediation effect model. In the benchmark regression equation, we have verified a significant positive correlation between education and the wages of workers. Therefore, according to the identification logic of mediating effect model, we can confirm that energy poverty will affect the wages of rural workers through the education effect as long as we verify that there is a significant negative effect of energy poverty on the education of rural workers. In **Table 4**, columns 1 and 2, respectively, report the net impact of extensive energy poverty and intensive energy poverty on the education of rural workers. It can be seen that both extensive energy poverty and intensive energy poverty reduce the average education level of rural workers, and the marginal coefficients are −0.56 and −0.24, respectively, which is in line with the above proposition 2. In addition, from the estimation results of female and male subsamples, the two types of energy poverty significantly reduce the average education level of female and male individuals. Comparatively speaking, the average education level of female workers is more restrained by energy poverty.

Health Effect

Theoretical research infers that energy poverty will damage the health of rural workers and then inhibit their labor productivity and wage. In fact, the extensive use of solid fuels such as firewood and coal will damage the health of residents, which has been fully verified in western countries. For example, Peabody et al. (2005) evaluated the health effects of various types of cooking fuels from the aspects of exhaled carbon monoxide content, maximum vital capacity, and the prevalence of chronic obstructive pulmonary disease and found that solid fuels were the most harmful source to health. Lim et al. (2012) evaluated the risk factors of diseases and

TABLE 3 | Heterogeneity analysis.

	Dependent variable: ln*(wage)*						
	Group by education		Group by work experience		Different region		
	High-skilled	Low-skilled	High-skilled	Low-skilled	East	Middle	West
Ex_poverty	−0.0791* (0.0445)	−0.3552** (0.1614)	−0.1531** (0.0704)	−0.2297** (0.1053)	−0.1174 (0.1032)	−0.1481** (0.0656)	−0.4084** (0.1523)
In_poverty	−0.1311*** (0.0434)	−0.4202** (0.1907)	−0.2238** (0.1093)	−0.3535** (0.1143)	−0.1685 (0.1647)	−0.2910** (0.1205)	−0.4007** (0.1518)

*Each grid is a separate regression. And the net effect of energy poverty on the wage of rural workers with different skills or in different regions is calculated after controlling individual attributes, family factors that affect the wage of rural workers. ***P < 0.01, **P < 0.05, and *P < 0.1, robust standard errors in parentheses.*

TABLE 4 | Education effect analysis.

	Dependent variable: education					
	All samples		Male workers		Female workers	
	(1)	(2)	(3)	(4)	(5)	(6)
Ex_poverty	−0.5603*** (0.1674)		−0.5407** (0.2316)		−0.5863** (0.2361)	
In_poverty		−0.2434** (0.1056)		−0.1884* (0.1202)		−0.2833** (0.1333)

****P < 0.01, **P < 0.05, and *P < 0.1, robust standard errors in parentheses.*

TABLE 5 | Health effect analysis.

	Dependent variable: health					
	All samples		Male workers		Female workers	
	(1)	(2)	(3)	(4)	(5)	(6)
Ex_poverty	−0.6129*** (0.1230)		−0.4608*** (0.1715)		−0.7893*** (0.1753)	
In_poverty		−0.3512*** (0.1217)		−0.1403** (0.0695)		−0.5952*** (0.1736)

****P < 0.01 and **P < 0.05, robust standard errors in parentheses.*

injuries and found that indoor air pollution caused by solid fuel utilization caused 3.55 million premature deaths worldwide in 2010. So, does the health damage effect from energy poverty exist in China? Similar to the education effect test, we tested the health effect of energy poverty on rural workers with the mediating effect model. In the benchmark regression equation, we have verified the significant positive correlation between health and the wages of workers. Therefore, as long as we verify that energy poverty has a significant negative effect on the health of rural workers, we can confirm that energy poverty will affect the wages of rural workers through the health effect. According to the estimated results in **Table 5**, both extensive energy poverty and intensive energy poverty significantly reduce the health level of rural workers, and this health damage effect is more obvious for female workers, that is, proposition 3 has been proved.

CONCLUSION AND POLICY IMPLICATIONS

This study deconstructed energy poverty into extensive energy poverty and intensive energy poverty and analyzed the net effect and its heterogeneity of energy poverty on rural labor wages with micrometric methods; it further investigated the impact mechanism of energy poverty on rural labor wages from education effect and health effect. The following main conclusions were reached: first, both extensive energy poverty and intensive energy poverty have a significant negative effect on the wages of rural workers, and the marginal effect of extensive energy poverty on the wages of rural workers is −0.21, which is lower than that of intensive energy poverty by −0.36. Second, the rural workers with middle wages are more negatively affected by the extensive energy poverty and intensive energy poverty. Third, extensive energy poverty and intensive energy poverty have a significant inhibitory effect on the wages of rural workers with different skills, and the wage of low-skilled workers is more restrained by two types of energy poverty. Fourth, the negative effect of extensive energy poverty and intensive energy poverty on the wages of rural workers is more prominent in the western regions. Fifth, energy poverty will limit the access of rural workers to education and damage their health, resulting in the decrease of labor productivity and wages.

There is often a vicious circle between the lack of adequate and affordable energy services and low income. As an important part of the millennium development goals of China and even the developing countries, eliminating energy poverty is helpful to optimize the energy consumption structure in rural areas and get rid of the vicious circle of energy poverty. To expand energy poverty alleviation and its positive spillover effects on economic poverty alleviation, in addition to enhancing the accessibility of energy consumption in rural areas and reducing the incidence of energy poverty, narrowing the gap between energy consumption of rural low-income families and energy poverty line is even more important. Furthermore, the implementation and optimization of energy poverty alleviation policy should give full consideration to labor force heterogeneity and regional heterogeneity, avoiding one-size-fits-all policy formulation and implementation.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

W-PW: conceptualization, writing – original draft, and methodology. W-KZ: data curation, software, and writing – review editing. S-WG: methodology and writing – review editing. Z-GC: data curation and supervision. All authors contributed to the article and approved the submitted version.

FUNDING

This research is supported by the National Natural Science Foundation of China (Grant Nos. 71903056 and 71774053), National Science Foundation for Post-doctoral Scientists of China (Grant No. 2020M672464), MOE (Ministry of Education in China) Project of Humanities and Social Sciences (Grant No. 19YJC790154), Consulting Project of Chinese Academy of Engineering (Grant Nos. 2020-XY-36 and 2020-XZ-053), Natural Science Foundation of Hunan Province in China (Grant Nos. 2020JJ5104 and 2020JJ4259), Philosophy and Social Science Foundation of Hunan Province in China (Grant No. 18YBQ075), Project of Hunan Social Science Achievement Appraisal Committee (Grant Nos. XSP20YBZ081 and XSP21YBZ094), Scientific Research Project of Hunan Education Department in China (Project No. 19C1038), and Research and Innovation Project for Graduate Students in Hunan Province (Grant Nos. CX20201083 and CX20201084).

REFERENCES

Aguirre, J. (2014). Impact of rural electrification on education: a case study from Peru. *Lahore J. Econ.* 22, 91–108. doi: 10.35536/lje.2017.v22.i1.a5

Apergis, N. (2015). Does renewables production affect income inequality? evidence from an international panel of countries. *Appl. Econ. Lett.* 22, 865–868. doi: 10.1080/13504851.2014.982852

Bardazzi, R., Bortolotti, L., and Pazienza, M. G. (2021). To eat and not to heat? energy poverty and income inequality in Italian regions. *Energy Res. Soc. Sci.* 73:101946. doi: 10.1016/j.erss.2021.101946

Barreca, A. I., Clay, K., and Tarr, J. (2014). *Coal, Smoke, and Death: Bituminous Coal and American Home Heating. IZA Discussion Papers*. Cambridge, MA: NBER.

Borjas, G. J. (1999). Chapter 28 - The economic analysis of immigration. *Handbook Labor Econ.* 3, 1697–1760. doi: 10.1016/S1573-4463(99)03009-6

Bradshaw, J., and Hutton, S. (1983). Social policy options and fuel poverty. *J. Econ. Psychol.* 3, 249–266. doi: 10.1016/0167-4870(83)90005-3

Cesur, R., Tekin, E., and Ulker, A. (2018). Can natural gas save lives? evidence from the deployment of a fuel delivery system in a developing country. *J. Health Econ.* 13, 420–427.

Chang, H. Y., He, K., and Zhang, J. B. (2020). Energy poverty in rural China: a psychological explanations base on households. *China Population Resour. Environ.* 30, 11–20.

Che, X., Zhu, B., and Wang, P. (2021). Assessing global energy poverty: an integrated approach. *Energy Policy* 2021:112099. doi: 10.1016/j.enpol.2020.112099

Cooke, P. A. (1998). The effect of environmental good scarcity on own-farm labor allocation: the case of agricultural households in rural Nepal. *Environ. Dev. Econ.* 3, 443–469. doi: 10.1017/s1355770x98000230

Dijk, K. V. (2012). The role of energy in creating opportunities for income generation in the Indian Himalayas. *Energy Policy* 41, 529–536. doi: 10.1016/j.enpol.2011.11.013

Ding, S. J., and Chen, C. B. (2002). Energy use by poor farmers and its impact on poverty alleviation. *Chin. Rural Econ.* 12, 27–32.

Dinkelman, T. (2011). The effects of rural electrification on employment: new evidence from South Africa. *Am. Econ. Rev.* 101, 3078–3108. doi: 10.1257/aer.101.7.3078

Fabbri, K., and Gaspari, J. (2021). Mapping the energy poverty: a case study based on the energy performance certificates in the city of Bologna. *Energy Build.* 234:110718. doi: 10.1016/j.enbuild.2021.110718

Faiella, I., and Lavecchia, L. (2021). Energy poverty. how can you fight it, if you can't measure it? *Energy Build.* 233:110692. doi: 10.1016/j.enbuild.2020.110692

Foster, J., and Thorbecke, G. E. (1984). A class of decomposable poverty measures. *Econometrica* 52, 761–766. doi: 10.2307/1913475

Gordon, S. B., Bruce, N. G., Grigg, J., Hibberd, P. L., Kurmi, O. P., Lam, K. B., et al. (2014). Respiratory risks from household air pollution in low and middle income countries. *Lancet Respir. Med.* 2, 823–860.

Grogan, L., and Sadand, A. (2013). Rural electrification and employment in poor countries: evidence from Nicaragua. *World Dev.* 43, 252–265. doi: 10.1016/j.worlddev.2012.09.002

Gupta, S., Gupta, E., and Sarangi, G. K. (2020). Household energy poverty index for India: an analysis of inter-state differences. *Energy Policy* 144:111592. doi: 10.1016/j.enpol.2020.111592

Ifeoluwa, G., and Richard, B. (2021). Energy poverty: estimating the impact of solid cooking fuels on GDP per capita in developing countries - case of sub-Saharan Africa. *Energy* 7:119770. doi: 10.1016/j.energy.2021.119770

International Energy Agency (IEA) (2010). *Energy Poverty: How to Make Modern Energy Access Universal? World Energy Outlook*. Paris: IEA.

Khandker, S. R., Samad, H. A., Ali, R., and Barnes, D. F. (2012). Who benefits most from rural electrification? evidence in India. *Energy J.* 35, 75–96.

Lim, S., Vos, T., and Bruce, N. (2012). The burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions 1990-2010: a systematic analysis. *Lancet* 380, 2224–2260.

Liu, Z. M., Deng, M. Y., and Cui, Z. W. (2020). The impact of energy poverty on residents' welfare and its mechanism: an analysis based on CGSS data. *China Soft Sci.* 8, 143–163.

Lucas, R. (1988). On the mechanics of economic development. *J. Monet. Econ.* 22, 3–42. doi: 10.4135/9781452204550.n1

Lucas, R. E. (2004). Life earnings and rural-urban migration. *J. Polit. Econ.* 112, 29–59.

Maji, P., Mehrabi, Z., and Kandlikar, M. (2021). Incomplete transitions to clean household energy reinforce gender inequality by lowering women's respiratory health and household labour productivity. *World Dev.* 139:105309. doi: 10.1016/j.worlddev.2020.105309

Martins, J. (2005). The impact of the use of energy sources on the quality of life of poor communities. *Soc. Indic. Res.* 72, 373–402. doi: 10.1007/s11205-004-5583-z

Nankhuni, F. J., and Findeis, J. L. (2004). Natural resource-collection work and children's schooling in Malawi. *Agrc. Econ.* 31, 123–134. doi: 10.1016/j.agecon.2004.09.022

Ndiritu, S., and Nyangena, W. (2011). Environmental goods collection and children's schooling: evidence from Kenya. *Reg. Environ. Change* 11, 531–542. doi: 10.1007/s10113-010-0168-7

Pachaul, S., Mueller, A., Kemmier, A., and Spreng, D. (2004). On measuring energy poverty in Indian households. *World Dev.* 32, 2083–2104. doi: 10.1016/j.worlddev.2004.08.005

Peabody, J. W., Riddell, T. J., Smith, K. R., Liu, Y., and Sinton, J. E. (2005). Indoor air pollution in rural china: cooking fuels, stoves, and health status. *Arch. Environ. Occup. Health* 60, 86–95. doi: 10.3200/aeoh.60.2.86-95

Qiu, H. G., Yan, J. B., and Li, D. W. (2015). Analysis of the current status of energy consumption, development trends and determinants of China's rural energy consumption: empirical research based on two-phase investigation in four province. *China Soft Sci.* 11, 28–38.

Sadath, A. C., and Acharya, R. H. (2017). Assessing the extent and intensity of energy poverty using multidimensional energy poverty index: empirical evidence from households in India. *Energy Policy* 102, 540–550. doi: 10.1016/j.enpol.2016.12.056

Sothea, O. (2019). Energy poverty in the Lao PDR and its impacts on education and health. *Energy Policy* 132, 247–253. doi: 10.1016/j.enpol.2019.05.030

Topcu, M., and Tugcu, C. T. (2019). The impact of renewable energy consumption on income inequality: evidence from developed countries. *Renew. Energy* 151, 1134–1140. doi: 10.1016/j.renene.2019.11.103

Wu, W. P., Cheng, Z. G., and Yang, D. X. (2020). Do internal migrants crowd out employment opportunities for urban locals in China?—reexamining under the skill stratification. *Physica A* 537, 1–16. doi: 10.1017/cbo9780511499401.002

Zhang, D., Li, J., and Han, P. (2019). A multidimensional measure of energy poverty in China and its impacts on health: an empirical study based on the China family panel studies. *Energy Policy* 131, 72–81. doi: 10.1016/j.enpol.2019.04.037

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 26 April 2021
doi: 10.3389/fenrg.2021.665140

Spatiotemporal Differences and Spatial Convergence of the Water-Energy-Food-Ecology Nexus in Northwest China

*Min Wang[1], Yi-fei Zhu[2], Si-wen Gong[3] and Chang-yu Ni[1]**

[1] School of Business, Central South University of Forestry and Technology, Changsha, China, [2] Key Laboratory of Digital Economy and High Quality Development, Hunan University of Technology and Business, Changsha, China, [3] School of Finance, Shanghai University of Finance and Economics, Shanghai, China

The Water-Energy-Food-Ecology (W-E-F-E) nexus is related to the realization of the goal of high-quality economic development in Northwest China. This paper analyzed the dynamic change trend, spatial evolution characteristics, and spatial convergence of identified W-E-F-E nexus in Northwest China utilizing the coupling coordination degree model, an ESDA instrument, and the spatial convergence model. The results show that: first, the W-E-F-E nexus in Northwest China presents a "V" shaped trend of decreasing first and then rising in time dimension. After a decline of 25.1% in 2002–2012, it increased by 29.7% in 2012–2017. Second, the W-E-F-E nexus in Northwest China shows positive spatial autocorrelation, and the Moran's I index of this is about 0.15. In spatial dimension, it shows a trend of high-value agglomeration around provincial capitals, and the distribution pattern is relatively stable. Thirdly, the W-E-F-E nexus in Northwest China has significant spatial convergence, that is, the W-E-F-E nexus gap between the prefectures in Northwest China is shrinking, and the convergence rate is between 2.83 and 3.16. Moreover, with the development of the economy, the rational allocation of land and labor resources, and the optimization of fiscal expenditure structure, the W-E-F-E nexus in Northwest China will converge to the same steady state level after a long period of time. In general, in the process of improving the W-E-F-E nexus in Northwest China, the heterogeneous characteristics of prefectures should be fully considered, and a trans-regional cooperative management and restriction mechanism of the W-E-F-E nexus should be explored to achieve high-quality development of the region.

Keywords: W-E-F-E nexus, spatiotemporal differences, spatial convergence, dynamic evolution, ESDA instrument

Edited by:
Chan Wang,
Guangdong University of Finance and Economics, China

Reviewed by:
Vincent Chen,
The University of Sheffield, United Kingdom
Hao-kuang Li,
Shanghai Academy of Social Sciences, China

***Correspondence:**
Chang-yu Ni
nichangyu@126.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

***Received:** 07 February 2021*
***Accepted:** 19 March 2021*
***Published:** 26 April 2021*

Citation:
Wang M, Zhu Y-F, Gong S-W and Ni C-Y (2021) Spatiotemporal Differences and Spatial Convergence of the Water-Energy-Food-Ecology Nexus in Northwest China. Front. Energy Res. 9:665140. doi: 10.3389/fenrg.2021.665140

INTRODUCTION

In recent years, the most prominent non-traditional security issues have been water, energy, food, and ecological security. The W-E-F-E nexus has drawn increasing attention from the international community (Fouladi et al., 2021). As a big consumer of resources, China's water resources per capita are only 25% of the world average, and external energy dependence exceeds 20%. China feeds 20% of the world's population on 7% of its arable land, and its average overloading rate of livestock in key natural grasslands is still higher than 10%, which indicates its contradiction between supply and demand of resources is prominent. Water resources are more abundant in the south and scarcer in the north, especially in the northwest, and energy resources are more abundant in the west and less in the east, which are obvious characteristics of the spatial distribution of resources in China. In particular, the lack of water resources and abundant energy reserves in the northwest region form a sharp contrast, and the innate ecological vulnerability also threatens food security in the northwest region. The imbalanced and unmatched spatial and temporal distribution of water, energy, food and ecological resources greatly affects the efficiency of resource flow and transformation and aggravates the imbalance between supply and demand of resources (Yuan et al., 2020). In November 2011, the German Federal Government summed up the relationship between water security, energy security, and food security as a "bond" of interdependence for the first time at the Bonn Conference. In September 2019, the Forum on Ecological Protection and High-Quality Development of the Yellow River Basin made it clear that promoting the intensive use of water resources, developing modern agriculture, and strengthening ecological and environmental protection were the current goals for ecological protection and high-quality development of the Yellow River Basin. In this context, it is of great value to incorporate ecology into the research of the coupling system. Only when water resources, energy, food, and ecology are studied as a whole, and the synergy of the four is enhanced and the overall efficiency of the system is improved, can high-quality regional development be more conducive to the realization of regional development. Therefore, how to promote the upgrading of the coupling system of water, energy, food, and ecology in Northwest China, where the contradiction between supply and demand of resources is prominent, so as to realize the intensive utilization of regional water resources, the efficient and unblocked energy channels, the security and stability of food supply, and the significant improvement of ecological environment, has become an important proposition concerning high-quality development in Northwest China and even the whole country. Moreover, it has important reference value for many countries and regions in the world with the same climate and resource distribution characteristics.

Water, energy, food, and ecology are an organic whole connected with and influencing each other (Chang et al., 2020). The exploitation of energy often causes damage to the local ecological environment. As an essential part of the ecosystem, water is an important index to measure the agricultural production potential of a region. Every link between social production and water and energy consumption will lead to environmental pollution through the global food and energy supply chain (Harris and Kennedy, 1999; Bhuiyan et al., 2010; Owen et al., 2018). However, there are very few studies that analyze it as a system, and the research on resource integration centered on a single resource not only fails to meet the demand of resource governance oriented by "multi-resource problem governance," but also fails to effectively deal with the changes of ecological environment, economy, and population (Muller, 2015; Sun et al., 2020). Moreover, the blind emphasis on the exploitation of the potential of a single resource will inevitably have a negative impact on other resources. Threats to the security of any subsystem will trigger a chain reaction within the system, and then affect the normal operation of the system as a whole (Bryan et al., 2014; Gao and Bryan, 2017; Melo et al., 2021). Most of the existing literatures focus on the study of the water—energy—grain coupling system (Zhang et al., 2018; Niva et al., 2020), however, bringing the ecological environment into the coupling system has rarely been explored. This is mainly because modeling the water-energy-food-ecology relationship faces the challenge of how to reduce multidimensional and interdependent uncertainty (Shi et al., 2020). At present, the coupling relationship evaluation methods of composite systems mainly include the coupling coordination degree model, the PSR model, and the SD model (Yin and Wu, 2019; Liu et al., 2020; Ravar et al., 2020), but the spatial differentiation and convergence of the coupling relation of complex coefficients are seldom discussed.

Based on the prefecture-level city panel data of five provinces in Northwest China from 2002 to 2018, this paper analyzes the W-E-F-E nexus and its temporal and spatial evolution characteristics in Northwest China, and constructs a spatial convergence model to further analyze the convergence and convergence rate of the W-E-F-E nexus, aiming to provide reference for ecologically fragile areas to improve their comprehensive development advantages and achieve high-quality development. The marginal contribution of this study mainly includes two points. First, considering the importance of the ecosystem for development in Northwest China, we put the ecosystem into the analysis framework and measure the W-E-F-E nexus with the coupling coordination degree (CCD) model. Secondly, the spatial correlation is further introduced into the traditional spatial convergence model to investigate the spatial convergence of the W-E-F-E nexus in Northwest China under the condition of the spatial spillover effect and its influencing factors. Through the study of the W-E-F-E nexus in Northwest China, this paper is expected to provide important policy implications for the promotion of high-quality development in Northwest China and other ecologically fragile areas in the world.

MATERIALS AND METHODS

In this paper, the comprehensive evaluation index, coupling coordination degree, and spatial convergence rate of the W-E-F-E nexus in Northwest China are calculated and analyzed to study the spatial and temporal evolution characteristics and spatial convergence of the W-E-F-E nexus in Northwest China.

Identification of W-E-F-E Nexus

Since the units and orders of magnitude of each indicator are different, in order to eliminate the influence caused by different dimensions or orders of magnitude of different indicators, the original data is firstly processed by dimensionless processing. The calculation formulas for positive and negative indicators are as follows:

$$x'_{it} = (x_{\text{it}} - x_{min}) \ / \ (x_{\max} - \ x_{min}) \tag{1}$$

$$x'_{it} = (x_{max} - x_{it}) \ / \ (x_{max} - x_{min}) \tag{2}$$

where x_{it}, x'_{it} are the original value and the normalized value, respectively. After processing the original data, according to Sun and Yan (2018), a logistic curve model and coefficient of variation method are used to conduct single-factor evaluation of each subsystem in the W-E-F-E nexus. Logistic curve function is shown in **Appendix Figure A1**, and the expression is:

$$P_{\text{it}} = \frac{1}{1 + \text{e}^{\text{a-b}x'_{it}}} \tag{3}$$

where x'_{it} is the standard value after dimensionless treatment, P_{it} is development evaluation value, and a and b are constants. In this paper, the undetermined coefficient method is used to determine the parameters a and b, that is, by setting up a binary system of first order equations, when x'_{it} = 0.01, P_{it} is approximately 0.001, and when x'_{it} = 0.99, P_{it} is approximately 0.999; thus, the values of a and b are 4.595 and 9.19, respectively. Then the Logistic curve formula is adjusted as follows:

$$P_{it} = \frac{1}{1 + \text{e}^{4.595 - 9.19x'_{it}}} \tag{4}$$

The comprehensive evaluation index P of water resources, energy, food, and ecological subsystems is:

$$P_n = f_n(x) = \sum_{j=1}^{4}(W_jP_j) \tag{5}$$

$$W_j = V_j / \sum_{j=1}^{4} V_j \tag{6}$$

$$V_j = \sigma_j / \bar{x}_j \tag{7}$$

where P_j is the development evaluation value of this index, W_j is the weight of each index in the subsystem determined by the coefficient of variation method, and V_j is the coefficient of variation of the j index in the subsystem. In Equation (7), σ_j and $\bar{x}_j$ are, respectively, the standard deviation and average value of the j index in the subsystem. Based on the comprehensive evaluation index of each subsystem, the calculation formula of the W-E-F-E nexus is finally obtained:

$$F = \alpha_1 f_1(x) + \alpha_2 f_2(x) + \alpha_3 f_3(x) + \alpha_4 f_4(x) \tag{8}$$

where F is the weighted evaluation index of water, energy, food, and the ecosystem, $F \in [0, 1]$; n is the number of subsystems, which is 4 in this paper; and α_1, α_2, α_3, and $\alpha_4$are undetermined coefficients. Considering the interconnection, mutual influence, mutual promotion and inseparable relationship characteristics among water, energy, food, and the ecology and the requirements of high-quality development, this paper believes that the target layers are equal in weight, so $\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 1/4$.

"Coordination" refers to the relationship between two or more subsystems that cooperate with each other and develop harmoniously and in a virtuous circle. According to the actual situation of 38 prefecture-level cities, regions, and county-level cities directly under the jurisdiction of autonomous regions in the five provinces of Northwest China, and based on the study of coordinated development degree model by Yang (2003), the W-E-F-E nexus evaluation model is established as follows:

$$C = \left\{ \frac{f_1(x) f_2(x) f_3(x) f_4(x)}{\left[\left(f_1(x) + f_2(x) + f_3(x) + f_4(x) \right) / 4 \right]^4} \right\}^4 \tag{9}$$

where C is the coupling degree, which is determined by the magnitude of $f_n(x)$. Because $f_n(x) \in [0, 1]$, so $C \in [0, 1]$. C = 0 indicates that the coupling degree of the system is the minimum, and the system is in an independent state. C = 1 indicates that the coupling degree of the system is the maximum and the benign coupling state is reached between the systems. However, the value of the coupling degree can only represent a kind of strong and weak relationship between subsystems, but cannot reflect the level of coordinated development, so this paper introduces the CCD model in order to analyze and solve the degree of coupling coordination development of several systems. Finally, the calculation formula of the W-E-F-E nexus is obtained as follows:

$$D = \sqrt{CF} \tag{10}$$

Spatial Convergence Model

The convergence theory of neoclassical economics was originally used to investigate whether the per capita income of different countries or regions converged or diverged. In recent years, the application of this theory has been extended to the research field of resources and the environment. In this paper, the convergence analysis is helpful to examine the convergence or divergence characteristics of the W-E-F-E nexus between different cities in Northwest China, that is, whether the gap between the W-E-F-E nexus is expanding or shrinking, and analyze the W-E-F-E nexus in different prefectures and different development stages of the same prefecture in Northwest China.

Absolute β Spatial Convergence Model

The absolute β convergence of the W-E-F-E nexus means that under strict assumptions, including the same land resources, labor market, economic development, public utility security level, etc., the W-E-F-E of all cities will converge to the same level over time. The absolute β convergence model is as follows:

$$\ln D_{i,t+1} / D_{i,t} = \beta \ln D_{i,t} + \varepsilon_{i,t} \tag{11}$$

Based on the idea of the spatial convergence model of Skidmore et al. (2004) and Elhorst (2005, 2010), this paper introduces spatial factors into the basic model, and constructs the absolute β-spatial convergence model of green efficiency of water resources in Northwest China:

$$\ln(D_{i,t+1}/D_{i,t}) = \lambda W^* \ln(D_{i,t+1}/D_{i,t}) + \beta \ln D_{i,t} + \varepsilon_{i,t} \tag{12}$$

In Equation (12), $D_{i,t}$ and $D_{i,t+1}$ are the W-E-F-E nexus of the city i in the year t and t+1, respectively, $\ln(D_{i,t+1}/D_{i,t})$

represents the logarithmic increase of CCD in the region i in the year t; W is the spatial weight matrix; and λ represents the spatial autoregressive coefficient, which is used to measure the spatial spillover effect of W-E-F-E nexus growth. β is the absolute convergence coefficient. If $\beta < 0$, it means that the W-E-F-E nexus has absolute convergence, that is, the area with low W-E-F-E has a tendency to catch up with the area with high environmental efficiency; otherwise, it is the opposite. According to the principle of econometrics, the convergence coefficient has an equality relation $|\beta| = 1 - e^{-\theta T}$. where θ is the rate of convergence (or speed of convergence) and T is the period of sample investigation, so the rate of convergence $\theta = -\ln[(1 - |\beta|)/T]$ can be obtained.

In terms of the setting of the spatial weight matrix, considering that the economic distance weight matrix may have endogenous problems, which may lead to errors in the estimation results, this paper finally chooses the geographical contiguity weight matrix (W_{cont}) and the geographical distance weight matrix (W_{dist}) for spatial econometric analysis. Here, the queen contiguity method is used to construct the geographic contiguity weight matrix, and $W_{ii'} = 1$ is regarded as the region i and i' are adjacent, and $W_{ii'} = 0$ is regarded as non-adjacent. In addition, the geographical distance weight matrix is constructed according to the formula $W_{ii'} = 1/d_{ii'}$, and $d_{ii'}$ represents the straight-line distance between two regional centers.

Conditional β Spatial Convergence Model

Different from the absolute β spatial convergence, the conditional β spatial convergence means that the urban W-E-F-E nexus converges to its own stable level over time when the characteristic differences between different prefectures are taken into account. On the basis of the absolute β spatial convergence model, the conditional β spatial convergence model is obtained by adding some control variables:

$$\ln(D_{i,t+1}/D_{i,t}) = \lambda W^{*}\ln(D_{i,t+1}/D_{i,t}) + \beta \ln D_{i,t} + \alpha X_{i,t} + \varepsilon_{i,t} \tag{13}$$

In Equation (13), $X_{i,t}$ represents the control variable affecting the W-E-F-E nexus and β is the conditional convergence coefficient. If β is less than zero and statistically significant, it indicates the existence of spatial conditional convergence; otherwise, there is no spatial conditional convergence. α is the estimated coefficient of the control variable, reflecting the size and direction of the influence effect of the corresponding control variable on the W-E-F-E nexus. The factors influencing the W-E-F-E nexus mainly include land resource status, labor supply, economic development level, and government fiscal expenditure. For this reason, the above factors are controlled in the estimation equation. The administrative area is used to measure land resources (area), the total population at the end of the year is used to measure labor market conditions (pop), the regional per capita GDP is used to measure economic development level (rjgdp), and the fiscal general budget expenditure is used to measure the government's control and use of social resources (fina).

Variables and Data

Evaluating the coupling coordination of water, energy, food, and the ecosystem is complicated. It is very important to select the evaluation index and grasp the structure of the index system, which should give consideration to the authenticity, systematicness, and scientificity. Based on the scientific connotation of the W-E-F-E nexus and reference to relevant literature, this paper constructs a comprehensive evaluation index system of the W-E-F-E nexus in Northwest China, which includes four subsystems and 16 specific indexes (**Table 1**).

TABLE 1 | W-E-F-E nexus evaluation index system.

The target layer	Index layer	Calculation method	Index properties
Water resources subsystem	Agricultural water consumption (billion cubic meters)	Taken from the statistics	−
	Industrial water consumption (billion cubic meters)	Taken from the statistics	−
	Domestic water consumption (billion cubic meters)	Taken from the statistics	+
	Ecological water consumption (billion cubic meters)	Taken from the statistics	+
Energy subsystem	Per capita energy consumption (tons per person)	Energy consumption/total population	−
	Energy consumption per 10,000 Yuan of industrial added value (tons/10,000 Yuan)	Total industrial energy consumption/industrial added value	−
	Total energy consumption of industries above designated size (tons of standard coal)	Taken from the statistics	−
	Investment in fixed assets in the production and supply of electricity, gas and water (10,000 Yuan)	Taken from the statistics	+
Grain subsystem	Total grain output (10,000 tons)	Taken from the statistics	+
	Oil production (10,000 tons)	Taken from the statistics	+
	Fertilizer application amount (10,000 tons)	Taken from the statistics	−
	Total sown area of crops (thousands of hectares)	Taken from the statistics	+
Ecology subsystem	Investment in landscaping (10,000 Yuan)	Taken from the statistics	+
	Park green area (ha)	Taken from the statistics	+
	Green coverage area of built-up areas (ha)	Taken from the statistics	+
	Industrial sulfur dioxide emissions (tons)	Taken from the statistics	−

Water, energy, food, and ecology are closely related to each other. First of all, water, as an important resource, not only ensures the orderly production activities of human society, but also maintains the ecological balance of nature. Therefore, four indexes of agricultural, industrial, domestic, and ecological water use are selected to measure the development status of the water resources subsystem. Secondly, energy systems provide power support for social production and development, and its development status can be measured through energy industry investment and construction, industrial energy consumption, and energy output efficiency. Therefore, this paper selects the per capita energy consumption, energy consumption per 10,000 Yuan of industrial added value, total energy consumption of industries above a designated size, and investment in fixed assets in the production and supply of electricity, gas, and water as the evaluation indexes. Then, food is the key factor to maintain the survival of human society. In this paper, the development of the grain subsystem is reflected by the input and output of grain; the total grain output and oil yield are taken as the output indexes, and the amount of chemical fertilizer and crop sown area are taken as the input indexes. Finally, the ecosystem provides a corresponding environment for production and life. The ecology subsystem is evaluated by investment in landscaping, park green area, green coverage area of built-up areas, and industrial sulfur dioxide emissions. The 16 indexes included in the above four subsystems jointly constitute the W-E-F-E nexus evaluation index system.

This paper selects the panel data of 38 prefecture-level cities, regions, and counties directly under the jurisdiction of autonomous regions in five provinces of Northwest China (Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang) from 2002 to 2018 for empirical analysis. The data are mainly from statistical yearbooks of provinces and cities, Bulletin of Water Resources Development, Statistical Bulletin of National Economic and Social Development, and EPS database; data that cannot be directly obtained are made up using the linear fitting method. In this paper, the panel data of 38 prefecture-level cities, regions, and counties directly under the jurisdiction of autonomous regions in Northwest China from 2002 to 2018 are selected as the analysis dataset. The data sources are as follows: (1) The data of green area of parks, green coverage area of built-up areas, industrial sulfur dioxide emissions, and fixed asset investment in the production and supply of electricity, gas, and water are mainly from the global statistical data/analysis platform of Economy Prediction System (EPS); (2) The data of agricultural water consumption, industrial water consumption, domestic water consumption, and ecological water consumption are mainly derived from Bulletin of Water Resources Development of each province and supplemented by the China Environmental Statistics Yearbook; and (3) The remaining data, such as total grain output, per capita energy consumption, and investment in landscaping, are mainly from the China Regional Economic Statistical Yearbook, and the missing data are supplemented by the Statistical Bulletin of National Economic and Social Development and the corresponding statistical Yearbook published by local governments.

RESULTS

W-E-F-E Nexus

Dynamic Evolution of the W-E-F-E Nexus

Comprehensive evaluation value is an overall quantitative evaluation of things or objects restricted by a variety of factors. The comprehensive evaluation value of each subsystem of water, energy, food, and ecology reflects its development status. As shown in **Figure 1**, the development of the four subsystems presents a dynamic evolution trend of alienation. First of all, the average comprehensive evaluation value of the energy system in Northwest China is the highest, which is about 0.7. In 2007–2008 especially, the comprehensive evaluation value of the energy system achieved rapid growth, reaching12.9% and peaking at 0.79 in 2008. This may be related to the investment and construction of energy industry infrastructure by the Chinese government's economic stimulus plan under the background of economic crisis. The high comprehensive evaluation value of the energy system is closely related to the natural energy advantages in Northwest China and the policy support of the country. On the one hand, the northwest region has abundant energy reserves, which is suitable for the development of the energy industry. On the other hand, the national western development strategy and the "One Belt and One Road" initiative have ensured the energy industry in the northwest region received greater support in investment and construction, so the development level is also higher.

Secondly, it can be seen that the comprehensive evaluation values of water and food systems in Northwest China are relatively close, at about 0.5. Due to the drought and water shortage in Northwest China, production and living water are limited. The comprehensive evaluation value of the water resources system shows a fluctuating upward trend, with an average annual growth rate of only 1.3%. However, it still indicates that the intensive utilization of water resources in Northwest China is improving. In addition, the development of the grain system in Northwest China is relatively stable, and its comprehensive evaluation value fluctuates slightly around 0.52. Food production cannot be separated from water. The natural conditions in Northwest China determine that the

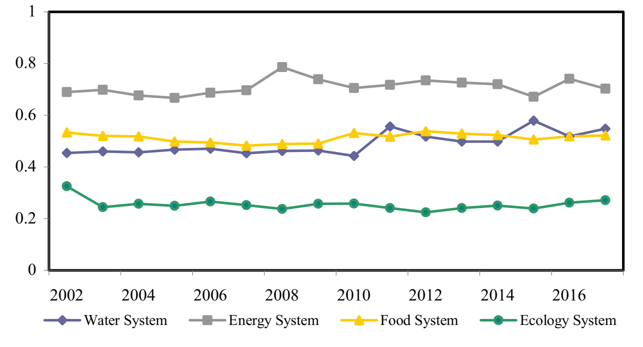

FIGURE 1 | Dynamic evolution of subsystems in Northwest China.

improvement of local agricultural production potential cannot avoid the rigid constraint of water resources. It is worth noting that in recent years, the development level of water resources system in Northwest China shows a trend of overtaking the grain system, which indicates that local awareness of water resources' protection and rational utilization has been strengthened, which is conducive to further developing the potential of food production in Northwest China and ensuring regional food security.

Finally, among the four subsystems, the development of the ecosystem in Northwest China is the worst. Except for in 2002, the comprehensive evaluation value of the ecosystem is always lower than 0.3, which is related to the local climate, terrain, and other natural conditions. However, the fragile ecological environment in Northwest China is also related to human's insufficient attention on ecological work and unreasonable development activities. Insufficient investment in ecological construction and excessive discharge of pollutants from production and living all make it impossible to effectively improve the ecological environment in Northwest China.

Based on the calculation of the comprehensive evaluation value of water, energy, food, and the ecosystem, this paper investigates the coupling and coordination status of all subsystems (as shown in **Figure 2**). As can be seen from the figure, the W-E-F-E nexus in Northwest China showed a fluctuating downward trend from 0.39 in 2002 to 0.29 in 2012, with a decrease rate of 25.6%. Among them, in 2003–2008 and 2009–2012, there was a V-shaped trend of first rising and then declining. This is because during the above period, a series of policies on water resources, energy resources, agricultural production, and ecological environment were issued in Northwest China, resulting in significant fluctuations in the W-E-F-E nexus in the short term. Each time the W-E-F-E nexus experienced a relatively large decline, there would be a relatively slow recovery process, which may be related to the local concept of development of natural resources first, protection later. Since 2012, the central government has paid more attention to coordinated development and ecological and environmental protection, and put forward a series of related policies. For example, the Measures for Examining the Implementation of the Strictest Water Resources Management System was officially released in 2013, and the Air Pollution Prevention and Control Act was revised in 2015 and implemented in 2016. The efficient exploitation and utilization of resources, the improvement and restoration of ecology, and the coordinated development of economic development and ecological protection will be promoted to a new height. This is reflected in the fact that the W-E-F-E nexus continued to increase from 2012 to 2017, rising from 0.29 in 2012 to 0.38 in 2017, with an average annual growth rate of 5.5%, and the growth rate from 2016 to 2017 was particularly obvious, reaching 12.8%.

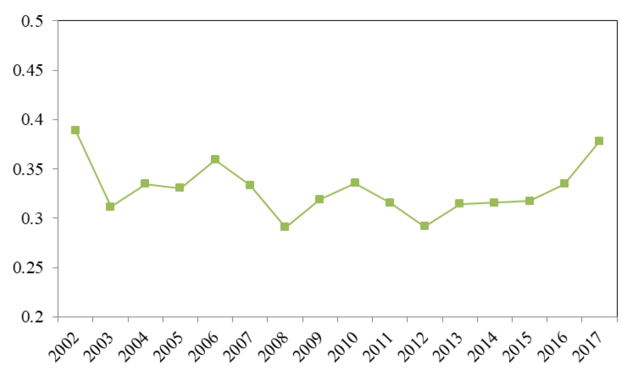

FIGURE 2 | Dynamic evolution of the W-E-F-E nexus in Northwest China.

Regional Heterogeneity of W-E-F-E Nexus

This paper calculates the W-E-F-E nexus of prefecture-level cities, regions, and counties directly under the jurisdiction of autonomous regions in Northwest China and analyzes its spatial heterogeneity. This paper has selected an observation point of every 5 years since 2002 and visualized the W-E-F-E nexus in Northwest China in 2002, 2007, 2012, and 2017 by using GeoDA spatial data statistical software (as shown in **Figure 3**). The darker the shadow color in the figure is, the higher the CCD of the composite system in this area is, while the white color shows areas with missing data.

Through data analysis, it is found that the majority of the W-E-F-E nexus between different cities or regions in the five northwest provinces from 2002 to 2012 is lower than 0.5. It indicates that the development of the W-E-F-E nexus in Northwest China is in a state of imbalance or near imbalance, and most cities or regions have shown a decline to varying degrees, with the number of cities or regions with W-E-F-E nexus misalignment (coupling coordination score less than 0.4[1]) nearly doubling from 18 in 2002 to 34 in 2012. Among these cities or regions, the W-E-F-E nexus in Yulin of Shaanxi Province, Wuwei of Gansu Province, and Zhongwei of Ningxia Province decreased most significantly, by 79.9, 58.1, and 52.2%, respectively. In many cases, economic development comes at the expense of the ecological environment, and the ecological cost of development is high. The waste of water resources, pollution, and destruction of the ecological environment restricts local food production, which in turn has a negative impact on the production of energy and gradually forms a vicious circle. In terms of spatial dimension, the W-E-F-E nexus is relatively high in other provincial capitals and nearby cities in Northwest China, except for Qinghai Province where the data is seriously missing. Such spatial agglomeration and a distribution trend are not obvious. W-E-F-E nexus is in a relatively static state in each city or region, that is, the spatial gap of W-E-F-E nexus development has not been significantly narrowed.

From 2012 to 2017, the overall trend of the W-E-F-E nexus in Northwest China was on the rise, with the nexus increasing significantly. The number of cities or regions with W-E-F-E nexus imbalance decreased from 34 in 2012 to 26 in 2012,

[1]Based on the practice of Liu and Chen (2016), we use the uniform distribution function method to grade the coupling coordination value. When the coupling coordination value is less than 0.4, the W-E-F-E nexus is in a state of imbalance; when the coupling coordination value is 0.4–0.5, the W-E-F-E nexus is in a state of imbalance; when the coupling coordination value is greater than 0.5, the W-E-F-E nexus is in a state of coordination.

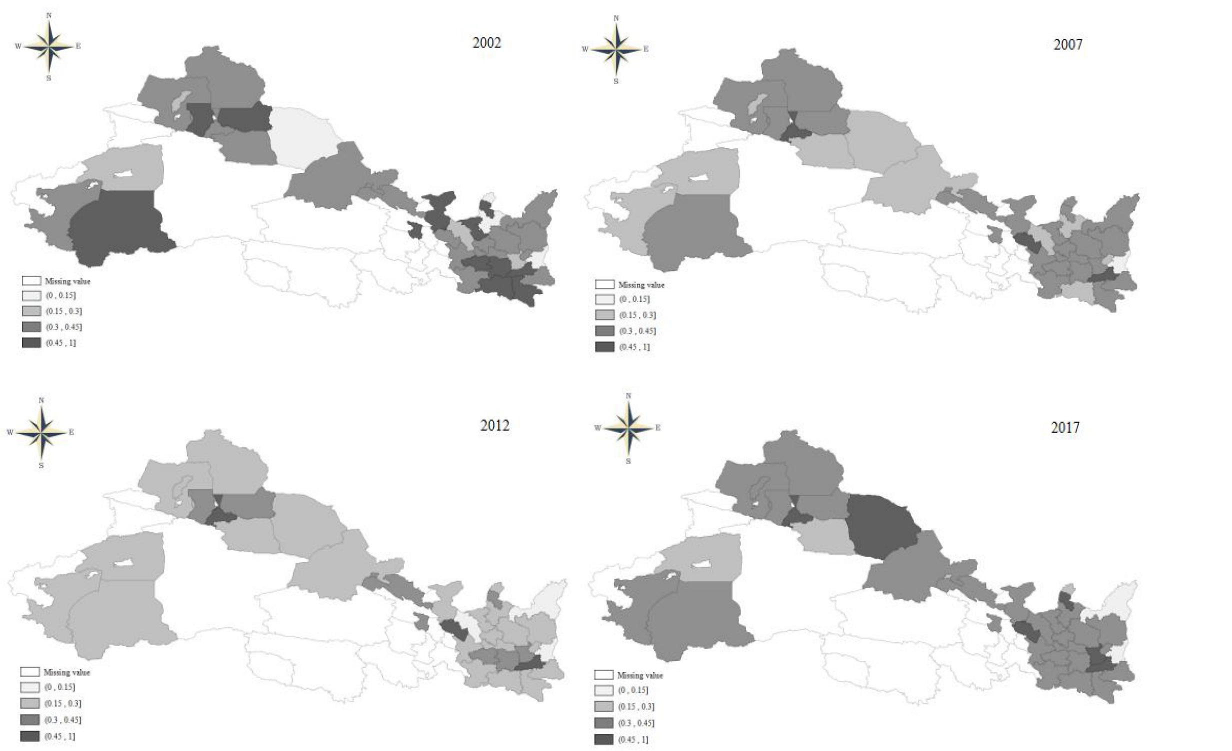

FIGURE 3 | Spatial evolution of the W-E-F-E nexus in Northwest China.

and in 32 of the 38 cities or regions covered by the data, the W-E-F-E nexus improved to varying degrees. Among these cities or regions, W-E-F-E nexus coupling coordination values of Hami of Xinjiang Province, Baiyin of Gansu Province, and Weinan of Shaanxi Province increased by 0.33, 0.29, and 0.24, respectively, and all of them got rid of the state of W-E-F-E nexus imbalance. From the perspective of spatial dimension, the W-E-F-E nexus in provincial capitals and nearby cities is still relatively high, showing an obvious trend of spatial agglomeration. Among the provincial capitals, the W-E-F-E nexus of Xi'an in Shaanxi Province reaches 0.77, realizing the moderate coordination of W-E-F-E nexus. These phenomena indicate the enhancement of the W-E-F-E nexus in Northwest China. With the strengthening of social ecological awareness and the implementation of the concept of coordinated development, the concept of development first followed by governance in the past has been gradually abandoned, replaced instead by development and governance. The concrete embodiment of the action is to strengthen the intensive use of water resources, pay attention to the development of new energy sources, develop efficient agriculture, and strengthen ecological restoration efforts. These actions have effectively improved the coordinated development of water, energy, food, and the ecosystem in Northwest China.

Spatial Correlation of the W-E-F-E Nexus

Since the W-E-F-E nexus in Northwest China shows obvious regional differences, does the coupling coordination of complex systems in this region have a spatial correlation effect? In this paper, GeoDa is used to calculate Moran's I index of the W-E-F-E nexus in Northwest China and to test its spatial autocorrelation. Wherein, the value range of Moran's I index is [−1,1]. The closer this index is to 1, the more similar attributes are clustered together; the closer the index is to −1, the more disparate attributes are clustered together. Through calculation, it is found that the Moran's I index value of the W-E-F-E nexus in northwest China is significantly positive, indicating that there is a significant spatial autocorrelation or spatial correlation effect of the W-E-F-E nexus in Northwest China (**Figure 4**).

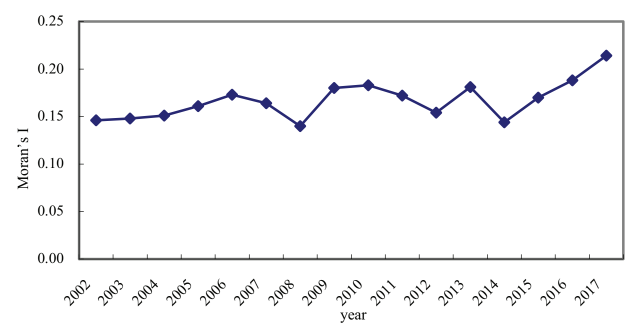

FIGURE 4 | Moran's I index of the W-E-F-E nexus in Northwest China.

Spatial Convergence Tests

Absolute and Conditional Spatial Convergence

Table 2 reports the absolute β-spatial convergence of the W-E-F-E nexus in Northwest China. From the perspective of its spatial convergence, the absolute convergence coefficient is significantly negative at the 1% level regardless of the spatial correlation effect of the W-E-F-E nexus, which means that the W-E-F-E nexus in Northwest China shows obvious absolute convergence. In other words, with the passage of time, the W-E-F-E nexus of the prefectures in Northwest China will gradually converge to a steady state level and increase along the steady state path, but the convergence is faster in developed regions than in less developed regions. In addition, after the introduction of spatial factors, it is found that the spatial spillover effect of W-E-F-E nexus growth rate is significant, and the spatial autoregression coefficients are 0.11 and 0.48, indicating that the improvement of the W-E-F-E nexus in a northwest region will also be affected by the positive spatial spillover effect from neighboring areas. After considering the spatial factors, both the absolute convergence coefficient and the convergence rate of the W-E-F-E nexus decreased slightly. Although the influence effect was not obvious, the existence of spatial spillover effect of the W-E-F-E nexus in Northwest China could not be ruled out.

The conditional β-spatial convergence estimation results of the W-E-F-E nexus in Northwest China are shown in **Table 2**. From the conditional β convergence, in the control of the administrative area, total population at year-end, per capita GDP, and general budgetary expenditures, the conditional β convergence coefficient of the W-E-F-E nexus is significantly negative at the 1% level, which indicates that the W-E-F-E nexus in Northwest China has obvious conditional convergence, that is, the growth rate of the W-E-F-E nexus in the low development stage is faster than that in the high development stage. It is worth mentioning that the existence of spatial spillover effect makes the relative convergence coefficient and convergence rate of the W-E-F-E nexus in Northwest China increase significantly, the absolute convergence coefficient rises from 0.09 to 0.31∼0.32, and the convergence rate rises from 2.87 to 3.14∼3.16. This also further confirms the inference that the failure to consider spatial factors in the traditional convergence studies of the W-E-F-E nexus will lead to errors in the final estimation results.

According to the estimated results of control variables, the increase of regional land area, population, and regional economic development can significantly promote the convergence of the W-E-F-E nexus in Northwest China. Among them, the regional land area and economic development status have a greater promoting effect on the overall W-E-F-E nexus convergence, while the promoting effect of population size is relatively small. Specifically, the regions with large administrative areas can take into account the development of water, energy, food, and the ecosystem, and the allocation of land use types is more flexible and reasonable, which is conducive to reducing the W-E-F-E nexus difference between regions. The regions with a higher degree of economic development provide a good economic environment for the coordinated development of social W-E-F-E nexus, which means that improving the level of economic development in Northwest China is still an important direction to promote the convergence of the W-E-F-E nexus. The reason why the convergence of the W-E-F-E nexus is less promoted in Northwest China may be due to the unreasonable structure of relevant practitioners in water, energy, food, and the ecosystem in Northwest China, which impeded the convergence of the W-E-F-E nexus. Therefore, to promote the convergence of the W-E-F-E nexus in Northwest China, we need to not only improve the population size in Northwest China, but also optimize the skill structure of the labor force.

In addition, the increase of general budget expenditure in regional finance will significantly lead to the divergence of the W-E-F-E nexus in Northwest China, but the effect is weak. This may be associated with the government's fiscal expenditure structure of the northwest region. Based on the analysis of the fiscal expenditure structure of local government in Northwest China, it was found that different local governments have different emphases in the financial expenditure on agriculture, forestry and water conservancy,

TABLE 2 | Spatial convergence estimation of W-E-F-E nexus.

	Absolute β convergence			Conditional β convergence		
	None	W_{cont}	W_{dist}	None	W_{cont}	W_{dist}
β	−0.0523*** (0.0102)	−0.0515*** (0.0101)	−0.0508*** (0.0010)	−0.0917*** (0.1030)	−0.3178*** (0.0400)	−0.3059*** (0.0409)
area				−0.0031* (0.0017)	−0.0112** (0.0049)	−0.0107** (0.0048)
pop				−0.0003*** (0.0001)	−0.0008*** (0.0002)	−0.0008*** (0.0002)
rjgdp				−0.0096** (0.0194)	−0.0168** (0.0070)	−0.0173** (0.0069)
fina				0.0002* (0.0001)	0.0003** (0.0001)	0.0003** (0.0001)
_cons	−0.0459*** (0.0120)	−0.0449*** (0.0119)	−0.0436*** (0.0117)	−0.0206 (0.0132)	−0.1008** (0.0404)	−0.0938** (0.0390)
λ		0.1131*** (0.0439)	0.4826*** (0.0869)		0.1160*** (0.0418)	0.4535*** (0.0852)
Convergence rate	2.8263	2.8255	2.8247	2.8688	3.1550	3.1377
Time	Yes	Yes	Yes	Yes	Yes	Yes
Region	Yes	Yes	Yes	Yes	Yes	Yes
R2	0.2501	0.2499	0.2555	0.2223	0.2451	0.2498

, ** and * indicate significant at 10%, 5% and 1% levels, respectively.*

infrastructure construction, and ecological and environmental protection; as a result, the development status of water, energy, food, and the ecosystem in different regions is uneven, thus the W-E-F-E nexus presents a divergent trend. It can be seen that further optimization of the fiscal expenditure structure in Northwest China is an important problem to be solved by the current government departments.

Spatial Convergence Evolution

A longer time span can better reflect the long-term evolutionary trend of the W-E-F-E nexus in Northwest China, but the variation trend in the sample period is ignored. Although the time effect is controlled in this paper, the time period of the sample is changed to further examine the spatial convergence characteristics of the W-E-F-E nexus in Northwest China in different time periods, in order to eliminate the lasting impact of economic cycles or external impacts in the sample period. To be specific, the year 2002 is still taken as the base period T, and then the final year is re-selected according to T+4 years (to 2006), T+8 years (to 2010), and T+12 years (to 2014) in a period of 4 years. In addition, in order to reflect the coordinated development of the W-E-F-E nexus in Northwest China more objectively and accurately, the influence of related control variables should be considered to conduct the spatial convergence evolution analysis of conditional β.

Table 3 reports the convergence characteristics of the W-E-F-E nexus in Northwest China at different time periods and under different spatial weight matrices, and it is found that the long-term evolution of the W-E-F-E nexus in Northwest China is consistent with the short-term variation trend in the sample period. Among them, the W-E-F-E nexus at different time periods all showed a significant trend of spatial convergence, but the convergence rate was different. In general, the convergence rate of the W-E-F-E nexus shows a trend of increasing with the passage of time, and the convergence rate rises from 1.72∼1.73 to 2.65∼2.66, with an increase rate of 53.8∼54.1%. The results of conditional β spatial convergence evolution analysis further confirm that there is spatial convergence of the W-E-F-E nexus in Northwest China, that is, the gap between different provinces and cities of the W-E-F-E nexus is shrinking, and shows a trend of accelerating reduction, and the concept of coordinated and sustainable development is constantly implemented and strengthened.

CONCLUSION AND DISCUSSION

In this paper, the prefectures from five provinces in Northwest China were selected as the study samples, and the CCD model was used to measure the W-E-F-E nexus. Moreover, the absolute β spatial convergence model and the conditional β spatial convergence model were established to further analyze the spatial convergence of the W-E-F-E nexus. The following findings were obtained through the study. First, the W-E-F-E nexus in Northwest China showed a V-shaped trend of decreasing first and then rising over time. From 2002 to 2012,

TABLE 3 | Spatial convergence evolution of the W-E-F-E nexus.

	T + 4		T + 8		T + 12		Full time	
	W_{cont}	W_{dist}	W_{cont}	W_{dist}	W_{cont}	W_{dist}	W_{cont}	W_{dist}
β	−0.1125*** (0.0223)	−0.1018*** (0.0195)	−0.0736*** (0.0186)	−0.0674*** (0.0171)	−0.0864*** (0.0179)	−0.0847*** (0.0177)	−0.3178*** (0.0400)	−0.3059*** (0.0409)
λ	0.2878*** (0.0664)	0.7149*** (0.0896)	0.2671*** (0.0514)	0.6234*** (0.0839)	0.1383*** (0.0491)	0.4839*** (0.0970)	0.1160*** (0.0418)	0.4535*** (0.0852)
Convergence rate	1.7288	1.7168	2.2737	2.2670	2.6553	2.6535	3.1550	3.1377
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.3389	0.2975	0.1613	0.1221	0.1535	0.1612	0.2451	0.2498

**** indicates significant at 1% levels.*

the overall decrease was 25.1%, and after 2012, there was an obvious rebound with an increase of 29.7%. Second, the W-E-F-E nexus in Northwest China shows positive spatial autocorrelation, and the Moran's I index of this is about 0.15. In spatial dimension, it shows a trend of high-value agglomeration around provincial capitals, and the distribution pattern is relatively stable. Thirdly, the W-E-F-E nexus in Northwest China has significant spatial convergence, that is, the W-E-F-E nexus gap between the prefectures in Northwest China is shrinking, and the convergence rate is in the level of 2.83∼3.16. With the development of the economy, the rational allocation of land and labor resources, and the optimization of fiscal expenditure structure, the W-E-F-E nexus of prefectures in Northwest China will converge to the same steady state level after a long period of time.

In view of the fact that the overall level of the W-E-F-E nexus in five provinces of Northwest China is low and there is spatial convergence, we should improve the W-E-F-E nexus in ecologically fragile and underdeveloped areas from multiple aspects. First of all, in the top-level design of regional development, the central government should consider the coordinated development relationship between water, energy, food, and the ecosystem by comprehensively promoting the coordination of regional water resources protection, energy efficient utilization, food security, and ecological restoration, rather than focusing on a single issue. Secondly, we should give full credit to the leading role of the provincial capitals in the comprehensive development of Northwest China. On the premise of considering the natural conditions and the heterogeneity of industrial structure in different regions, we should extend the experience of the comprehensive development of provincial capital cities to other regions with low coupling coordination degree of the W-E-F-E nexus, so as to achieve a qualitative breakthrough in the overall comprehensive development level of Northwest China. Thirdly, according to the actual situation of different prefectures in Northwest China, we should formulate targeted measures to make up for the shortcomings in water, energy, food, and ecology, and promote the coordinated development of the W-E-F-E nexus. For prefectures with a high level of coordinated development, we should optimize their industrial layout according to their own resource endowment, carry out technological transformation and upgrading of high-energy consumption and high-pollution enterprises, and strengthen the development of green and environmental protection industries. For prefectures with a low level of coordinated development, the research and development of agricultural water-saving technologies should be strengthened, efficient water-saving irrigation and wastewater recycling should be promoted, and the development of new energy projects with low energy consumption and low pollution should be encouraged. Finally, we should pay attention to the optimization of labor force, land use, and government financial expenditure structure in Northwest China, promote the coordinated development of the local W-E-F-E nexus, and improve the quality of economic development.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

MW: conceptualization, writing—original draft. Y-FZ: methodology, data curation. S-WG: software, visualization. C-YN: supervision, writing—review and editing. All authors contributed to the article and approved the submitted version.

FUNDING

This research was supported by the National Natural Science Foundation of China (Grant No. 71903056), the National Science Foundation for Post-doctoral Scientists of China (Grant No. 2020M672464), MOE (Ministry of Education in China) Project of Humanities and Social Sciences (Grant No. 19YJC790154), Natural Science Foundation of Hunan Province in China (Grant Nos. 2020JJ5104 and 2020JJ4259), Philosophy and Social Science Foundation of Hunan Province in China (Grant No. 18YBQ075), and the Project of Hunan Social Science Achievement Appraisal Committee (Grant Nos. XSP20YBZ081 and XSP21YBZ094).

REFERENCES

Bhuiyan, M. A. H., Parvez, L., Islam, M. A., Dampared, S. B., and Suzukia, S. (2010). Heavy metal pollution of coal mine-affected agricultural soils in the northern part of Bangladesh. *J. Hazard. Mater.* 173, 384–392. doi: 10.1016/j.jhazmat.2009.08.085

Bryan, B. A., Nolan, M., Harwood, T. D., Connor, J. D., Garcia, J. N., King, D., et al. (2014). Supply of carbon sequestration and biodiversity services from Australia's agricultural land under global change. *Glob. Environ. Change* 28, 166–181. doi: 10.1016/j.gloenvcha.2014.06.013

Chang, N. B., Hossain, M. U., Valencia, A., Qiub, J., and Kapucuc, N. (2020). The role of food-energy-water nexus analyses in urban growth models for urban sustainability: a review of synergistic framework. *Sustain. Cities Soc.* 63:102486. doi: 10.1016/j.scs.2020.102486

Elhorst, J. P. (2005). Unconditional maximum likelihood estimation of linear and log-linear dynamic models for spatial panels. *Geogr. Anal.* 37, 85–106. doi: 10.1111/j.1538-4632.2005.00577.x

Elhorst, J. P. (2010). *Spatial Panel Data Models*. Berlin: Springer.

Fouladi, J., Alnouss, A., and Al-Ansari, T. (2021). Sustainable energy-water-food nexus integration and optimisation in eco-industrial parks. *Comput. Chem. Eng.* 146:107229. doi: 10.1016/j.compchemeng.2021.107229

Gao, L., and Bryan, B. A. (2017). Finding pathways to national-scale land-sector sustainability. *Nature* 544, 217–222. doi: 10.1038/nature21694

Harris, J. M., and Kennedy, S. (1999). Carrying capacity in agriculture: global and regional issues. *Ecol. Econ.* 29, 443–461. doi: 10.1016/s0921-8009(98)00089-5

Liu, C., and Chen, Q. H. (2016). Evaluation of port group interaction and mutual coupling coordination dispatching based on coordination theory. *Econ. Longitude Latitude* 5, 8–12. (in Chinese), Liu, J., Liu, C. S., Li, X., Wang, G. Q., and Bao, Z. X. (2020). Security evaluation of water-energy-food nexus system in China. *Hydro Sci. Eng.* 4, 24–32. (in Chinese)

Melo, F. P. L., Parry, L., Brancalion, P. H. S., Pinto, S. R. R., Freitas, J., Manhães, A. P., et al. (2021). Adding forests to the water–energy–food nexus. *Nat. Sustain.* 4, 85–92.

Muller, M. (2015). The 'nexus' as a step back towards a more coherent water resource management paradigm. *Water Altern.* 8, 675–694.

Niva, V., Cai, J. L., Taka, M., Kummu, M., and Olli, V. (2020). China's sustainable water-energy-food nexus by 2030: impacts of urbanization on sectoral water demand. *J. Clean. Prod.* 251:e119755.

Owen, A., Scott, K., and Barrett, J. (2018). Identifying critical supply chains and final products: an input-output approach to exploring the energy-water-food nexus. *Appl. Energy* 210, 632–642. doi: 10.1016/j.apenergy.2017.09.069

Ravar, Z., Zahraie, B., Sharifinejad, A., Gozini, H., and Jafari, S. (2020). System dynamics modeling for assessment of water-food-energy resources security and nexus in Gavkhuni basin in Iran. *Ecol. Indic.* 108:e105682.

Shi, H., Luo, G., Zheng, H., Chen, C., Bai, J., Liu, T., et al. (2020). Coupling the water-energy-food-ecology nexus into a Bayesian network for water resources analysis and management in the Syr Darya river basin. *J. Hydrol.* 581:124387. doi: 10.1016/j.jhydrol.2019.124387

Skidmore, M., Toya, H., and Merriman, D. (2004). Convergence in government spending: theory and cross-country evidence. *Kyklos* 57, 587–620. doi: 10.1111/j.0023-5962.2004.00270.x

Sun, C. Z., and Yan, X. D. (2018). Security evaluation and spatial correlation pattern analysis of water resources-energy-food nexus coupling system in China. *Water Resour. Prot.* 34, 1–8. (in Chinese), doi: 10.1016/j.advwatres.2016.12.017

Sun, J., Li, Y. P., Suo, C., and Liu, J. (2020). Development of an uncertain water-food-energy nexus model for pursuing sustainable agricultural and electric productions. *Agric. Water Manag.* 241:106384. doi: 10.1016/j.agwat.2020.106384

Yang, S. H. (2003). *Urban Ecological Environment*. Beijing: Science Press.

Yin, Q. M., and Wu, Y. (2019). Cases studies on water-energy-food coupling coordinated development in china. *Resour. Ind.* 21, 20–29. (in Chinese),

Yuan, M. H., Chiueh, P. T., and Lo, S. L. (2020). Measuring urban food-energy-water nexus sustainability: finding solutions for cities. *Sci. Total Environ.* 752:141954. doi: 10.1016/j.scitotenv.2020.141954

Zhang, C., Chen, X. X., Li, Y., Ding, W., and Fu, G. (2018). Water-energy-food nexus: concepts, questions and methodologies. *J. Clean. Prod.* 195, 625–639. doi: 10.1016/j.jclepro.2018.05.194

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX

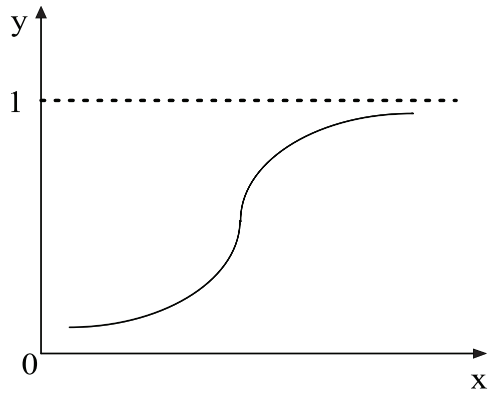

FIGURE A1 | Logistic curve.

frontiers in Energy Research

POLICY BRIEF
published: 29 April 2021
doi: 10.3389/fenrg.2021.661585

The Prospect of China's Renewable Automotive Industry Upon Shrinking Subsidies

Lin-Shu Qiu[1], Dong-Xiao Yang[2,3]*, Kai-Rong Hong[1], Wei-Ping Wu[2,3] and Wei-Kang Zeng[2]

[1]Business School, Central South University, Changsha, China, [2]Key Laboratory of Digital Economy and High Quality Development, Hunan University of Technology and Business, Changsha, China, [3]School of Econimics and Trade, Hunan University, Changsha, China

Increased emissions from road traffic resulting from the increase in car ownership have put enormous pressure on China's environmental problems. To solve this problem, the Chinese government has attached great importance to the development of a new energy vehicle industry. This paper summarizes the incentive policies of China's new energy vehicle industry. By sorting through the incentive policy system of the new energy vehicle industry, we find that the Chinese government's promotion policy for the new energy vehicle industry is a process of gradual transformation from being government-led to being market-led. In this process, with the decrease of the subsidy amount, it is bound to cause a huge impact on the new energy vehicle industry.

Keywords: renewable automotive, subsidy, policy system, shrink, review

OPEN ACCESS

Edited by:
Chan Wang,
Guangdong University of Finance and Economics, China

Reviewed by:
Chen Ziyue,
Norwegian University of Science and Technology, Norway
Yi Fu,
Central South University, China

***Correspondence:**
Dong-Xiao Yang
ydx622@hutb.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *31 January 2021*
Accepted: *18 February 2021*
Published: *29 April 2021*

Citation:
Qiu L-S, Yang D-X, Hong K-R, Wu W-P and Zeng W-K (2021) The Prospect of China's Renewable Automotive Industry Upon Shrinking Subsidies. Front. Energy Res. 9:661585. doi: 10.3389/fenrg.2021.661585

INTRODUCTION

The automotive industry is a pillar industry of China's national economy and social development. In the past decade or so, driven by rapid economic development and accelerated urbanization, the car parc as well as production in China has increased dramatically. In the past 25 years, the total number of vehicles in China has increased 26 times (Wu and Zhang, 2017). In accordance with the practice of developed countries, the rapid growth of vehicle sales in China is likely to continue in the coming years as a result of rigid demand and consumption upgrades.

With a population of about 1.4 billion, energy shortages and environment issues would become more prominent as the sales of vehicles grows. The International Energy Agency (IEA) reported that China's road transportation sector has discharged 618 million tons of carbon dioxide emissions (International Energy Agency, 2015), accounting for more than 10% of the total emissions in China and approximately 2% of the global fossil fuel emissions, respectively. If the car parc continues to grow at its current rate, the total carbon dioxide emissions generated from transportation may reach 12 to 17 billion tons by 2030 (He et al., 2005; Yan and Crookes, 2009; Huo and Wang, 2012). To solve the problems of energy shortage and pollution, accelerating the development of green vehicles has become extremely important.

Xi Jinping, general secretary of the Communist Party of China, proposed in 2014 that the development of new energy vehicles was the only way out for the auto industry. This has been raised in meetings and important speeches, showing that speeding up the cultivation and development of new energy vehicles, can, not only effectively reduce the pressure on energy and the environment, but is also a solution to the people of China's yearning for a better life environment and is an important measure of the contradiction of environmental degradation. With the help of policy, China's new energy vehicle market has become the fastest growing market in the world. However, with the decline

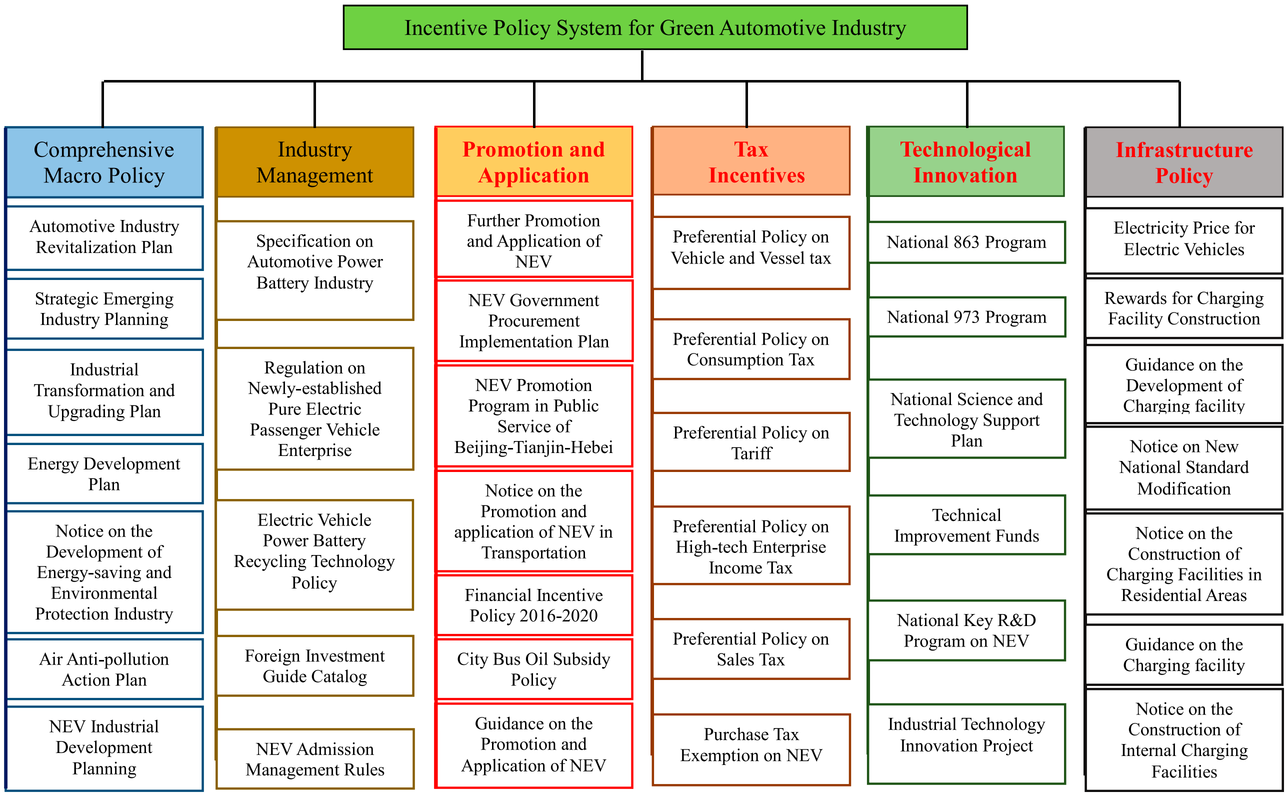

FIGURE 1 | Incentive policy system for green automotive industry.

in subsidies, how should new energy vehicle enterprises face the "greenhouse" and "post-subsidy" era? How will they have to change to survive? How will new industrial incentive policies be decided in the future? It has clearly become a topic of practical significance. Based on this, this paper takes a systematic look at the promotion policies of China's new energy vehicle industry and puts forward policy suggestions for the development path of China's new energy vehicle policy.

THE CARDING OF POLICY PATH

As shown in **Figure 1**, China has formulated a comprehensive policy system for green vehicles, including macro-economic integration, industry management, tax incentives, technological innovation, promotion and application, and infrastructure.

At its initial stage, the development of the green automotive industry is dominated by the government, mainly reflected by the demonstration and promotion of green vehicles in large and medium-sized cities. In 2001, relying on the National High-tech R&D Program (863 Program), the electric vehicles project was launched, and the industrial distribution characterized as "Three Longitudinal Axes and Three Transverse Axes" was established. Specifically, "Three Longitudinal Axes" refer to hybrid vehicles, pure electric vehicles, and fuel cell vehicles, and "Three Transverse Axes" refer to the multi-energy powertrain control system, motor control system, and the battery management system. Between 2001 and 2008, China launched a series of industrial policies to encourage automotive technology to be energy-saving, environmentally friendly, and sustainable. The government proposed that the percentage of electric vehicles in the car parc should be 5–10% by 2010 and more than 50% by 2030.

Due to the 863 Program, green vehicle technology innovations emerged in large numbers. In particular, during the "Eleventh Five-Year Plan" period, China implemented Green Vehicle Major Projects, focusing on the R&D activities related to the improvement of power systems and key components of green vehicles. Great progress has been achieved in technical standards, testing techniques, demonstration operations, etc. China's electric vehicle industry grew from scratch as the technology systems were gradually established, issuing 56 national standards and more than 3,000 patents. Some of the representative demonstration projects were shown at the Beijing Olympics, the Shanghai World Expo, and the Shenzhen Universiade.

Based on practical experience, it is rational to expect that purely electric-driven vehicles instead of conventional hybrid vehicles would be the major development trend of electric vehicles. Relying on appropriate technical routes, guidance and planning, a lot of leading R&D projects have been completed as expected. There is no doubt that the outputs of such research projects significantly improve the development of green vehicles, whereas there is still a large gap between the achievement and the demand of the industrialization. The existence of such a gap

TABLE 1 | A summary of subsidy policies for green vehicles in China.

Issued time	Document title	Subsidy criteria	Covered regions
1/23/2009	Notice on launching pilot programs for the demonstration and promotion of energy-saving and green vehicles	Passenger vehicles and light commercial vehicles for public service, vehicles using hybrid energy, pure electric, and fuel cells may receive 50,000, 60,000, and 250,000 yuan, respectively. Urban public buses longer than 10 m, buses using hybrid energy, and pure electric and fuel cells may receive 420,000, 500,000, and 600,000 yuan, respectively.	13 cities like Beijing, Shanghai and Chongqing and so on
5/31/2010	Notice on pilot of subsidy for private purchase of green vehicles	For green vehicles satisfying the given criteria, the subsidy standard is 3,000 Yuan/kWh. The subsidies for plug-in hybrid passenger vehicle and pure electric passenger vehicles could be up to 50,000 and 60,000 yuan, respectively.	Shanghai, Changchun, Shenzhen, Hangzhou, Hefei, Beijing
8/6/2012	Notice on expanding the pilot of demonstration and promotion of public hybrid buses	Depending on the fuel-saving rate, hybrid power system, and maximum electric power ratio, the subsidies range from 50,000 to 420,000 yuan.	Winners in the bidding are responsible for the promotion in non-pilot cities.
9/17/2013	Notice on subsequent promotion and application of green vehicles	Pure electric and plug-in hybrid passenger cars could receive subsidies ranging from 35,000 to 60,000 yuan. Buses could get a subsidy ranging from 250,000 to 500,000 yuan in accordance with the length, and another subsidy of 2,000 Yuan/kWh with a limit of 150,000 yuan depending on batteries. Fuel cell passenger vehicles and commercial vehicles may get 200,000 yuan and 500,000 yuan as subsidies, respectively. A back slope mechanism is applied, implying that the subsidy standards in 2014 and 2015 would be reduced by 10 and 20% on this basis.	Promote green vehicles relying on big cities.
1/28/2014	Notice on further promotion and application of green vehicles	The subsidy standard for green vehicles is adjusted downwards by 5 and 10% in 2014 and 2015, respectively.	39 city groups including 88 cities
4/22/2015	Notice on the financial incentive policy for the promotion and application of green vehicles from 2016 to 2020	Pure electric passenger vehicles and plug-in hybrid passenger vehicles may receive a subsidy amount ranging from 25,000 to 55,000 yuan per vehicle. The subsidy for fuel cell vehicles ranges from 200,000 to 500,000 yuan. The subsidy standard for electric vehicles, plug-in hybrid vehicles, and other special vehicles and trucks is set at 1800 Yuan/kWh. A back slope mechanism is applied, from 2017 to 2020, except for fuel cell vehicles, subsidies for other types of vehicles would be reduced gradually, including a reduction of 20% in 2017–2018 and another decline of 40% in 2019–2020.	Nationwide
12/30/2016	Notice on adjusting the financial subsidies policies of promotion and application for green vehicles	Raise the threshold standard with dynamic adjustment of recommended vehicle types. Under the premise of maintaining the overall stability of the subsidy policy from 2016 to 2020, the subsidy standard for green vehicles is adjusted as follows. For pure electric passenger vehicles, the subsidies are 20,000 yuan, 36,000, and 40,000 yuan in accordance to cruising mileage. Plug-in hybrid passenger vehicles may receive 24,000 yuan. Except for fuel cells, the subsidy standards for other types of vehicles reduces to 20% from 2019 to 2020 on the basis of current standards.	Nationwide
2018	Adjustment of subsidies for new energy vehicles	New energy subsidies will be phased out one year ahead of schedule, and a transitional period of subsidies will be proposed for the first time; non-individuals will be required to drive 20,000 km instead of 30,000 km for new energy purchases; non-personal purchases of a new energy sales license can apply for a part of the subsidy fund, after reaching the mileage requirements of the full allocation	Nationwide
2019/3/26	Notice on further improving the fiscal subsidy policy for the promotion and application of new energy vehicles	Starting from 2019, for vehicles with operational mileage requirements, part of the fund will be allocated in advance upon completion of sales license, and the liquidation will be applied upon reaching the mileage requirements, that is, the "advance payment" mechanism will be proposed; local governments can continue to subsidize the purchase of new-energy buses	Nationwide

(Continued on following page)

TABLE 1 | (*Continued*) A summary of subsidy policies for green vehicles in China.

Issued time	Document title	Subsidy criteria	Covered regions
2020/4/23	Notice on further improving the fiscal subsidy policy for the promotion and application of new energy vehicles	New energy subsidies, which expire at the end of the year, will be extended until 2022, with an annual limit of about 2 million vehicles; support "vehicle electric separation" and other new business models	Nationwide

arouses controversial discussions on the topic on whether the existing planning sufficiently matches the need for industrial development.

As an emerging industry, the development of electric vehicles depends on two key factors, namely market demand and technology innovation. The former is the foundation while the latter plays into the engineering required for the development required of electric vehicles. Only with the inherent market demand can we achieve a virtuous circle under the boost of technological innovation. Taking this into account, the incentive policy for green vehicles of China has gradually shifted from being technology-oriented to being market-oriented. On January 14, 2009, the State Council of China proposed a specific green vehicle strategy in the "Rejuvenation Plan for the Automotive Industry," arranging 10 billion Yuan to support the industrialization of green vehicles and related key components. Then, on January 23 of the same year, another document entitled "Circular on Launching Pilot Programs for Energy Conservation and Green Vehicles Demonstration and Promotion" was promulgated, clarifying that those purchasing green vehicles in pilot cities may receive fixed lump-sum subsidies from the central government. These two documents initiated the development of the green automotive industry, based upon subsidies. As shown in **Table 1**, seven national subsidy policies were issued from 2009 to 2020.

The major trends of the varying subsidy policies for green vehicles could be summarized as follows. First, the sub-grades of subsidies depending on cruising mileage are more meticulous. Second, the criterion of energy density of battery increases. Third, banding subsidy policy that relies on the coefficient of energy dissipation becomes more popular. Two major considerations should be given; one is the objective of quality improvement and the other is the constraint of budget, resulting in the adjustment of subsidy policies. Notice that the subsidy for green vehicles tends to shrink with an expansion of covered regions and fields, indicating policy uncertainty for the producers and the market. For a traditional automotive producer, it takes at least 3–5 years to achieve mass production from design, while the accompanying strategic layout and planning requires 5–10 years. As an emerging industry, the time required from design to mass production for green the automotive industry is much longer than that for the traditional automotive industry. The incentive policies stimulate the development of the green automotive industry significantly, whereas the policy instability generates tremendous pressure for green vehicle producers. To maximize profits with these varying policies, some producers are prone to instant success with the R&D activities of green vehicles. One representative case is to obtain subsidies by shortening the product life cycle, i.e., promoting artificial green vehicles by installing a battery onto the internal-combustion engine or by tuning older electro-mobiles. Such "great leap forward" type of development would harm the sustainability of the green vehicle industry and be extremely wasteful in terms of governmental financial resources.

Aiming to consolidate the leading function of market mechanisms, the government decided to reduce the subsidy intensity as well as to raise the subsidy threshold for green vehicles in 2018. The latest subsidy policies introduced higher criteria in many aspects such as cruising mileage, battery life, charging efficiency, and sales price. More importantly, the two market-orientated policies, the green license plate policy and the double-credit policy, were introduced to stimulate the development of the green vehicle industry in China. Note that only green vehicles could satisfy the requirement of the green license plate policy to obtain the license plates painted in green, which implies quite a lot of extra benefits for buyers. Specifically, such extra benefits include: 1) reduced waiting time caused by purchase restrictions and a registration lottery; 2) avoiding the inconvenience of the application of odd-and-even license plate rules in some cities; 3) enjoying a purchase loan that accounts for up to 85% of the vehicle price; 4) enjoying free parking in some specific parking lots. As presented, the implementation of the incentive policy for green vehicles is undoubtedly a boon for potential consumers who worry about the expenditure of buying and driving a vehicle.

As green vehicles with green license plates become more popular in pilot cities, the green license plate policy has greatly stimulated consumers' desire to purchase green vehicles instead of traditional ones. Meanwhile, the document entitled "Measures for the Parallel Management of the Average Fuel Consumption and Integral for Green Vehicles of Passenger Vehicle Enterprises" that was published on September 28, 2017, forces vehicle producers to gradually switch to clean energy. In comparison, European countries mainly adopt the integral policy depending on the average fuel consumption of passenger vehicles, while in California in the United States, the integral policy of green vehicles is applied. As the largest auto market in the world, China has introduced both integral policies in parallel with promoting the development of the green automotive industry. In practice, the management and assessment of the two policies are separate. The only link between them lies in the integral deduction, i.e., a negative integral yielded by average fuel consumption that could be deducted by a positive integral of green vehicles, whereas the sole way to remove a negative integral of green vehicles is to buy a positive one. The Chinese government plans to cancel all subsidies for green vehicles by 2020, while the calculation parameters of CAFT would decrease gradually during this period. It is rational to forecast that auto producers have to face greater emission reduction pressure because of the policy variation. Inevitably, investing more in green vehicles would become a more important alternative strategic direction for most auto producers.

CONCLUDING REMARKS

To improve the positive effects of green vehicles on energy conservation and emission reduction, China has gradually shifted from being government-oriented to being market-oriented in the policy formulating the process of the green automotive industry. In the coming development stages of the green automotive industry, advanced clean technologies and low-emission incentives may play key functions. It is expected that the introduction and implementation of the two policies could achieve objectives on emission reduction as well as the improved development of green vehicles in the near future.

In addition, at the micro level, the government should pay more attention to the construction of charging and changing the infrastructure for new energy vehicles. Charging and changing infrastructure is a very important key link in the development of new energy vehicles and is also important in supporting the promotion of the new energy vehicles industry. In recent years, the National Development and Reform Commission, the National Energy Administration, the Ministry of Industry and Information Technology, and other departments have introduced a series of policies and measures, which have effectively promoted the construction of China's charging and changing infrastructure. However, China still faces many problems in the construction of charging and changing power facilities. The main reason is that in some old residential areas with large population densities it is difficult to construct charging and electricity exchange facilities due to the insufficient carrying capacity of the power system. In addition, some consumers or residents have raised objections to the construction of charging piles because of concerns about safety. Therefore, in the future transformation of older urban areas in China, the transformation of the electric power system will become a particularly important driving force to promote the development of the new energy vehicle industry.

AUTHOR CONTRIBUTIONS

L-SQ: Conceptualization, Data curation, Formal analysis, Writing—review and editing. D-XY: Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing—review and editing. K-RH: Manuscript revision/review, Funding acquisition, W-PW: Formal analysis, Investigation, Project administration, Resources, Software. W-KZ: Investigation, original draft.

FUNDING

This work is partially supported by the National Natural Science Foundation of China (71771057,72003044,72003045,71903056), National Social Science Foundation of China(20FGLB072), Natural Science Foundation of Hunan Province (2020JJ5111, 2020JJ5104), Project of Hunan Social Science Achievement Appraisal Committee (XSP20YBZ081), Youth Innovation Driven Project of Hunan University of Technology and Bussiness (19QD04), Guangdong Social Science Project (GD20SQ15), Guangzhou Social Science Project (2020GZQN39), the Foundation for High-level Talents in Higher Education of Guangdong, GDUPS (2019), National Science Foundation for Post-doctoral Scientists of China (2020M672464), MOE (Ministry of Education in China) Project of Humanities and Social Sciences (19YJC790154), Philosophy and Social Science Foundation of Hunan Province in China (18YBQ075), and Research and Innovation Project for Graduate Students in Hunan Province (CX20201083).

REFERENCES

He, K., Huo, H., Zhang, Q., He, D., An, F., Wang, M., et al. (2005). Oil Consumption and CO2 Emissions in China's Road Transport: Current Status, Future Trends, and Policy Implications. *Energy Policy* 33 (12), 1499–1507. doi:10.1016/j.enpol.2004.01.007

Huo, H., and Wang, M. (2012). Modeling Future Vehicle Sales and Stock in China. *Energy Policy* 43, 17–29. doi:10.1016/j.enpol.2011.09.063

International Energy Agency (2015). CO_2 Emissions from Fuel Combustion Highlights. https://www.iea.org/publications/freepublications/publication/co2-emissions-from-fuel-combustion-highlights-2015.html. Accessed June 22, 2017.

Wu, Y., Zhang, S. J., Hao, J. M., Liu, H., Wu, X., Hu, J., et al. (2017). On-Road Vehicle Emissions and Their Control in China: A Review and Outlook. *Sci. Total Environ.* 574 (1), 332–349. doi:10.1016/j.scitotenv.2016.09.040

Yan, X., and Crookes, R. J. (2009). Reduction Potentials of Energy Demand and GHG Emissions in China's Road Transport Sector. *Energy Policy* 37 (2), 658–668. doi:10.1016/j.enpol.2008.10.008

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer (YF) declared a shared affiliation with one of the authors, (LQ), to the handling editor at time of review.

frontiers in Energy Research

POLICY BRIEF
published: 30 April 2021
doi: 10.3389/fenrg.2021.685735

Check for updates

Evolution Logic and Comparative Advantage of China's Power System Reform—A Comparative Study on Transmission Management Between China and the United States

Wei-ping Wu[1,2], *Wei-kang Zeng*[1], *Li-fan Lu*[1]* *and Zi-gui Chen*[1,3]*

[1] Key Laboratory of Digital Economy and High Quality Development, Hunan University of Technology and Business, Changsha, China, [2] School of Economy & Trade, Hunan University, Changsha, China, [3] Design and Art Institute, Hunan University of Technology and Business, Changsha, China

OPEN ACCESS

Edited by:
Chan Wang,
Guangdong University of Finance and Economics, China

Reviewed by:
Vincent Chen,
The University of Sheffield, United Kingdom
Ze-zhou Wen,
Huazhong University of Science and Technology, China

***Correspondence:**
Li-fan Lu
lulifan0107@163.com
Zi-gui Chen
chenzigui0213@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: 25 March 2021
Accepted: 06 April 2021
Published: 30 April 2021

Citation:
Wu W-p, Zeng W-k, Lu L-f and Chen Z-g (2021) Evolution Logic and Comparative Advantage of China's Power System Reform—A Comparative Study on Transmission Management Between China and the United States. Front. Energy Res. 9:685735. doi: 10.3389/fenrg.2021.685735

This paper examines the differences of power systems between China and the United States from the perspective of transmission management, and finally summarizes the institutional advantages of China's power system reform. The research shows that there are significant operation and supervision differences between China and the United States in transmission management. China has always maintained a unified management in transmission management, while the United States has adopted a decentralized management model in transmission. The implementation of centralized unified management in transmission links cannot only ensure the timely and effective allocation of national power energy, but also be helpful to concentrate all kinds of resources to develop large-scale power projects.

Keywords: power systems reform, transmission management, institutional advantages, China, the United States

INTRODUCTION

Every leap of productivity in human society is accompanied by the improvement and replacement of energy. "Electric power revolution" has greatly improved the efficiency of social operation, and also tends to industrialization with the rising social demand (Rothe, 2019). Power industry has natural monopoly, and monopoly always leads to low efficiency. In the 1990s, the United States, Japan and some European developed countries have carried out the market-oriented reform of power system, trying to break the low efficiency of monopoly through the reform of system and mechanism, and further optimize the allocation of power resources, so that the power system can better serve the social and economic development (Michaels, 2006). But things were ordered otherwise. The power outage in Texas in 2021 reflects the significant security risks brought by the segmented grid management to the stable operation system under the market-oriented reform.

In the early days of the founding of new China, the Chinese central government found that there were various drawbacks in the decentralized management of power grid, which seriously affected the stability and development of the power industry. Thus, the long-term centralized management of China's power system has become a feature of the economic planning. With the advancement of China's socialist market economic system reform, the problems of unclear management responsibility and inefficient operation of enterprises caused by the "integration of government and enterprise" in the power system are gradually exposed, so the central government has issued a series of policy documents aimed at giving full play to the power's role in ensuring social and economic development. In 2002, the State Council issued the *Power System Reform Plan*, marking the formal opening of the power system reform of "separation of power plant and power grid," in order to introduce competition in the generation side to improve the efficiency of the power system. In 2015, the State Council issued *Several Opinions on Further Deepening the Reform of Power System*, focusing on solving five major problems, such as the lag of legislative amendment law, the lack of trading mechanism, the perfection of coordination mechanism, incomplete pricing mechanism and imperfect development mechanism. Both the vertical historical experience and the horizontal comparison between countries have proved that China's power system has its unique advantages in transmission management.

This paper analyzes the differences of power transmission management between China and the United States from the perspective of historical evolution (**Figure 1**), and finally summarizes the institutional advantages and optimization measures of China's power system reform.

THE EVOLUTION OF POWER SYSTEM REFORM IN CHINA AND THE UNITED STATES

In the 1980s-1990s, with the development of market economy, the incompatibility of power system policies originated from the planned period has become increasingly prominent in the market economy. Under the planned economy, the "un-separation of government and enterprise" cannot guarantee the effective management of the power system by government departments, and it is difficult to improve the market efficiency of the power industry, which hinders the further development of the power industry. Moreover, the experience from other countries shows that the power industry does not need the integration of generation, transmission, distribution and sales (Chawla and Pollitt, 2013). Based on the consideration of enhancing the effective management of power system and improving the market efficiency of power industry, China's power system reform is imminent (Bai, 2019).

In January 1997, the State Council decided to establish the state power company, which marked the transition of China's power management system from planned economy to socialist market economy, and laid the foundation for the reform of China's power system. In February 2002, the *Power System Reform Plan* was issued by the State Council, marking the official opening of China's power system reform. In March 2003, the State Electricity Regulatory Commission (SERC) was established, whose responsibility is to supervise and manage the operation order of the power market. In March 2013, the State Council decided to integrate the responsibilities of the National Energy Administration (NEA) and SERC to further improve the energy management system. In April 2015, the State Council issued *Several Opinions on Further Deepening the Power System Reform*, which started a new round of China's power system reform, focusing on solving such important problems as the lack of power system market trading mechanism, imperfect power system planning coordination mechanism, and difficulties in the development and utilization of emerging energy. In November 2017, the National Development and Reform Commission (NDRC) and NEA issued the notice on *Accelerating the Pilot Reform of Incremental Distribution Business*, and clearly defined the goal of deepening the reform focusing on the marketization of incremental distribution and direct transactions between power plants and power users. In a word, the reform of China's electric power system not only strengthens the management of the state in the transmission link, but also improves the market allocation efficiency of power generation and sales, and realizes the unity of power system stability and efficiency to a certain extent (**Table 1**).

The development of the United States power industry is relatively mature, and its power system has undergone many rounds of reform. Its power reform mainly revolves around breaking the integration, liberalizing the control of power generation and distribution terminal, realizing free competition, and maintaining the monopoly of transmission terminal at the same time. The reform of the United States power system began with the *Energy Policy Act* of October 1992, which establishes the separation of power generation, transmission and distribution, to eliminate the monopoly of power industry and promote market competition and technological progress. In 1996, the Federal Energy Regulatory Commission (FERC) issued orders 888 and 889, requiring power companies with transmission facilities to open up the transmission network. In response to the FERC act, some power companies in the United States spontaneously joined forces and formed an Independent System Operation Company (ISO). In December 1999, FERC issued another order 2000, facilitating the establishment of Regional Transmission Organizations (RTO), and requiring all public utility companies with transmission networks to join RTO. Actually, the function of RTO is similar to ISO, but it adds the function of trans-regional transmission network planning and reliability maintenance on the basis of ISO. In 2003, ISO and RTO jointly established a power industry cooperation organization in most parts of the United States, called the ISO/RTO Committee (IRC).

In August 2005, the Energy Policy Act 2005 of the United States was promulgated, which aimed to optimize the energy use structure of the United States and promote competition in the wholesale electricity market. Since then, FERC issued a series of decrees from 2006 to 2015, trying to further improve the level of power system marketization from the aspects of pricing, trading and management. However, due to the implementation of private ownership in the transmission sector in the United States, and the overlapping regulatory functions among different organizations, the unified centralized management of transmission has not yet been realized.

DIFFERENCES OF TRANSMISSION MANAGEMENT SYSTEM BETWEEN CHINA AND THE UNITED STATES

On the whole, the goal of power system reform in China and the United States is to establish a competitive power market, but the

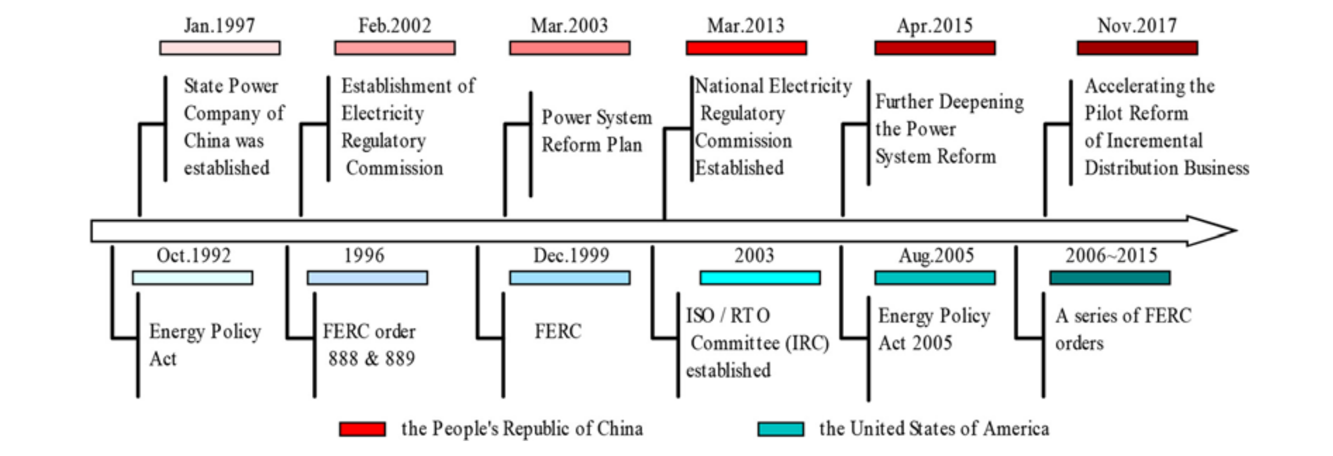

FIGURE 1 | Evolution of China and the United States power system reform.

TABLE 1 | Policies and contents of power system reform in China and the United States.

China		The United States	
Policies	**Content**	**Policies**	**Content**
Establishment of the state power company of China	• Company system reform of Ministry of electric power industry • set up a state-owned power company	Energy Policy Act	• Non-public companies are allowed to enter the wholesale electricity market • Transmission companies provide transmission services at reasonable prices
The power system reform plan	• The assets of the State Power Company were reorganized into 5 power generation companies and 2 transmission and distribution companies • Establishment of a power dispatching and trading center implementation of electricity bidding online • Electricity price is divided into feed-in price, transmission price, distribution price and terminal selling price	Federal Energy Commission Decrees No.888 and No. 889	Open and fair access for all utility companies through open grid • Promoting the competition in the wholesale electricity market.
SERC established	• Power market regulation and operation supervision • Put forward price adjustment suggestions to government price department	Federal Energy Commission Decrees No.2000	• All utility companies with transmission network join regional transmission organization (RTO)
SERC merged with NEA	• Realizing the integration of power regulatory responsibilities • Improve the energy management system	IRC established	• Coordinate and manage power systems in different regions
Further deepening the power system reform	• Orderly deregulation of electricity price in competitive links other than transmission and distribution • Promote the independent and standardized operation of trading institutions • The profit model of electric power company is changed into the model combining cost and profit	Energy Policy Act 2005	Promoting competition in wholesale electricity market • Improve the competition level of power market
Accelerating the pilot reform of incremental distribution business	• Increase the pilot scope of incremental distribution business reform • Further deregulation of power distribution	Federal Energy Commission Decrees No.681, 719, 768, 816, 890, 1000	• Establish guidelines and operational rules for independent transmission organizations • Improve the operation ability and market competition of wholesale electricity market • Refine market pricing policies and procedures • Optimization of transmission network open access control framework • Improve transmission cost and cost allocation mechanism of power grid access

path choice to achieve the goal is very different, especially in the transmission management.

Operation of Transmission Network

The distribution of energy resources in China is unbalanced, and there is a large space gap between the power supply center and the power load center in China. This kind of spatial mismatch of power supply and demand objectively requires China to build cross regional UHV power grid. This has created conditions for the construction of the national unified power grid, and gradually formed the power grid pattern of UHV power transmission from west to East and north to south. In natural monopoly industries such as electric power, state-owned capital is dominant. In view of the disadvantages of domestic and foreign power systems in the decentralized management of transmission links, China has not implemented marketization in the transmission link. State Grid and China Southern Power Grid are the two central enterprises to manage and operate the transmission link, and the state-owned capital in the transmission link is centrally managed. Under this kind of management system, the power system puts more emphasis on the overall planning and operation stability. The control of state-owned capital also ensures that large-scale construction projects can get sufficient financial support, can realize the efficient allocation of cross regional power, and fully guarantees the integrity and stability of the power system. Under the public ownership, the power industry has made great achievements to meet the continuous and stable growth of power demand (Yu, 2014).

Transmission management in the United States is different from that in China. Its power system has four layers from top to bottom. The first layer is NERC, the second layer is FERC, the third layer is RTO and ISO, and the fourth layer is AEP. The transmission links in the United States are mainly managed by the third and fourth tier power companies. Under the privatization system, the United States has implemented the privatization of the whole process of power generation, transmission, distribution and sales, each power company is a local industry monopolist, and the power enterprises lack the overall dispatching. Due to the decentralization of transmission management functions and the lack of unified power transmission network, one of the hidden dangers is that in case of sudden power crisis, it is impossible to achieve timely and effective cross regional power allocation, which is unfavorable to the overall power stability of the country. In addition, because of the low return rate of power grid investment projects and long construction period, considering the return rate of investment, the private power companies are not willing to make large-scale investment in power grid construction, and even are not willing to upgrade the power grid. So the power supply system is facing a huge challenge of power supply reliability.

Supervision of Transmission Network

In terms of power regulation, after the first session of the 11th National People's Congress, the National Energy Commission, NEA and the Electricity Regulatory Commission are jointly responsible for China's power development planning and market operation regulation. In order to improve the effectiveness of power regulation, in March 2013, the State Council integrated the functions of the former State Power Regulatory Commission into the NEA. Therefore, the national coverage of electric power supervision and unified electric power supervision standards are realized, which effectively avoids the overlapping of electric power supervision functions among different institutions, reduces the time lag of relevant policies in decision-making and implementation, improves the overall efficiency of electric power system.

However, the development process of power system in different regions of the United States is not the same. The power and obligation of power management in different departments are different, and the supervision mode of power wholesale market is also different. There are nine electricity markets in the United States. The management power of power transmission is distributed among RTO, ISO, and AEP, which are at the third and fourth levels of the United States power system. NERC and FERC, which are at a higher level of the power system, are mainly responsible for the work of macro nature, such as the formulation of power industry standards and the management of energy trade. The differentiation of power system regulators and their functions may lead to lack of supervision or overlapping of functions, which will have a negative impact on the efficiency of transmission management, increase the decision-making delay of relevant departments in case of transmission emergency, and may not be able to restore power transmission in time.

INSTITUTIONAL ADVANTAGES OF CHINA'S TRANSMISSION MANAGEMENT

Timely and Effective National Power Allocation

China can become one of the few countries in the world without large-scale blackouts for a long time. In 2018, China's average power supply reliability rate is 99.82%, the average outage time of users is 15.75 h per household, and the average outage frequency of users is 3.28 times per household. In the final analysis, it has a unified power grid management system, which makes the power grid planning, construction, operation, maintenance, dispatching and other links coordinate and operate efficiently, and ensures the long-term safe and stable operation of China's power system. In 2018, China's trans regional power transmission had reached to 136 million KW. Adhering to the integrated management of power grid is conducive to the optimal allocation of new energy in the whole country, the transformation of the energy resource advantages of the western region into economic advantages, and the promotion of the coordinated and balanced development of the national regional economy. Throughout history, in the process of dealing with major natural disasters, it is precisely because of the overall coordination of power grid management and dispatching that accidents can be timely and effectively handled, the losses caused by power accidents can be minimized, and the efficient post disaster reconstruction of power system can be guaranteed (She et al., 2020).

Concentrating Resources to Develop Large Power Projects

State Grid and its supporting facilities need to invest a lot of resources. Limited by their own resources, private enterprises are difficult to undertake the nationwide power grid construction. In addition, the profit orientation of private enterprises makes it difficult to maximize social benefits in the construction of power infrastructure. Therefore, in the important infrastructure construction related to the national economy and people's livelihood, the advantages of the Chinese government in concentrating on a large number of systems are fully reflected. Centralized management is conducive to the rational allocation of human, material, financial and intellectual resources, avoiding the negative impact of resource dispersion and excessive capital profit on social development under the privatization system, and improving the construction efficiency and social benefits of large-scale power projects to a large extent. In terms of the length of China's power grid lines, in 2018, the length of transmission lines with voltage level of 35 kV and above has reached 1.89 million kilometers, which is equivalent to 47 circles around the earth's equator, 291 times of that in the early days of China. In terms of power technology, the transmission line loss rate of power grid decreased from 23.35% in 1949 to 6.21% in 2018, and the coal consumption of power supply decreased from 1020 kgce/kwh in 1949 to 308 kgce/kwh in 2018.

CONCLUSION

After two effective power system reforms, China has basically achieved the vertical separation of power production, transmission and distribution, breaking the previous monopoly situation of the state power company on all aspects of power production, transmission and distribution, and making the power system more efficient. The centralized and unified management of transmission links and the market-oriented reform of both sides of power generation and distribution effectively realize the balance between power system security and efficiency. However, China still needs to further optimize its power system. Firstly, on the basis of centralized and unified management of transmission links, the competition of different companies in generating and selling electricity is further standardized, so as to ensure the healthy development of power generation enterprises and the power accessibility of the public. Secondly, in terms of improving the functions of the power market, a complete power market integrating spot, long-term and auxiliary services should be established to reduce the impact of emergencies on the power system and improve the quality of power service supply. Thirdly, in terms of energy security, we should further optimize the power generation structure, reduce the dependence of China's power system on thermal power generation, increase the proportion of renewable energy power generation, reduce the potential safety hazard of single power generation mode to power stability, and fulfill China's international commitment of emission reduction and ecological environment protection.

AUTHOR CONTRIBUTIONS

WW: writing-original draft, methodology, and supervision. WZ: data curation, writing-review, and editing. LL: methodology, writing-review, and editing. ZC: conceptualization and software.

FUNDING

This research was supported by the National Natural Science Foundation of China (No. 71903056), the National Science Foundation for Post-doctoral Scientists of China (No. 2020M672464), MOE (Ministry of Education in China) Project of Humanities and Social Sciences (No. 19YJC790154), Consulting Project of Chinese Academy of Engineering (Nos. 2020-XY-36 and 2019-ZD-38), the Natural Science Foundation of Hunan Province in China (Nos. 2020JJ5104, 2020JJ4259, and 2020JJ5111), Philosophy and Social Science Foundation of Hunan Province in China (No. 18YBQ075), Project of Hunan Social Science Achievement Appraisal Committee (Nos. XSP20YBZ081 and XSP21YBZ094), Scientific Research Project of Hunan Education Department in China (No. 19C1038), and Research and Innovation Project for Graduate Students in Hunan Province (Nos. CX20201083 and CX20201084).

REFERENCES

Bai, M. (2019). 70 years' development achievements of power industry in New China. *Electr. Ind.* 229, 18–26.

Chawla, M., and Pollitt, M. G. (2013). Global trends in electricity transmission system operation: where does the future lie? *Electr. J.* 26, 65–71. doi: 10.1016/j.tej.2013.05.004

Michaels, R. J. (2006). Vertical integration and the restructuring of the U.S. electricity industry. *Policy Anal.* 572.

Rothe, F. S. (2019). *Introduction to Power System Analysis*. Hoboken, NJ: John Wiley & Sons, Ltd.

She, Z. Y., Meng, G., Xie, B. C., and O'Neill, E. (2020). The effectiveness of the unbundling reform in China's power system from a dynamic efficiency perspective. *Appl. Energy* 264:114717. doi: 10.1016/j.apenergy.2020.114717

Yu, H. (2014). The ascendency of state-owned enterprises in china: development, controversy and problems. *J. Contemp. China* 23, 161–182. doi: 10.1080/10670564.2013.809990

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 30 April 2021
doi: 10.3389/fenrg.2021.652832

Carbon Emission and Endogenous Growth Between Two Economic Systems

Peng Sun, Shijie Li and Kechong Zhou*

School of Economics, Hainan University, Haikou, China

In recent years, many scholars have shown an increasing interest in the problem of pollution (carbon emission) in the endogenous growth but less concern about the interactions of polluting activities between two economy systems. This study explains the effects of carbon emission on the optimal balanced growth path by establishing an endogenous growth model involving exhaustible resources, human capital, physical capital, and labor time under one economy and a similar system involving two economic systems. The second system is used to analyze the interactions of polluting activities across the two economic systems that it covers. The results show that the negative externality (carbon emission) caused by one economy will bring remarkable adverse impacts on the optimal resource extraction and growth rates of other economies. If the people in one economy pay greater attention to the environmental problem (carbon emission), its own resource input will be lowered to reduce carbon emissions, but carbon emissions of another economy will be increased simultaneously to accelerate the economic growth. That is why carbon emission is one of the most challenging issues in global governance. Therefore, the global environmental pollution control needs the help of the cross-regional governance mechanism.

Keywords: endogenous growth, carbon emission, exhaustible resources, human capital, two-economic-system

Edited by:
You-hua Chen, South China Agricultural University, China

Reviewed by:
Minxing Jiang, Nanjing University of Information Science and Technology, China
Chen Ziyue, Norwegian University of Science and Technology, Norway

****Correspondence:***
Peng Sun
newsp2008@126.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *13 January 2021*
Accepted: *26 March 2021*
Published: *30 April 2021*

Citation:
Sun P, Li S and Zhou K (2021) Carbon Emission and Endogenous Growth Between Two Economic Systems. Front. Energy Res. 9:652832. doi: 10.3389/fenrg.2021.652832

INTRODUCTION

The environment is the material basis and constraint to human survival. Man-made environmental problems came up with population growth and development. In recent times, one of the most challenging global environmental problems is the global climate change caused by greenhouse gases (primarily, carbon compounds). Carbon emission issues have attracted worldwide attention. How to allocate global environmental responsibility among countries is the focus of debate. According to the BP statistical review of world energy of 2018, the global carbon dioxide emissions rose by 2.2% to 33,444 million tons in 2017, which was higher than the 1.2% rise experienced in 2016 and is the fastest pace since 2013.

Economic growth raised the level of carbon emissions, which loop back into the economy through their adverse effects. Meadows et al. (1972) put forward the "Growth Limit Theory" in their research report to the club of Rome. They believed that economic growth would be constrained by natural resources and could not be sustained. In order to protect environmental resources, we must artificially reduce the speed of economic growth. The international community hopes to make economic growth both fair and sustainable by establishing an effective system to coordinate benefit distribution and cost sharing. However, in order to maximize their own interests, it is difficult for countries to reach an effective consensus on environmental responsibility. Stiglitz (1974) was the first literature to introduce the non-renewable resource into the field of a neoclassical growth model. A number of authors, thereafter, began to introduce flow pollution problems caused by non-renewable resources into the endogenous growth model. During recent years, there has been some focus on the interactions between economic growth and carbon emissions. Scholars pointed out that the growth rate of an unregulated market economy is sub-optimally high because the negative effects of pollution are not taken into account (Gradus and Smulders, 1993; Bovenberg and Smulders, 1995; Schou, 2000). The focus of some studies is on finding the optimal extraction and growth rates when considering the pollution problem (Michel and Rotillon, 1995; Withagen, 1995; Byrne, 1997; Reis, 2001; Dietz and Stern, 2015; Kollenbach, 2015; Aznar-Márquez and Ruiz-Tamarit, 2016). Other scholars focus far more on the policy effects in an endogenous growth model of pollution (Bovenberg and Smulders, 1996; Jones and Manuelli, 2001; Greiner, 2005; Chu and Lai, 2014; Afonso and Afonso, 2015; Lorente and Álvarez-Herranz, 2016; Bianco, 2017; Marsiglio, 2017). Although there are many scholars who have explored economic growth and carbon emissions, none of them considers the possibility of the interaction of polluting activities between the two economic systems, which is especially important when facing the problems of global pollution.

This study combines ideas from the areas of endogenous growth, environmental economics, and economic theory of non-renewable resources to examine how the conventional results from growth models with carbon emissions may be affected by the inclusion of the non-renewable resources. An endogenous growth model between the two economic systems is then built to analyze the interaction of polluting activities, with interesting and important conclusions. This study argues that, in the face of the increasingly severe contradiction between the global environmental deterioration and the demand for economic development, a global environmental regulation policy must be established to realize the clean technology progress of the global value chain under the condition of the heterogeneity of environmental regulation. In order to practice the development concept of "the unity of human destiny" and walk out of the extensive economic development mode of "pollution before governance," we can realize the green sustainable development of the global economy.

The rest of this study is organized as follows: The basic model and primary results of one economy are outlined in section The Basic Model and Primary Results of One Economy. In section The Extended Model Between Two Economies, the extended model between the two economies is addressed. The conclusions and remarks are drawn in section Conclusions, while Appendices A–C are at the end of this article.

THE BASIC MODEL AND PRIMARY RESULTS OF ONE ECONOMY

Basic Settings

The final output $Y$is a function of four inputs: physical capital K, stock of technology A, rate of resources use R, and labor time devoted to the final output production l_1. All of the variables considered in the model are functions of the time t. To enhance the readability of the study, the subscript (t) has been suppressed in the ensuing discussion. The C-D production function is:

$$Y = K^{\alpha_1}(Al_1)^{\alpha_2}R^{\alpha_3}, \tag{1}$$

where $\alpha_i \quad (i = 1, 2, 3)$ is the elasticity coefficient and $\sum_{i=1}^{3}\alpha_i = 1$. The investment in the physical capital is:

$$\dot{K} = Y - C \tag{2}$$

where $K(0) = K_0, K(t) \geq 0$. Equation (2) is a constraint which considers the change of the physical capital over time. For the sake of simplicity, depreciation in K is not considered here. Aggregate consumption is denoted by $C = xY$, with $0 < x \leq 1$. Aggregate saving is $s = zY = \dot{K}$, where $0 < z \leq 1$ and $z = 1 - x$. Human capital accumulation depends linearly on time spent on R&D activities (Romer, 1990):

$$\dot{A} = \xi(1 - l_1)A, \tag{3}$$

where $A(0) = A_0, A(t) \geq 0$. Equation (3) is the core of the neoclassical endogenous growth model which expresses that labor time may not only to be devoted to the final output but also in the R&D activity. The total number of skilled workers N is normalized to 1. $l_2 = 1-l_1$ is the R&D input of the human capital, wherein $l_i > 0$ for $i = 1, 2$. $\xi > 0$ is a productive parameter of the R&D activity. Technological change is costly and does not occur by chance; it depends rather on the effort devoted to it and is an outcome of one sector of our economy (Kamien and Schwartz, 1978; Romer, 1990; Scholz and Ziemes, 1999). The carbon stock Q moves during time according to

$$\dot{Q} = \frac{\partial Q}{\partial t} = -\tau Q + \psi R, \tag{4}$$

where $0 < \tau \leq 1$ is a constant that expresses the capacity of the environment to assimilate carbon. $0 < \psi < 1$ is the carbon emissions factor of using the non-renewable resource R (Di Vita, 2006). The social welfare, at any point in time, is a function of the flow of consumption C and the intensity of carbon Q (Smith, 1972; Aronsson and Löfgren, 1999; Di Vita, 2007). The instantaneous standard constant elasticity utility function can be indicated by

$$U(Q, C) = \frac{C^{1-\theta} - 1}{1 - \theta} - \frac{Q^{1+\omega} - 1}{1 + \omega}. \tag{5}$$

The inclusion of Q in our utility function indicates that we will pay a price to reduce the amount of accumulated carbon. Equation (5) has continuous first and second partial derivatives, with $U_C > 0$, $U_{CC} < 0$, $U_Q < 0$, $U_{QQ} < 0$, and $U_{CQ} = 0$. Second-order conditions ensure the concavity of the utility function. $\theta, \omega > 0$ are two more parameters representing the elasticity of the marginal utility with respect to the consumption and carbon concentration.

The social welfare associated with any particular time path for C and Q comes from summing the discounted flow, assuming that the social discount rate $\delta > 0$ is exogenous. The problem of the social planner is to choose C and Q, so as to maximize:

$$\begin{cases} W = \underset{C,R,l_1}{U(C,Q)} = \int_0^{\infty} e^{-\delta t}\left(\frac{C^{1-\theta}-1}{1-\theta} - \frac{Q^{1+\omega}-1}{1+\omega}\right)dt \\ s.t.\quad \dot{Q} = -\tau Q + \psi R \quad \text{and } Q(0) = Q_0,\ Q(t) \geq 0 \\ \dot{K} = Y - C \quad \text{and} \quad K(0) = K_0, K(t) \geq 0 \\ \dot{A} = \xi(1-l_1)A \quad \text{and} \quad A(0) = A_0, A(t) \geq 0 \end{cases} \tag{6}$$

The current-value Hamiltonian function is

$$H = \frac{C^{1-\theta}-1}{1-\theta} - \frac{Q^{1+\omega}-1}{1+\omega} - \lambda_1(-\tau Q + \psi R) + \lambda_2\left[K^{\alpha_1}(Al_1)^{\alpha_2}R^{\alpha_3} - C\right] + \lambda_3\left[\xi(1-l_1)A\right] \tag{7}$$

where $\lambda_i,\ i = 1,2,3$ are the dynamic Hamilton multipliers of the stock variables. Note that we consider the shadow price of the carbon concentration λ_1 to be negative because that flow generates disutility.

The Optimal Balanced Growth Path

According to the optimal control theory (Pontryagin et al., 1962), necessary first-order conditions for an interior optimal solution with respect to the three control variables, C, R, and l_r, are:

$$\frac{\partial H}{\partial C} = C^{-\theta} - \lambda_2 = 0. \tag{8}$$

$$\frac{\partial H}{\partial R} = -\lambda_1\psi + \lambda_2\alpha_3\frac{Y}{R} = 0. \tag{9}$$

$$\frac{\partial H}{\partial l_1} = -\lambda_3\xi A + \lambda_2\alpha_2\frac{Y}{l_1} = 0. \tag{10}$$

Then, from Euler Formula, we can obtain

$$\dot{\lambda}_1 = -\frac{\partial H}{\partial Q} + \delta\lambda_1 = Q^{\omega} + (\delta - \tau)\lambda_1. \tag{11}$$

$$\dot{\lambda}_2 = -\frac{\partial H}{\partial K} + \delta\lambda_2 = \delta\lambda_2 - \lambda_2\alpha_1\frac{Y}{K}. \tag{12}$$

$$\dot{\lambda}_3 = -\frac{\partial H}{\partial A} + \delta\lambda_3 = \delta\lambda_3 - \lambda_2\alpha_2\frac{Y}{A} - \lambda_3\xi(1-l_1). \tag{13}$$

$\lambda_i (i = 1,2,3)$ are the shadow values of carbon concentration, physical capital, and human capital, respectively. An interior balanced-growth path that solves the problem of the social planner will fulfill the conditions (8)–(13) and the appropriate non-negativity and transversality conditions:

$$Q(t) \geq 0, K(t) \geq 0, A(t) \geq 0 \tag{14}$$

$$\lim_{t\to\infty} e^{-\delta t}\lambda_1(t)Q(t) = 0 \tag{15}$$

$$\lim_{t\to\infty} e^{-\delta t}\lambda_2(t)K(t) = 0 \tag{16}$$

$$\lim_{t\to\infty} e^{-\delta t}\lambda_3(t)A(t) = 0 \tag{17}$$

Here, it is assumed that all the conditions in Chiang (2015, p. 131), together with the concavity on the maximized Hamiltonian, are satisfied. The proof that the model describes a stable saddle point equilibrium path is given in Appendix C.

Along the balanced growth path, Y, K, and C must necessarily have the same growth rate (which we call, g). Otherwise, Equation (2) could not hold true for all time. If A grows with a constant rate, l_1 must be constant [from Equation (3)]. Also, if Q grows with a constant rate, Q and R must necessarily have the same growth [from Equation (4)]. Using these results, we obtained the steady-state growth rate of the final output (which is equal to the growth rate of capital and consumption). And growth rate for carbon concentration and the human capital was obtained as follows[1]

$$g = g_Y = g_C = g_K = \frac{\alpha_2(\xi-\delta)(1+\omega)}{(\alpha_3+\theta\alpha_2)\omega + \theta(\alpha_2+\alpha_3)} \tag{18}$$

$$g_Q = g_R = \frac{\alpha_2(\xi-\delta)(1-\theta)}{(\alpha_3+\theta\alpha_2)\omega + \theta(\alpha_2+\alpha_3)} \tag{19}$$

$$g_A = \frac{(\xi-\delta)[(\alpha_2+\alpha_3)\omega + \alpha_2 + \theta\alpha_3]}{(\alpha_3+\theta\alpha_2)\omega + \theta(\alpha_2+\alpha_3)}. \tag{20}$$ [2]

Later, the steady-state growth rate is impacted if the disutility of carbon emission is considered. And we obtained some propositions as follows.

Primary Results Analysis

Proposition 1: When carbon emission and its disutility are considered in the endogenous growth model, g_A and g_Y are greater than zero all the time and $g_Q(g_R)\begin{cases} >0 & if\ \theta<1 \\ <0 & if\ \theta>1 \end{cases}$ in the steady state. In this way, $g_A > g_Y(g_C) > g_Q(g_R)$ is always true as confirmed by Appendix B.

Proposition 1 shows that, if carbon concentration impacting the utility level of consumers is considered in the model, in the steady state, the growth rate of output (consumption), g_Y, and the growth rate of knowledge accumulation, g_A, are always greater than zero. But the sign of g_Q depends on the value of θ. If the elasticity of the marginal utility of consumption is lower than 1, which means people are not concerned with having a smooth consumption profile over time (θ is small), the growth rate of carbon concentration will be positive. The growth rate of output (consumption) is greater than the growth rate of the resource extraction (carbon concentration) all the time, and the growth rate of knowledge accumulation is always higher than the growth rate of the output. The result in this model shows that the economic growth depends more on the human capital input and less on the resource extraction when the disutility of the carbon concentration is considered. So, g_A is always greater than g_Y, and g_Q is always lower than g_Y. The conclusion made by Stiglitz (1974) and Scholz and Ziemes (1999) is different in the results obtained by both authors, which showed that g_A may be either smaller or larger than g_Y in conventional models.

[1] Solving the balanced growth path see Appendix A.

[2] An interior pathimplies that labor time must be spent in both the education sector and the final output. So the growth rate of human capital must be positive, but less than the highest possible value, which is ξ (for $l_1 = 0$). We have $0 < g_A < \xi$.

Another issue that is worth considering is the impacts of the elasticity of the marginal utility with respect to carbon concentration and the balanced growth rate.

Proposition 2: In steady state, taking the partial derivative of g_Q, g_A, and g_Y with respect to ω results in $\frac{\partial g_A}{\partial \omega} < 0$ all the time. The sign of $\frac{\partial g_Q}{\partial \omega}$ and $\frac{\partial g_Y}{\partial \omega}$ depends on the value of θ. The sign of the first-order condition is positive only if $\theta > 1$ as shown in Appendix B.

Proposition 2 shows that, if $\theta > 1$ (which means, $g_Q < 0$ according to proposition 1), a positive relationship exists between the growth rate of carbon concentration, g_Q, and the elasticity of the marginal utility with respect to carbon concentration ω. The increase of ω will bring two effects to the optimal path: raising the level of output (and consumption) to increase the positive utility (which will increase carbon concentration at the same time) and cutting down the recourse use to reduce the disutility level. If marginal utility with respect to consumption θ is big, the positive utility of g_Q will be bigger than the disutility level of it. So, g_Q (less than zero) will increase with the increase of ω and vice versa. The conclusion is the same with the analysis of g_Y. It was noticed that $\partial g_A/\partial \omega < 0$ holds all the time, which means that the increase of ω will bring a certain negative influence to the optimal steady-state growth rate of knowledge accumulation.

And then, taking the partial derivative of the growth rate of shadow prices with respect to ω, the next proposition was obtained as follows:

Proposition 3:

$$\frac{\partial g_{\lambda_1}}{\partial \omega}\begin{cases} >0 \ if \ \theta<1 \\ <0 \ if \ \theta>1 \end{cases}, \frac{\partial g_{\lambda_2}}{\partial \omega}\begin{cases} >0 \ if \ \theta<1 \\ <0 \ if \ \theta>1 \end{cases}, \text{ and } \frac{\partial g_{\lambda_3}}{\partial \omega}=0 \tag{21}$$

Proof. **See Appendix B**.

The shadow price λ_1 represents the sensitivity of the change of carbon concentration impacting the optimal utility level. The high growth rate of λ_1 means that high carbon concentrations will bring more negative effects to the optimal utility. Proposition 2 shows that if θ is relatively small (<1), g_{λ_1} is less than zero, and g_{λ_1} will grow with the increase of the elasticity of the marginal utility with respect to carbon concentration ω. g_{λ_2} (which represents the growth rate of shadow price of physical capital) has the same conclusion with g_{λ_1}, which means that, if θ is relatively small (<1), the increase of ω will enhance the influence of physical capital to the optimal utility level. Note that g_{λ_3} would not be impacted by the change of ω.

THE EXTENDED MODEL BETWEEN THE TWO ECONOMIES

This section explored a two-economy system endogenous growth model based on the basic assumptions in section The Basic Model and Primary Results of One Economy. Consider two economies of M and N, which have different utility preferences, output elasticities, and efficiencies of knowledge accumulation. The social optimal problem for the two economy systems can be changed to Equation (22)

$$\begin{cases} W^i = U(C^i, Q) = \int_0^{\infty} e^{-\delta t}\left(\frac{C^{i(1-\theta^i)}-1}{1-\theta^i} - \frac{Q^{1+\omega^i}-1}{1+\omega^i}\right)dt \\ s.t. \quad \dot{Q} = -\tau Q + \psi^i R^i + \psi^j R^j \ \text{ and } Q(0) = Q_0, \ Q(t) \geq 0 \ , \\ \dot{K} i = Y^i - C^i \ \text{ and } \ K^i(0) = K_0^i, K^i(t) \geq 0 \\ \dot{A} i = \xi^i(1-l_1^i)A^i \ \text{ and } \ A^i(0) = A_0^i, A^i(t) \geq 0 \end{cases} \tag{22}$$

where $(i,j) \in \{M, N\}$ *and* $i \neq j$. Note that the only thing that the two economies need to face together is the carbon concentration Q. According to the optimal control theory, necessary first-order conditions for an interior optimal solution and Euler formula from Equation (8) to Equation (13) still hold. So, this section will not cover those again. Along the balanced growth path, Q grows with a constant rate, Q and $\psi^M R^M + \psi^N R^N$ should necessarily have the same growth[3]. It is easy to prove that[4]

$$g_Q = g_{(\psi^M R^M + \psi^N R^N)} = g_{R^M} + g_{R^N} \tag{23}$$

Equation (A9) can be rewritten

$$\omega^i(g_{R^M} + g_{R^N}) = (1-\theta)g_{Y^i} - g_{R^i} \tag{24}$$

Solving this system of Equations (A7), (A11), and (24) with respect to g_{R^i} g_{Y^i}, and g_{A^i}, we obtained

$$g^i = g_{Y^i} = g_{C^i} = g_{K^i} = \frac{\alpha_2^i(\xi^i-\delta)(1+\omega^i) - \alpha_3^i\omega^i g_{Rj}}{(\alpha_3^i + \theta^i\alpha_2^i)\omega^i + \theta^i(\alpha_2^i + \alpha_3^i)} \tag{25}$$

$$g_{R^i} = \frac{\alpha_2^i(\xi^i-\delta)(1-\theta^i) - (\alpha_3^i + \theta^i\alpha_2^i)\omega^i g_{Rj}}{(\alpha_3^i + \theta^i\alpha_2^i)\omega^i + \theta^i(\alpha_2^i + \alpha_3^i)} \tag{26}$$

$$g_{A^i} = \frac{(\xi^i-\delta)[(\alpha_2^i + \alpha_3^i)\omega^i + \alpha_2^i + \theta^i\alpha_3^i] - (1-\theta^i)\alpha_3^i\omega^i g_{Rj}}{(\alpha_3^i + \theta^i\alpha_2^i)\omega^i + \theta^i(\alpha_2^i + \alpha_3^i)} \tag{27}$$

From Equations (25) and (26), it is obvious that $\partial g^i/\partial g_{Rj*} < 0$ and $g_{R^i}/\partial g_{Rj*} < 0$ show that the economic activities of one economy will produce negative externality (carbon emission) to another economy at the same time. It will bring adverse impacts to other activities of the economies (Y, R) on the balanced path. Facing the global public goods (carbon concentration), multi-agent decisions often will cause the tragedy of the commons (Hardin, 1968). Both the implementer and sufferer will be punished (lower utility) by the environment. Also, from Equation (27), if $\theta^i < 1$, then $\partial g_{A^i}/\partial g_{Rj*} < 0$ and if $\theta^i > 1$, then $\partial g_{A^i}/\partial g_{Rj*} > 0$. It means that, if people are concerned with having a smooth consumption profile over time ($\theta^i$is bigger than 1), the increase in the rate of resource depletion of one economy will boost the growth rate of knowledge accumulation of another economy. That is because higher carbon concentrations

[3]Other conditions in section The Basic Model and Primary Results of One Economy have remained the same.
[4]For a similar explanation of Equation (23) see (Vita, 2005).

caused by one economy's activities will stimulate the knowledge accumulation input of another economy to replace the resource depletion and reduce the growth rate of carbon emission when greater attention is paid to the consumption ($\theta^i > 1$). Conversely, the growth rate of knowledge accumulation of one economy will go down with the increase of resource depletion of another economy.

Using the symmetry of the optimal solution, we can obtain the optimal solutions of g_{R^M} and g_{R^N}, respectively. concentration of another economy and with the decrease of its own elasticity of the marginal utility under the condition of $g_Q > 0$. If the people in one economy pay greater attention to carbon emission, the economy will lower its own resource input but increase the resource input of another economy simultaneously. It is similar to the real world, in that the public in some developed countries place a high value on carbon emission and force the government to reduce emissions but promote emissions imperceptibly of other countries. That is why the problem of carbon emission is one of the thorniest problems in the global governance.

$$g_{R^i} = \frac{[(\alpha_3^j + \theta^j\alpha_2^j)\omega^j + \theta^j(\alpha_2^j + \alpha_3^j)]\alpha_2^i(\xi^i - \delta)(1-\theta^i) - \alpha_2^j(\xi^j - \delta)(1-\theta^j)(\alpha_2^i\theta^i + \alpha_3^i)\omega^i}{[(\alpha_3^j + \theta^j\alpha_2^j)\omega^j + \theta^j(\alpha_2^j + \alpha_3^j)]\theta^i(\alpha_2^i + \alpha_3^i) + \theta^j(\alpha_2^j + \alpha_3^j)(\alpha_2^i\theta^i + \alpha_3^i)\omega^i}, \tag{28}$$

where $(i,j) \in \{M,N\}$ *and* $i \neq j$, and $g_Q = g_{(\psi^M R^M + \psi^N R^N)} = g_{R^M} + g_{R^N}$ can be expressedx as

$$g_Q = \frac{\alpha_2^M(\xi^M - \delta)(1-\theta^M)\theta^N(\alpha_2^N + \alpha_3^N) + \alpha_2^N(\xi^N - \delta)(1-\theta^N)\theta^M(\alpha_2^M + \alpha_3^M)}{[(\alpha_3^N + \theta^N\alpha_2^N)\omega^N + \theta^N(\alpha_2^N + \alpha_3^N)]\theta^M(\alpha_2^M + \alpha_3^M) + \theta^N(\alpha_2^N + \alpha_3^N)(\alpha_2^M\theta^M + \alpha_3^M)\omega^M}. \tag{29}$$

It is obvious that $g_Q/\omega^i < 0$[5], which means that the increase of the elasticity of the marginal utility with respect to the carbon concentration of every economy will lower the growth rate of carbon concentration. Also note that the sign of g_Q/ξ^i depends on the value of θ^i[6]. If $\theta^i > 1$, the increase of the efficiency of knowledge accumulation will reduce the growth rate of carbon concentration. On the contrary, the increase of the efficiency of knowledge accumulation will speed up the growth rate of carbon concentration. The increase of the efficiency of knowledge accumulation will replace the resource input and decrease the carbon emission (which can be called substitution effect) and, on the other hand, promote economic growth and increase the carbon emission (which can be called growth effect). If $\theta^i > 1$, the substitution effect is bigger than the growth effect, and the growth rate of carbon concentration will decline with the increase of the efficiency of knowledge accumulation. Based on these results, the impacts of the parameters of one economy on the optimal balanced path of the other economy will be analyzed following the proposition below

Proposition 4: In the steady state, we have $\frac{\partial g_{R^i}}{\partial \omega^i}\begin{cases} > 0 & if \;\; g_Q < 0 \\ < 0 & if \;\; g_Q > 0 \end{cases}$ and $\frac{\partial g_{R^i}}{\partial \omega^j}\begin{cases} > 0 & if \;\; g_Q > 0 \\ < 0 & if \;\; g_Q < 0 \end{cases}$. What is more, we have $\frac{\partial g_{R^i}}{\partial \xi^i}\begin{cases} > 0 & if \;\; \theta^i < 1 \\ < 0 & if \;\; \theta^i > 1 \end{cases}$ and $\frac{\partial g_{R^i}}{\partial \xi^j}\begin{cases} > 0 & if \;\; \theta^j > 1 \\ < 0 & if \;\; \theta^j < 1 \end{cases}$.

Proof. See Appendix B.

Proposition 4 shows that the growth rate of resource exploitation of one economy will rise with the increase of the elasticity of the marginal utility with respect to the carbon concentration of another economy and with the decrease of its own elasticity of the marginal utility under the condition of $g_Q > 0$.

Also, the efficiency of knowledge accumulation has a similar effect to the growth rate of resource exploitation. If the elasticity of the marginal utility with respect to the consumption of the two economies have $\theta^i > 1$ *and* $\theta^j > 1$, the increase of ξ^i will lower its own growth rate of resource exploitation and boost other economies' growth rate of resource exploitation. Further, we have the next corollary based on proposition 4.

Corollary 1: In the steady state, based on proposition 4, using Equation (26) and (27), we have $\frac{\partial g_{Y^i}}{\partial \omega^j} = \frac{\partial g_{Y^i}}{\partial g_{R^j}} \cdot \frac{\partial g_{R^j}}{\partial \omega^j}\begin{cases} < 0 & if \;\; g_Q < 0 \\ > 0 & if \;\; g_Q > 0 \end{cases}$, $\frac{\partial g_{Y^i}}{\partial \xi^j} = \frac{\partial g_{Y^i}}{\partial g_{R^j}} \cdot \frac{\partial g_{R^j}}{\partial \xi^j}\begin{cases} < 0 & if \;\; \theta^j < 1 \\ > 0 & if \;\; \theta^j > 1 \end{cases}$, $\frac{\partial g_{A^i}}{\partial \omega^j} = \frac{\partial g_{A^i}}{\partial g_{R^j}} \cdot \frac{\partial g_{R^j}}{\partial \omega^j}\begin{cases} > 0 & if \;\; g_Q < 0, \theta^i > 1 \;\; or \;\; g_Q > 0, \theta^i < 1 \\ < 0 & if \;\; g_Q > 0, \theta^i > 1 \;\; or \;\; g_Q < 0, \theta^i < 1 \end{cases}$, and

$$\frac{\partial g_{A^i}}{\partial \xi^j} = \frac{\partial g_{A^i}}{\partial g_{R^j}} \cdot \frac{\partial g_{R^j}}{\partial \xi^j}\begin{cases} > 0 & if \;\; \theta^i < 1, \theta^j > 1 \;\; or \;\; \theta^i > 1, \theta^j < 1 \\ < 0 & if \;\; \theta^i > 1, \theta^j > 1 \;\; or \;\; \theta^i < 1, \theta^j < 1 \end{cases}$$

Corollary 1 reflects that one economy's activities will exert influence on another economy through the changing fossil resource input and carbon emission. The increase of ω of one economy will have a positive influence on the economic growth of other economies when the balanced growth rate of carbon concentration is positive. If one economy has a higherθ, the increase of efficiency of knowledge accumulation will lower his own growth rate of resource exploitation and then promote the balanced growth rate of another economy.

The sign of first-order condition between g_{A^i} and ω^j depends on both the values of g_Q and θ^i. If g_Q and 1-θ^i have the same positive or negative sign, there is a positive relationship between g_{A^i} and ω^j. If the people in the two economies have the same preference degree (which means $\theta^i - 1$ *and* $\theta^j - 1$ have the same sign), the increase of efficiency of knowledge accumulation

[5]Note that ω^i only appears in the denominator of Equation (29).

[6]Note that ξ^i only appear in the numerator of Equation (29).

of one economy will lower the balanced growth rate of knowledge accumulation of another economy.

CONCLUSIONS

The unity of opposites between economic development and environmental protection is an important proposition of environmental economics. At the present stage, the division of labor in economic development is becoming more and more detailed. Global production has already made the production links not only concentrated in a few countries. The differences in economic development between countries also bring about huge differences in the intensity of environmental regulation among countries. As a result, the research on environmental regulation with industries and enterprises as the main body is no longer applicable to the actual production practice, and the global environmental problems cannot be effectively solved. A natural resource that causes carbon emission is introduced into an endogenous growth model with human capital and is addressed in this study. If the carbon concentration impacting the utility level of consumers is considered in the model, in the steady state, the growth rate differs in several ways from usual models combining growth with environmental questions; the growth rate of output and knowledge accumulation is always greater than zero. If the elasticity of the marginal utility of consumption is lower than 1, which means people are not concerned with having a smooth consumption profile over time, and the growth rate of carbon concentration will be positive. The growth rate of output (consumption) is greater than the growth rate of resource extraction (carbon concentration) all the time. Economic growth depends more on the human capital input and less on resource extraction when the disutility of carbon concentration is considered.

Furthermore, the reaction of the two economies was considered in the model, as this is closer to the real world. In the two-economy system model, the activities of both economies will produce carbon compounds and reduce the utility of consumers. The economic activities of one economy will bring remarkable adverse impacts to the activities of other economies on the balanced path. Facing the global public goods (carbon concentration), the multi-agent decision will often cause the tragedy of the commons. Both the implementer and sufferer will be punished (lower utility) by the environment. The increase of the elasticity of the marginal utility with respect to carbon concentration of every economy will lower the growth rate of the carbon concentration. On the contrary, if the people in one economy pay more attention to the carbon emission environmental problem, the economy will lower its own resource input but increase another economy's resource input simultaneously. It is similar to the real world that the public in some developed countries put a high value on the carbon emission and force the government to reduce emission but promote the emission of other countries imperceptibly, making carbon emission one of the most difficult challenges in global governance.

Therefore, the cross-border and cross-industry characteristics of carbon emission problems make it difficult for the existing environmental regulation policies with the single country, industry, or enterprise as the main body to achieve the desired effect. The global environmental pollution control needs the help of the cross-regional governance mechanism. We should establish a global environmental regulation policy, so as to realize the clean technology progress of the global value chain under the condition of heterogeneity of environmental regulation, reduce the transfer of pollution links, practice the development concept of "community of human destiny," walk out of the extensive economic development mode of "pollution before governance," and realize green sustainable development.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**supplementary material**, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

PS: framework construction and model processing. KZ: text sorting. SL: model analysis and verification. All authors contributed to the article and approved the submitted version.

FUNDING

This research was supported by the National Natural Science Foundation of China (Project 71563008), High-level Talent Project of Hainan Provincial Natural Science Foundation (Project 720RC578), the Hainan Philosophy and Social Science Planning General Project [Project HNSK(YB)20-13], and the Hainan Natural Science Foundation High-level Talents Program in 2020.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.652832/full#supplementary-material

REFERENCES

Afonso, O., and Afonso, A. C. (2015). Endogenous growth effects of environmental policies. *Panoeconomicus* 62, 607–629. doi: 10.2298/PAN1505607A

Aronsson, T., and Löfgren, K. G. (1999). Pollution tax design and "Green" national accounting. *Eur. Econ. Rev.* 43, 1457–1474. doi: 10.1016/S0014-2921(98)00028-2

Aznar-Márquez, J., and Ruiz-Tamarit, J. R. (2016). Environmental pollution, sustained growth, and sufficient conditions for sustainable development. *Econ. Model.* 54, 439–449. doi: 10.1016/j.econmod.2016.01.017

Bianco, D. (2017). Environmental policy in an endogenous growth model with expanding variety. *Rev. d'économiepolitique* 127, 1013–1028. doi: 10.3917/redp.276.1013

Bovenberg, A. L., and Smulders, S. (1995). Environmental quality and pollution-augmenting technological change in a two-sector endogenous growth model. *J. Public Econ*. 57, 369–391. doi: 10.1016/0047-2727(95)80002-Q

Bovenberg, A. L., and Smulders, S. A. (1996). Transitional impacts of environmental policy in an endogenous growth model. *Int. Econ. Rev*. 37, 861–893. doi: 10.2307/2527315

Byrne, M. M. (1997). Is growth a dirty word? Pollution, abatement and endogenous growth. *J. Dev. Econ*. 54, 261–284. doi: 10.1016/S0304-3878(97)00043-6

Chiang, A. C. (2015). *Elements of Dynamic Optimization*. Beijing: China Renmin University Press.

Chu, H., and Lai, C. (2014). Abatement R&D, market imperfections, and environmental policy in an endogenous growth model. *J. Econ. Dyn. Control*. 41, 20–37. doi: 10.1016/j.jedc.2014.02.011

Di Vita, G. (2006). Natural resources dynamics: exhaustible and renewable resources, and the rate of technical substitution. *Res. Policy* 31, 172–182. doi: 10.1016/j.resourpol.2007.01.003

Di Vita, G. (2007). Exhaustible resources and secondary materials: a macroeconomic analysis. *Ecol. Econ*. 63, 138–148. doi: 10.1016/j.ecolecon.2006.10.004

Dietz, S., and Stern, N. (2015). Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions. *Econ. J*. 125, 574–620. doi: 10.1111/ecoj.12188

Gradus, R., and Smulders, S. (1993). The trade-off between environmental care and long-term growth—pollution in three prototype growth models. *J. Econ*. 58, 25–51. doi: 10.1007/BF01234800

Greiner, A. (2005). Fiscal policy in an endogenous growth model with public capital and pollution. *Japan. Econ. Rev*. 56, 67–84. doi: 10.1111/j.1468-5876.2005.00299.x

Hardin, G. (1968). The tragedy of the commons. *Science* 162, 1243–1248. doi: 10.1126/science.162.3859.1243

Jones, L. E., and Manuelli, R. E. (2001). Endogenous policy choice: the case of pollution and growth. *Rev. Econ. Dyn*. 4, 369–405. doi: 10.1006/redy.2000.0118

Kamien, M. I., and Schwartz, N. L. (1978). Optimal exhaustible resource depletion with endogenous technical change. *Rev. Econ. Stud*. 45, 179–196. doi: 10.2307/2297093

Kollenbach, G. (2015). Endogenous growth with a ceiling on the stock of pollution. *Environ. Res. Econ*. 62, 615–635. doi: 10.1007/s10640-014-9832-6

Lorente, D. B., and Álvarez-Herranz, A. (2016). Economic growth and energy regulation in the environmental Kuznets curve. *Environ. Sci. Pollut. Res*. 23, 16478–16494. doi: 10.1007/s11356-016-6773-3

Marsiglio, S. (2017). A simple endogenous growth model with endogenous fertility and environmental concern. *Scott. J. Polit. Econ*. 64, 263–282. doi: 10.1111/sjpe.12125

Meadows, D. H., Randers, J., Meadows, D. L., and Behrens, D. D. (1972). *The Limits to Growth*. New York, NY: Universe Books.

Michel, P., and Rotillon, G. (1995). Disutility of pollution and endogenous growth. *Environ. Res. Econ*. 6, 279–300.

Pontryagin, L. S., Boltyanskii, V. G., Gamkrelidze, R. V., and Mishchenko, E. F. (1962). *The Mathematical Theory of Optimal Processes, Translated From Russian by Triroyoff, K. N*. New York, NY: Interscience.

Reis, A. B. (2001). Endogenous growth and the possibility of eliminating pollution. *J. Environ. Econ. Manage*. 42, 360–373. doi: 10.1006/jeem.2000.1159

Romer, P. M. (1990). Endogenous technological change. *J. Polit. Econ*. 98, 71–102. doi: 10.1086/261725

Scholz, C. M., and Ziemes, G. (1999). Exhaustible resources, monopolistic competition, and endogenous growth. *Environ. Res. Econ*. 13, 169–185. doi: 10.1023/A:1008201811142

Schou, P. (2000). Polluting non-renewable resources and growth. *Environ. Res. Econ*. 16, 211–227. doi: 10.1023/A:1008359225189

Smith, V. L. (1972). Dynamics of waste accumulation: disposal versus recycling. *Q. J. Econ*. 86, 600–616. doi: 10.2307/1882044

Stiglitz, J. (1974). Growth with exhaustible natural resources: efficient and optimal growth paths. *Rev. Econ. Stud*. 41, 123–137. doi: 10.2307/2296377

Vita, G. D. (2005). Renewable resources and waste recycling. *Environ. Model. Assessment* 9, 159–167. doi: 10.1007/s10666-005-3798-2

Withagen, C. (1995). Pollution, abatement and balanced growth. *Environ. Res. Econ*. 5, 1–8. doi: 10.1007/BF00691906

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 24 May 2021
doi: 10.3389/fenrg.2021.677873

The Spillover Effect Evaluation of Chinese Emissions Trading Scheme

Xinwu Li[1], *Chan Wang*[2], *Lianggui Liao*[1] *and Hongxin Wen*[3]*

[1] School of Finance, Guangdong University of Finance and Economics, Guangzhou, China, [2] Guangdong Institute of Economic and Social Development, Guangdong University of Finance and Economics, Guangzhou, China, [3] National Economic Research Center, Guangdong University of Finance and Economics, Guangzhou, China

Carbon emissions trading scheme (ETS) is becoming a crucial policy in mitigating global climate change. This paper purposes to evaluate the spillover effect of Chinese ETS policy with the data of 30 provinces' carbon emissions in China by China-MRIO model and input-output analysis. The MRIO model provides the change in production value in each region in the intermediate demand and final demand. 2012 and 2015 were selected as case study years to highlight the spillover effects of ETS policy. The results show that some pilot regions such as Beijing, Tianjin, Shanghai and Chongqing reduced their directed CO_2 emissions while Guangdong and Hubei increased their directed CO_2 compared to 2012. However, there were places like Hebei, Shanxi, Inner Mongolia, Ningxia, and Xinjiang that undertook a mass of embodied CO_2 emissions which were majorly caused by providing intermediate products. Similarly, the pilot regions transferred out CO_2 emissions by using a good deal of intermediate products. Thus, it is argued that carbon transfer evaluation can provide scientific support for carbon allowance formulating and it is important for policymakers to consider embodied carbon emissions in intermediate product trading when allocating carbon allowance under the market strength of ETS.

Keywords: carbon emissions trading scheme, carbon transfer, MRIO model, spillover effect, effect evaluation

Edited by:
You-Hua Chen,
South China Agricultural University,
China

Reviewed by:
He Nie,
National University of Singapore,
Singapore
Peng Sun,
Hainan University, China

Correspondence:
Hongxin Wen
hxwen2011@126.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *08 March 2021*
Accepted: *13 April 2021*
Published: *24 May 2021*

Citation:
Li X, Wang C, Liao L and Wen H (2021) The Spillover Effect Evaluation of Chinese Emissions Trading Scheme. Front. Energy Res. 9:677873. doi: 10.3389/fenrg.2021.677873

INTRODUCTION

China has concerned about further climate change impacts caused by greenhouse gas, and it is undergoing the process of carbon dioxide (CO_2) emission reduction. Since 2006, China has been the first rank of CO_2 emission in the world and added 0.32 billion tones of CO_2 to the atmosphere in 2019. Overall, China emitted 9.83 billion tons of CO_2 emissions, 28.8% of the world's total share in 2019 (BP, 2020). The Paris Agreement was officially in force in 2016. Since then, China was becoming one of the most concerned countries in mitigating climate change. China formally approved Beijing, Shanghai, Tianjin, Chongqing, Hubei, Guangdong, and Shenzhen to practice the "cap and trade" carbon emissions trading scheme (ETS) in 2011. And Shenzhen presented the first practice of ETS in China in 2013. Consequently, environmental and economic impacts of ETS have been a major issue of research over the last decade. The focus of these studies includes carbon price and renewable policies (Koch et al., 2014), firms' inventory management (Hua et al., 2011), carbon allowance allocation (Daskalakis et al., 2009; Zhang et al., 2018) and financial analysis such as carbon trading and tax (Otaki, 2013; Barragán-Beaud et al., 2018). Regression analyses were used to study economics and environmental impacts of the adoption of ETS pilots in China. For example, the authors demonstrated that the trading carbon volume at Shanghai market would be 6.2 million ton in 2030 (Wu et al., 2016). In other studies, carbon leakage was concerned because products' consuming places were ignored (Peters and Hertwich, 2008a). To overcome this neglect, consumption-based accounting of CO_2 emissions was employed to calculate the exact CO_2 emission (Peters and Hertwich, 2008b; Davis and Caldeira, 2010).

Leontief proposed an IO method to capture the relations between sectors and industries in the 1930s (Leontief, 1970). Further, the single region national input-output (SRIO) model was employed to assess the net transfer of CO_2 between countries which reveals unfair responsibility on emission and negative impacts on developing countries due to providing the majority of industrial products of the world (Su and Ang, 2013; Kulionis and Wood, 2020). However, studies that focus on policy effect or employ the SRIO model cannot evaluate the spatial distribution of impacts. One limitation of the studies based on SRIO and regression is that they treat the entire state economy as one and incapable of calculating region-wise impacts. On the other hand, the MRIO model can identify trading flows between regions, sectors, and final demand. Therefore, the MRIO model can effectively distinguish the pollutant emissions in other regions caused by the consumption of a given region (Wiedmann et al., 2011).

Implementing carbon ETS pilots could result in regional spillover of environmental and economic impacts due to the interconnected nature of the regional production structure. Hence, it is crucial to quantify the distribution of these impacts to avoid any unplanned consequence of ETS pilots' expansion. To our best knowledge, few studies quantified the regional spillover effects for ETS pilots implementation in China, which can provide important multi-regional insights for policy management departments to allocate carbon allowance between provinces reasonably. Thus, the multi-regional input-output (MRIO) model is employed in this paper to address the gap of multi-regional impacts of carbon transfer during the ETS pilots period.

The MRIO model enables us to compute the spillover effects of ETS pilots among the six pilot provinces and all the other interconnected regions. These spillover effects can be in the form of change in energy consumption and production volume of different commodities in regions that are not included in ETS pilots. This advantage of MRIO methodology to provide a comprehensive insight into spillover effects across different areas because of planned changes in the economic sectors of a region makes MRIO a robust tool to be used for assessing the impact of planned development. Thanks to the fast evolution of technology, MRIO data panels are available for assessment of the impact of these emerging pilot policies before wide-scale adoption (Liang et al., 2007; Mi et al., 2018). Nowadays, there are several studies that work out net transferred CO_2 based on China's MRIO data table (Meng et al., 2013; Mi et al., 2017). Nevertheless, the multi-regional CO_2 flow behind the ETS pilots is not fully understood.

In this paper, we perform calculation analysis and attempt to answer the following two questions: (1) How much would the carbon emissions change pre- and post-the ETS pilots' intervention? (2) What can we know about the spillover effects that an MRIO can provide for the case of implementing ETS pilots in China? To address these issues, we first compute every province's CO_2 emission considering both the production side and consumption side by using China's MRIO model and then indicate the direction of CO_2 transfer among provinces. The China-MRIO table can capture regional contribution and distribution of CO_2 emission.

In sum, this study considers the potential changes of carbon emissions transfer to help understand the effect of ETS policy implementation within China. By breaking up the CO_2 emissions into the intermediate trade and final consumption, we can figure out the adjustment of CO_2 transfer of the pilot regions and the transfer directions of CO_2 emissions. The results of this study could facilitate the optimization of China's ETS pilots policy and minimize the adverse side effects of the policy implementation on the economy and environment.

The Rest of this paper is organized as follows: we first provide the details about calculating regional level direct and indirect CO_2 emission with MRIO analytical framework and the China-MRIO data table. This is followed by details on data sources used for studying energy consumption and carbon footprint between pilots and non-pilots areas of China. In the "Results and Discussions" section, we report our major findings for decomposition of regional level CO_2 emissions, embodied CO_2 emissions for regional sector using MRIO model and CO_2 transfer impact of executing ETS pilots followed by conclusion from the work.

METHODOLOGY AND DATA SOURCES

Calculation of Carbon Emission and Carbon Intensity

In this study, the equation that we use to estimate carbon emissions is defined below (Liu et al., 2016) :

$$CE = \sum D \times e \tag{1}$$

Where CE is CO_2 emissions from different sectors of regions, D is the combusted fossil fuels measuring in monetary; and e is the CO_2 emission of different types of energy per monetary unit.

By summarizing the emissions from different fossil fuels together, we calculate the emission intensity for a region in the following equation:

$$CI^r = CE/GDP^r \tag{2}$$

where CI^r is the CO_2 emission intensity for a region, and GDP^r is the gross domestic product of that region.

MRIO Model

This paper employs the MRIO model to estimate the spillover effect of carbon transfer under the ETS policy in China. The MRIO model internalizes the stream of commodities and services among areas using inter-regional trading data which present as an MRIO table. The methodology starts with an existing m region MRIO table (Aichele and Felbermayr, 2015). The

"Intermediate product" provides the input-output data from a region's department itself and other regions' departments; the "Final Product" provides the final consumption data of a region from every region's departments.

Since the MRIO matrix has been established, area r's input-output identical equation can be defined as follows:

$$Q = (I - A)^{-1} (AX + Y + EX) \quad (3)$$

Where Q is the total output of the system; A is the direct consume coefficient matrix whose elements indicate the number of intermediate products from sector i in region r that produces a unit output for sector j in region s; X is a vector representing the intermediate demand; and Y is a vector representing the final demand, including household consumption, government consumption, fixed asset formation and inventory; EX is a vector indicating the net export.

To calculate the spatial CO_2 footprint of economic activities across China, we first construct a carbon intensity matrix which is symbolized by CI^r to indicate the CO_2 emissions per unit output of region r. If the X, Y, and EX in Eq. 3 are known, then the carbon emissions of departments of region r can be calculated as follows:

$$E^r = CI^r (I - A)^{-1} (AX + Y + EX) \quad (4)$$

Where CI^r is a vector whose elements are identified as the amount of direct CO_2 emissions per unit GDP; $(I - A)^{-1}$ is the Leontief inverse matrix.

The net CO_2 emission transfer can be calculated as follows:

$$netET^r = E^r_{pro} - E^r_{con} \quad (5)$$

Where $netET^r$ is the net CO_2 transfer from region r to other regions. If the $netET^r > 0$, region r is the embodied CO_2 importer; respectively, if the $netET^r < 0$, region r is the embodied CO_2 exporter.

By breaking it down into different demands, the net CO_2 emission transfer of the intermediate demand can be calculated as follows:

$$netET^r_{in} = CI^r (I - A)^{-1} A \left(X_{pro} - X_{con}\right) \quad (6)$$

Where $netET^r_{in}$ is the net CO_2 transfer resulted from the consume and produce of intermediate products; X_{pro} is the vector indicates the intermediate products produced in region r and consumed in other regions; and X_{con} is the vector indicates the intermediate products produced in other regions and consumed in region r.

The net CO_2 emission transfer of the final demand can be calculated as follows:

$$netET^r_{fi} = CI^r (I - A)^{-1} \left(Y_{pro} - X_{con}\right) \quad (7)$$

Where $netET^r_{fi}$ is the net CO_2 transfer resulted from the consume and produce of final products; Y_{pro} is the vector indicates the final products produced in region r and consumed in other regions; and Y_{con} is the vector indicates the final products produced in other regions and consumed in region r.

The domestic net CO_2 emission transfer can be calculated as follows:

$$netET^r_d = netET^r_{in} + netET^r_{fi} \quad (8)$$

Where is $netET^r_d$ the net CO_2 transfer between region r and other regions in China. If the $netET^r_d > 0$, region r imports the embodied CO_2 from other regions in China; respectively, if the $netET^r_d < 0$, region r exports the embodied CO_2 to other regions in China.

Since this study focus on the spillover effect of ETS policy implementation within China, we need to pay attention to the results of Eqs 6–8.

Data Sources

Two types of data are needed in this research, including China's national MRIO table and annual emission inventories of 30 provinces in China. This research is conducted to analyze the spillover effect of ETS pilots implementation which was carried out in 2013 and 2014. By the way, the shift of labor-intensive and resource-intensive industries in eastern China to the central and western regions is accelerating in 2010, thus selecting 2012 and 2015 as the case study years is helpful to detect the ETS policy's effects and defects. The data of 2012 MRIO table and 2015 MRIO table are the most recent data that are available from the China Emission Accounting and Datasets (CEADs) (CEADs, 2012, 2015; Liu et al., 2016). The datasets published by CEADs are the results of current research projects funded by the National Natural Science Foundation of China, Ministry of Science and Technology of China, Chinese Academy of Sciences, Science and Technology Research Council UK, Newton Fund, which ensure the accuracy of economic and trade data in the MRIO table. The industries in the 2015 MRIO table were merged into 30 industries to reconcile 2012 and 2015's different classification criteria. The MRIO table consists of 30 provinces and 30 industrial departments, and the missing data of Tibet, Hongkong, Macao, and Taiwan are unavailable so that this research does not include these regions. Data of energy activities for calculating CO_2 emissions was capturing via the National energy balance sheet in *China Energy Statistical Yearbook 2013 And China Energy Statistical Yearbook 2016* which recorded previous year data. Besides, carbon emission factors that we use are recommended in the IPCC 2006 guidelines (IPCC, 2014). Due to the China-MRIO table contains four energy industries which are Coal mining, Petroleum and gas, Petroleum refining and coking and Gas and water production and supply, we categorize energy materials that every province consumes into these four energy genres (Wang et al., 2017). Besides, the part of energy materials to convert has to be distinguished which will result in overrating emissions of intermediate consumption and underrating emissions of final consumption (Liu Y. et al., 2015).

RESULTS

Provincial Level Direct CO_2 Emission and Emission Intensity

Direct CO_2 Emission

Based on the methodology and relevant data files above, China emitted 8,623 million tons (million tons) CO_2 in 2012 and 9,231 million tons CO_2 in 2015, which are basically matching with the results of existing researches (Liu Z. et al., 2015; Shan et al., 2018).

Figure 1 provides an overview of variations of CO_2 emissions of 2012 and 2015. In 2012, top five emitting provinces were Shandong, Hebei, Jiangsu, Hebei, Henan, and Guangdong and they shared 41.48% of total emissions. The biggest emitter was Shandong which produced 1,002.54 million tons CO_2. In 2015, Jiangsu, Guangdong, Shandong, Hebei, and Zhejiang became the top five spots direct CO_2 emissions and they shared 42.27% of total emissions. And then the biggest emitter was Jiangsu which emitted 1,049.12 million tons CO_2.

The CO_2 emitted by six pilot provinces increased from 1,322.47 million tons in 2012 to 1,638.43 million tons in 2015, the differential of which was generated by Guangdong and Hubei. During this period, Beijing, Tianjin, Shanghai and Chongqing decreased their share of direct CO_2 emissions while Guangdong raised its share of direct CO_2 emissions from 5.80 to 8.52% and Hubei's share rised from 2.22 to 4.10%.

CO_2 Emission Intensity

According to **Figure 2**, the carbon emission intensity top five were Qinghai, Ningxia, Gansu, Hebei, and Guizhou in 2012, while in 2015 were Ningxia, Xinjiang, Guizhou, Anhui, and Gansu. And the quantity of emission intensity of these regions were in a strong uptrend. It is shown that the emission intensities of the six pilot places remained low. Besides, Beijing, Tianjin, Shanghai, and Chongqing had slightly declined. Correspondingly, Guangdong increased its emission intensity from 0.87 tons per 10 k RMB in 2012 to 1.38 tons per 10 k RMB in 2015 and Hubei's emission intensity increased from 0.86 tons per 10 k RMB in 2012 to 1.70 tons per 10 k RMB in 2015.

Carbon Footprint

Implementing ETS pilots induces new regional throughput for the whole of China. Using Eqs 8, 9, we calculate 30 provinces' carbon footprint of production and carbon footprint of consumption in 2 years, respectively, and the results are presented in **Table 1**.

Carbon Footprint of Consumption

Beijing, Tianjin, Shanghai, Hubei, Guangdong, and Chongqing increased much more CO_2 emissions by 146.08 million tons, 30.04 million tons, 229.79 million tons, 234.02 million tons, 780.92 million tons and 190.79 million tons, respectively, through consuming intermediate and final products from other provinces from 2012 to 2015. In 2012, the pilot regions contributed 24.2% of consumption-based CO_2 emissions. And in 2015, the pilot regions shared 27.6% of the carbon footprint of consumption.

Carbon Footprint of Production

From 2012 to 2015, the majority of provinces were increasing their CO_2 emissions due to production activities within the province boundary. Only Beijing, Tianjin, Shanghai, Sichuan, and Yunnan's carbon footprint of production were declining. Beijing's carbon emission of production dropped from 147.43 million tons in 2012 to 75.00 million tons in 2015. Tianjin reduced about 96.36 million tons of carbon emissions in production activity. And Shanghai decreased slightly by 9.17 million tons.

Carbon Transfer of Provinces

According to **Figure 3**, Beijing's domestic CO_2 emissions transfer in 2015 was −395.74 million tons which were more than twofold that in 2012. Tianjin's net CO_2 emissions transfer was −109.30 million tons which was reversed a lot in volume from 2012. Shanghai's net CO_2 emissions transfer was −238.46 million tons which was about fourfold that in 2012. Guangdong's net CO_2 emissions transfer was −575.63 million tons which is much higher than that in 2012. This situation also emerged in Chongqing.

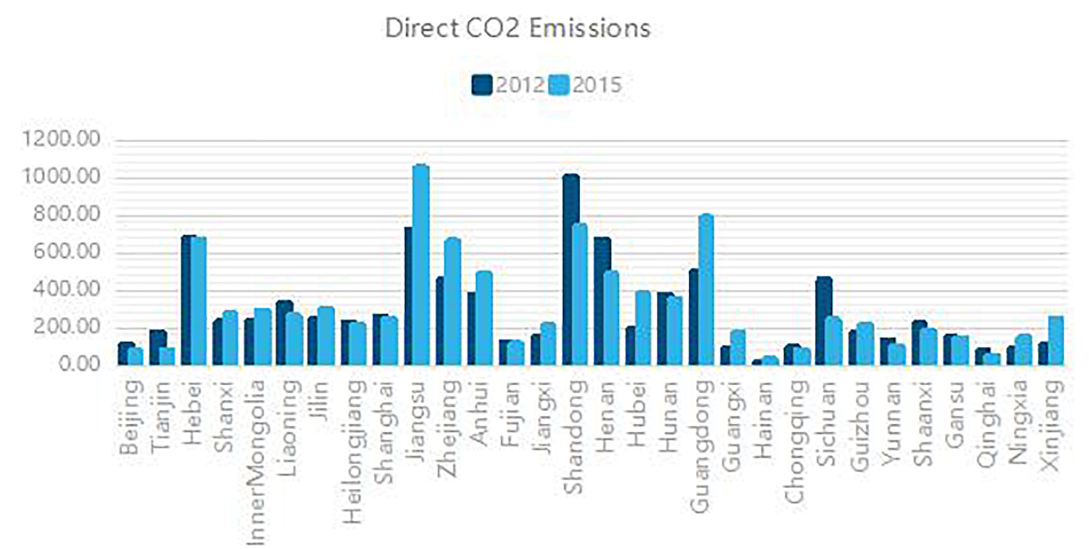

FIGURE 1 | Direct CO_2 emissions in 2012 and 2015.

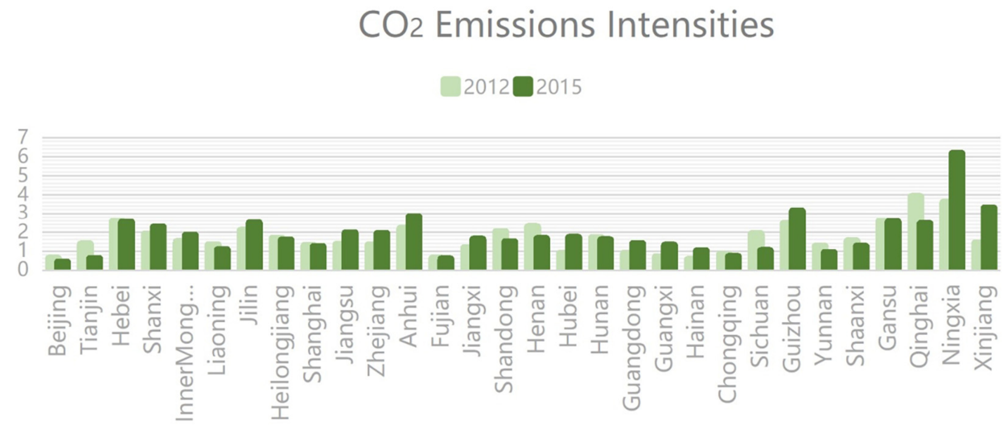

FIGURE 2 | Carbon intensities in 2012 and 2015.

TABLE 1 | CO_2 emissions and transfer calculation of 30 province in China in 2012 and 2015 (Unit: Mt).

Region	2012			2015		
	Intermediate products	Final product	Domestic	Intermediate products	Final product	Domestic
Beijing	−139.68	−25.62	−165.3	−368.16	−27.58	−395.74
Tianjin	21.55	−5.01	16.54	−97.44	−11.86	−109.3
Hebei	184.87	30.69	215.56	615.46	29.99	645.45
Shanxi	50.06	−14.95	35.11	330.62	−14.24	316.38
InnerMongolia	68.28	−1.65	66.63	455.08	2.17	457.25
Liaoning	−17.54	78.11	60.57	−31.06	88.95	57.89
Jilin	34.52	8.12	42.64	93.37	12.12	105.49
Heilongjiang	43.98	−8.14	35.84	60.54	−11.13	49.41
Shanghai	−26.95	−18.98	−45.93	−213.39	−25.07	−238.46
Jiangsu	−144.47	13.95	−130.52	−190.81	29.57	−161.24
Zhejiang	−96.53	−2.76	−99.29	−571.96	6.73	−565.23
Anhui	42.70	14.90	57.6	198.36	26.45	224.81
Fujian	−11.12	3.20	−7.92	−77.15	2.62	−74.53
Jiangxi	−19.63	−4.31	−23.94	−30.11	−2.41	−32.52
Shandong	−1.10	9.73	8.63	27.52	1.07	28.59
Henan	91.90	27.76	119.66	−39.51	8.03	−31.48
Hubei	−19.66	0.97	−18.69	−119.14	5.75	−113.39
Hunan	21.57	19.22	40.79	−63.44	15.95	−47.49
Guangdong	−95.00	−10.78	−105.78	−569.48	−6.15	−575.63
Guangxi	−16.36	−8.81	−25.17	10.90	−5.01	5.89
Hainan	−9.30	−3.44	−12.74	−34.56	−2.99	−37.55
Chongqing	−56.31	−14.95	−71.26	−234.09	−16.05	−250.14
Sichuan	−1.02	9.25	8.23	−103.39	0.76	−102.63
Guizhou	32.84	3.35	36.19	182.73	7.18	189.91
Yunnan	−12.07	−5.81	−17.88	−109.81	−10.98	−120.79
Shaanxi	15.81	−12.74	3.07	−17.82	−14.61	−32.43
Gansu	25.66	−0.30	25.36	107.93	−0.79	107.14
Qinghai	7.87	−2.62	5.25	34.04	−2.88	31.16
Ningxia	24.63	0.17	24.8	370.53	2.21	372.74
Xinjiang	0.49	−9.12	−8.63	384.21	−0.75	383.46

The negative numbers indicate that regions export embodied carbon emissions; The positive numbers indicate that regions import embodied carbon emissions.

In addition, we can figure out that Hebei, Inner Mongolia, Xinjiang, Ningxia, Shanxi, and Anhui digested the vast majority of CO_2 emissions transfer. Their CO_2 emissions imports dramatically increased by hundreds of million tons. Their transferred-in quantities increased 429.89 million tons, 390.62 million tons, 392.09 million tons, 347.94 million tons,

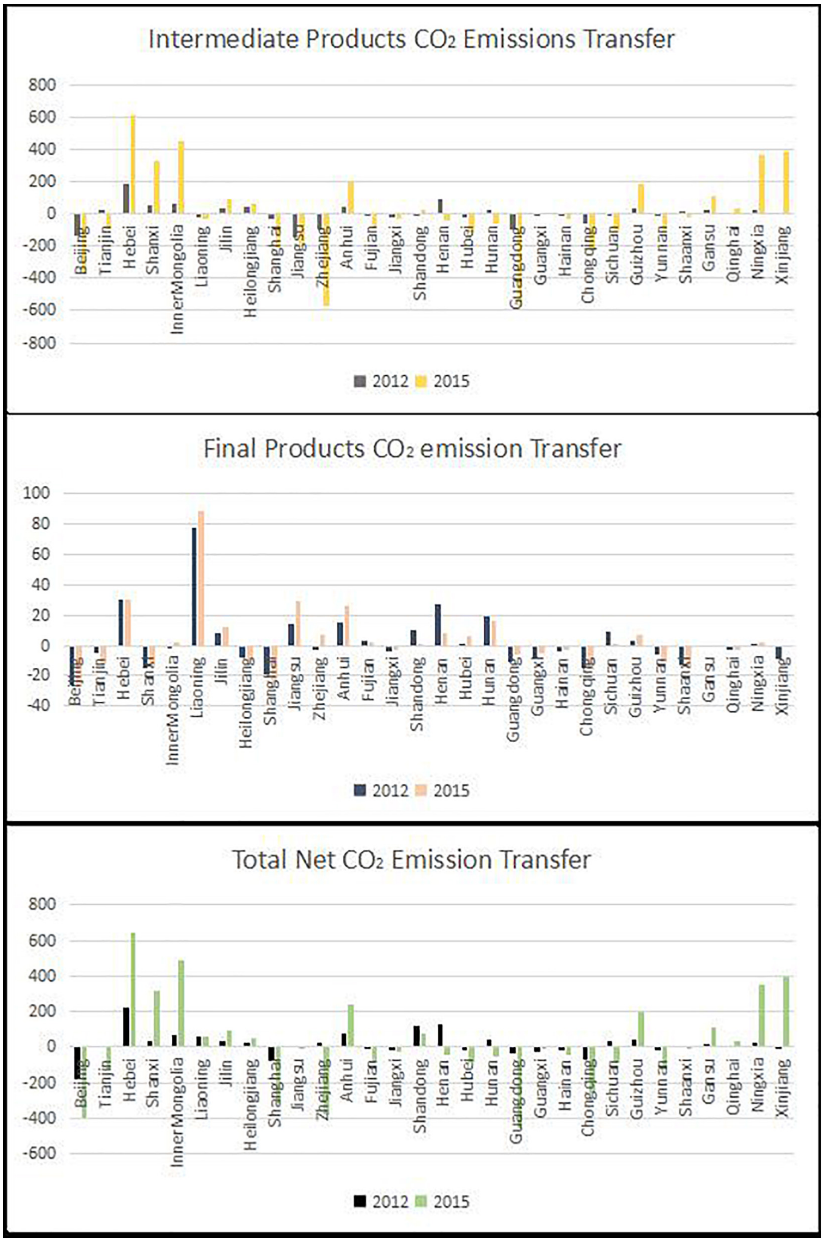

FIGURE 3 | Details of CO_2 transfer in 2012 and 2015.

281.27 million tons, and 167.21 million tons, respectively, in 2015.

In terms of the CO_2 emissions transfer of two types of products, Beijing, Tianjin, Shanghai, Hubei, Fujian, Guangdong, and Chongqing increased much more CO_2 emissions exports by 228.49 million tons, 118.99 million tons, 186.43 million tons, 99.48 million tons, 66.03 million tons, 474.47 million tons, and 177.77, respectively, by consuming intermediate products from other provinces in 2015. Hebei, Shanxi, Inner Mongolia, Anhui, Ningxia, and Xinjiang augmented a lot of importing CO_2 by 430.59 million tons, 280.56 million tons, 386.80 million tons, 155.65 million tons, 345.90 million tons, and 383.72 million tons due to providing much more intermediate products relatively in 2015. In addition, Jiangsu, Zhejiang, Hunan, and Hubei were the same bearing transferred-in CO_2 emissions due to providing final products although they transfer CO_2 emissions out by purchasing intermediate products.

Carbon Transfer Between Provinces

The details of multi-regional CO_2 emissions transfer in 2015 for analyzing transferring properties between provinces are calculated and shown in **Table 2**. It must be noticed that the row data express the transferring volume of CO_2 by consuming intermediate and final products provided by other provinces. For

TABLE 2 | Details of multi-regional CO_2 emissions transfer for consuming intermediate and final products.

	Beijing	Tianjin	Hebei	Shanxi	Inner Mongolia	Liaoning	Jilin	Heilongjiang	Shanghai	Jiangsu	Zhejiang	Anhui	Fujian	Jiangxi	Shandong
Beijing		4.67	59.82	19.61	34.99	11.32	11.19	9.06	8.00	46.98	11.06	41.88	2.34	6.47	23.64
Tianjin	1.61		20.92	5.74	9.00	4.98	7.11	6.35	2.50	17.21	4.48	16.82	0.65	2.09	7.13
Hebei	1.91	2.00		26.33	23.82	6.62	6.42	7.44	6.74	18.97	4.47	17.59	0.67	3.45	11.55
Shanxi	0.46	1.21	19.27		9.08	2.56	7.29	2.63	2.94	16.90	2.69	17.92	0.70	1.81	8.76
Inner Mongolia	0.72	1.16	15.51	5.72		5.12	4.52	5.16	2.64	16.33	4.71	14.98	1.21	1.60	8.89
Liaoning	0.64	1.64	22.80	8.74	15.32		14.51	8.09	4.52	25.29	5.69	24.92	1.29	2.86	10.22
Jilin	1.02	1.18	11.27	12.98	10.23	5.46		2.58	3.89	9.49	4.86	9.79	1.12	1.25	6.47
Heilongjiang	0.53	0.87	14.69	6.90	10.04	5.85	16.48		2.53	11.37	4.21	13.30	0.76	2.36	7.17
Shanghai	1.06	2.79	36.06	22.56	26.97	11.32	12.11	11.74		43.59	19.15	50.64	2.97	6.02	21.28
Jiangsu	1.30	4.90	103.42	63.35	84.01	14.11	19.76	16.20	12.47		16.58	106.91	2.59	18.27	33.67
Zhejiang	1.74	4.00	89.46	40.86	60.27	18.77	19.19	14.78	19.49	68.38		90.44	3.37	21.56	31.13
Anhui	2.23	3.72	82.60	39.00	47.81	19.74	8.68	16.36	20.51	54.63	21.59		3.08	15.21	36.20
Fujian	0.15	0.70	10.69	4.21	7.41	1.90	5.71	2.93	2.82	12.96	3.06	15.58		2.24	4.64
Jiangxi	0.84	0.94	15.91	17.02	16.41	2.59	4.54	5.14	3.69	12.74	5.43	21.27	1.24		4.23
Shandong	1.34	2.07	43.16	27.06	33.89	7.69	8.82	23.69	6.23	10.19	4.34	22.00	0.98	3.39	
Henan	1.91	3.16	74.57	19.46	36.96	15.56	12.42	14.01	15.47	44.14	19.44	58.30	1.60	8.96	38.17
Hubei	1.02	1.40	13.98	26.25	22.99	2.90	4.93	6.42	2.70	7.22	5.55	17.33	1.32	2.02	5.08
Hunan	0.41	1.01	20.29	17.09	17.63	4.36	4.25	3.51	3.71	12.16	5.60	18.90	1.15	3.67	10.46
Guangdong	2.58	5.20	74.47	44.37	43.89	13.22	18.49	14.67	17.36	79.36	15.26	86.07	4.36	12.21	31.86
Guangxi	0.50	0.79	9.27	7.78	6.65	2.65	3.57	2.16	4.59	13.38	4.94	13.40	0.95	1.58	5.71
Hainan	0.09	0.42	5.47	2.05	4.17	0.92	1.68	1.76	1.16	5.92	1.58	7.40	0.44	1.05	2.19
Chongqing	0.87	1.60	33.36	10.07	20.80	5.99	5.59	5.09	5.31	21.19	7.08	29.20	1.84	5.66	11.87
Sichuan	0.35	1.02	17.01	5.27	11.61	2.69	3.98	2.91	3.34	18.17	2.89	19.35	0.87	2.98	5.47
Guizhou	0.39	0.81	12.04	3.25	6.10	2.64	2.45	2.01	3.38	11.81	3.60	12.50	0.88	1.82	6.57
Yunnan	0.38	0.84	13.57	3.33	5.33	2.76	3.90	2.27	3.51	24.20	6.74	21.64	1.80	2.78	8.33
Shaanxi	0.86	1.75	22.89	7.69	15.41	3.94	4.95	3.93	5.18	26.35	8.12	27.74	1.87	3.39	10.48
Gansu	0.23	0.75	8.52	3.11	10.28	1.35	3.52	1.51	1.82	10.04	2.55	11.02	0.70	1.30	5.08
Qinghai	0.10	0.14	1.27	2.07	1.46	0.35	0.60	0.48	0.45	1.69	0.79	1.86	0.17	0.20	0.92
Ningxia	0.09	0.23	4.49	3.85	5.65	0.69	1.97	1.48	0.57	2.56	0.76	3.97	0.20	0.47	1.60
Xinjiang	0.42	0.44	9.88	1.49	6.61	1.94	1.93	1.81	2.52	8.43	4.07	7.37	0.50	1.08	5.06

	Henan	Hubei	Hunan	Guangdong	Guangxi	Hainan	Chongqing	Sichuan	Guizhou	Yunnan	Shaanxi	Gansu	Qinghai	Ningxia	Xinjiang
Beijing	28.39	4.26	6.38	8.55	5.20	1.08	1.85	2.26	10.48	2.57	7.51	9.23	1.84	20.52	20.33
Tianjin	13.61	2.35	3.02	2.43	2.12	0.58	0.88	1.29	5.16	1.04	2.63	3.46	0.53	4.89	10.12
Hebei	13.99	2.78	3.69	2.64	2.43	0.82	1.29	1.57	7.87	1.42	6.32	6.84	1.97	14.53	15.08
Shanxi	12.69	1.99	3.23	2.85	2.20	0.14	1.24	1.07	3.89	0.52	2.81	2.30	0.65	7.09	3.96
Inner Mongolia	8.47	1.38	2.93	3.19	1.88	0.63	0.99	0.98	4.12	0.82	3.57	5.07	0.27	14.28	10.66
Liaoning	13.83	2.27	3.59	4.33	2.82	0.30	1.36	1.39	5.61	0.84	3.97	3.22	0.94	9.18	9.50
Jilin	5.19	0.63	1.41	2.18	0.80	0.30	0.73	0.43	2.45	0.72	2.59	2.52	0.41	8.99	4.15
Heilongjiang	8.70	1.21	3.12	2.36	1.97	0.39	0.68	0.76	5.57	0.77	3.00	3.53	0.66	8.94	8.04
Shanghai	24.36	4.64	7.79	9.11	4.55	1.18	3.09	3.07	11.05	2.33	9.78	8.53	1.59	22.62	26.53
Jiangsu	63.37	8.74	14.81	11.75	15.11	1.50	3.35	4.79	34.03	4.69	24.36	23.24	7.53	54.73	43.36
Zhejiang	65.40	11.26	16.94	11.14	12.94	1.68	3.55	2.65	27.02	4.43	17.66	23.86	8.77	38.74	37.03
Anhui	36.14	7.16	11.36	9.45	9.34	2.87	3.11	2.92	18.70	4.67	16.09	19.45	4.75	26.08	31.84
Fujian	7.53	1.41	3.19	2.16	2.11	0.19	1.03	1.17	5.37	0.89	1.97	2.44	0.71	5.22	5.77
Jiangxi	7.84	1.31	2.73	2.96	2.30	0.59	1.02	1.20	7.90	1.28	4.33	2.89	0.43	8.95	12.55

(Continued)

TABLE 2 | Continued

	Henan	Hubei	Hunan	Guangdong	Guangxi	Hainan	Chongqing	Sichuan	Guizhou	Yunnan	Shaanxi	Gansu	Qinghai	Ningxia	Xinjiang
Shandong	9.06	0.48	4.80	3.20	5.92	2.69	2.28	1.30	14.01	2.29	14.30	11.47	1.79	9.18	57.62
Henan		4.67	12.16	9.34	8.35	2.49	3.34	3.30	15.29	3.40	16.60	16.07	2.43	25.65	24.35
Hubei	8.31		2.63	3.39	2.61	0.59	1.18	1.44	10.82	1.72	6.37	4.90	0.85	15.80	17.70
Hunan	13.01	2.42		5.21	3.60	0.85	1.24	1.78	10.96	1.19	6.52	5.56	1.15	16.78	8.67
Guangdong	38.89	9.97	17.32		17.16	3.22	6.02	4.93	38.33	4.27	17.32	16.98	3.58	38.54	32.11
Guangxi	5.88	1.43	3.13	5.03		0.75	1.89	1.21	7.67	0.92	2.82	2.17	0.42	6.67	4.51
Hainan	4.28	0.76	2.00	2.49	2.30		0.49	0.52	3.67	0.56	1.63	1.34	0.45	2.17	5.02
Chongqing	23.07	3.49	7.70	6.95	6.37	0.85		3.99	17.39	3.34	7.00	11.65	3.31	19.44	19.48
Sichuan	10.16	1.56	4.13	3.52	3.15	0.40	1.61		6.88	1.25	3.37	4.68	1.40	8.05	8.09
Guizhou	6.97	1.54	2.96	3.90	2.72	0.57	1.38	1.31		1.08	2.48	3.05	0.67	6.21	4.51
Yunnan	13.24	2.78	4.54	6.85	3.84	0.69	1.75	2.28	10.25		3.41	3.54	0.81	9.26	6.36
Shaanxi	18.01	2.87	5.35	5.43	3.13	0.49	2.18	2.35	7.43	1.89		5.44	1.28	10.75	16.20
Gansu	7.97	1.11	2.08	2.54	1.40	0.21	0.81	1.45	3.26	0.56	2.43		1.82	5.07	8.00
Qinghai	0.93	0.18	0.32	0.71	0.35	0.08	0.20	0.44	0.91	0.16	0.52	0.92		2.12	1.30
Ningxia	3.94	0.46	0.70	0.63	0.62	0.07	0.24	0.39	1.54	0.14	1.95	0.97	0.66		9.93
Xinjiang	6.86	0.92	1.65	2.08	1.02	0.27	0.66	1.27	1.90	0.46	2.10	2.29	1.18	3.10	

The numbers in this table indicate the net CO_2 exportation among provinces. Moreover, the numbers indicate the CO_2 transfer from the region in the first row to the region in the first column. The elements in the diagonal are empty for this table focusing on the regional carbon transfer.

example, the data located at the second line and third column indicated that Beijing transfers CO_2 to Tianjin by using Tianjin's intermediate and final products.

As mentioned previously, the quantity of CO_2 transfer of the six pilot places had increased a lot in 2015 compared to the volume in 2012. Guangdong was the biggest CO_2 exporter in 2015, and it mainly transferred to Jiangsu (79.36 million tons), Anhui (86.07 million tons), Hebei (74.47 million tons), Henan (38.89 million tons), and Ningxia (38.54 million tons) which indicated that Guangdong used these regions' products as primary sources. Followed Guangdong, Beijing was the second CO_2 exporter who mainly transferred to Inner Mongolia (34.99 million tons), Hebei (59.82 million tons), Jiangsu (46.98 million tons), and Anhui (41.88 million tons). Overview, we can figure out that embodied CO_2 emissions continued to flow to nearby provinces and Northern, central and northwest provinces of China which were also poorly-developed in economics according to **Table 2**. Interestingly, Jiangsu, a developed province whose GDP ranked second place after Guangdong in 2015, accepted embodied CO_2 emissions from pilot regions as a primary recipient. It is believed that Jiangsu created increment mainly through manufacturing.

DISCUSSION

The present study was designed to determine the effect of ETS implementation on multi-regional carbon footprint in China. The MRIO analysis results showed that the six early pilot provinces enhanced their CO_2 emissions exports from 372.48 million tons in 2012 to 1631.63 million tons in 2015 after ETS policy implementation.

From the standpoint of direct carbon emissions, the reduction potential of pilot regions was limited. However, the results showed that the carbon emission intensity of pilot regions remained low even a bit lower, which may be explained by the development of tertiary industry and allow them to create more value with less energy consumption. This encouraging result indicates that both to develop and to reduce emission and it had better further consider improving the combustion efficiency.

In terms of emission responsibility, the summarizing carbon footprint of the production of six pilot regions declined by 4.15% from 2012 to 2015, while the six pilot regions' summarizing carbon footprint of consumption increased about 3.39% from 2012 to 2015. From a life cycle perspective, the upstream material consumption in these pilot regions was becoming higher than other regions from 2012 to 2015, for this kind of material required more fossil fuel. Despite the demand within the province boundary, some regions can only develop through undertake high energy consumption industries. For example, Ningxia, Xinjiang, Guizhou, Anhui, and Gansu had much higher carbon intensity in 2015 which indicated that they were producing on low combustion efficiency. These regions were underdeveloped but full of natural resources and inevitably resulted in more carbon emissions in development.

Although some pilot regions decreased their direct carbon emission and carbon emission intensity, the carbon leakage should take into consideration in defining CO_2 emissions responsibilities, especially the influences on central and western regions of China. According to the calculation above, the pilot regions created much more carbon emission exports comparing to the number of carbon exports in 2012. Conversely, during that period, some provinces endured heavy CO_2 emissions imports. In response to environmental regulations, the pilot regions tended to eliminate backward production and purchased high energy consumption products depending on imports from other regions, which could lead to carbon leakage.

The immense quantity of carbon leakage in China makes it necessary to balance the economy and environment between regions. Thus, laws and regulations should be further improved to regularize actual carbon emissions. Moreover, introducing innovation factors into the western regions with the aid of "China's Western Development Strategy" could improving these backward regions' green economic efficiency encouragingly (Yang et al., 2018).

CONCLUSION

Growing concerns about the impact of greenhouse gas emissions due to rising population and energy demand are leading to the adoption of comprehensive package policies. The CO_2 ETS can play a significant role in reducing CO_2 emissions and the policy's spillover effect should be concerned as well. Therefore, a China-MRIO model was conducted to estimate the spillover effect of ETS implementation in China from 2012 to 2015. In this study, we could demonstrate that the adoption of ETS in six pilot provinces has had a huge positive environmental impact on themselves but negative impacts on the rest of China.

In this paper, the CO_2 emissions on production based and consumption based of 30 provinces were calculated, respectively, by using 2012 MRIO table and 2015 MRIO table. And then the CO_2 transfer among provinces in 2012 and 2015 was computed to capture the spillover effect. The direct CO_2 emissions of pilot regions like Beijing, Tianjin, Shanghai, and Chongqing were reduced, while Guangdong and Hubei which were members of pilot regions increased their direct carbon emissions. Hebei, Shanxi, Inner Mongolia, Ningxia, and Xinjiang increased a mass of transferred-in CO_2 emissions mainly by providing intermediate products, which indicated that ETS pilot regions had transferred a great amount of embodied CO_2 emissions to underdeveloped areas by cutting down intermediate products production and enhancing intermediate products trading. These phenomena also happened in final products trading.

The high emission intensities of central and western China's regions are the first reason for their high carbon emissions for input-output processes. The development of the east and the west is still unbalanced. There should be great variation in resources endowment, economic size, environmental capacity and industrial structure. The low carbon reduction policy is needed to be developed according to the local conditions. The eastern regions of China possess advanced technologies, human talents and intellectual resources, which must place priority on strategic high-tech industries. The rest regions of China need to take due development of forward-looking strategic industries with technology and assistance from the eastern regions of China under Environmental strict constraints.

Moreover, it is necessary to consider building a sound carbon emission credits allocation system based on multi-regional net CO_2 transfer. The embodied carbon transfer among regions results from regional division. With the deepening of regional division, cooperation and commerce, the consumption side should share responsibility with the production side with the support of clearing up carbon transfer direction.

According to the results shown above, China's ETS policy is facing challenges to CO_2 emissions management in multi-regions. The ETS policy is considered as an effective tool to reach the 2030 carbon-neutral vision under the strength of market regulation. However, the 30 provinces of China offer a wide variety of economics and development stages. To guarantee economic growth, underdeveloped areas are likely to undertake more industrial manufacture with much more carbon emissions. Therefore, when allocating carbon allowance, policymakers should not only consider the direct carbon emissions but also be aware of embodied CO_2 emissions that happened in product trading, especially intermediate product trading. Thus, it is helpful to reduce employing intermediate products that require high consumption of energy of downstream companies and promoting efficiency in the production process.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: CEADs, https://www.ceads.net.cn/.

AUTHOR CONTRIBUTIONS

XL, CW, LL, HW conception and design of study, analysis and/or interpretation of data, drafting the manuscript, and approval of the version of the manuscript to be published. XL and LL acquisition of data. XL and CW revising the manuscript critically for important intellectual content. All authors contributed to the article and approved the submitted version.

FUNDING

This work was partially supported by the Key Program of the National Social Science Foundation of China (20&ZD117), the National Natural Science Foundation of China (71771057, 72003044, and 72003045), National Social Science Foundation of China (20FGLB072), Guangdong Social Science Project (GD20SQ15 and GD2018CYJ01), Guangdong Natural Science Foundation (2021A1515011960 and 2020A1515010863), Guangzhou Social Science Project (2020GZQN39 and 2020GZGJ120), and the Foundation for Guangdong Province Universities and Colleges Pearl River Scholar Funded Scheme (GDUPS2019).

REFERENCES

Aichele, R., and Felbermayr, G. (2015). Kyoto and carbon leakage: an empirical analysis of the carbon content of bilateral trade. *Rev. Econ. Stat.* 97, 104–115.

Barragán-Beaud, C., Pizarro-Alonso, A., Xylia, M., Syri, S., and Silveira, S. (2018). Carbon tax or emissions trading? An analysis of economic and political feasibility of policy mechanisms for greenhouse gas emissions reduction in the Mexican power sector. *Energy Policy* 122, 287–299. doi: 10.1016/j.enpol.2018.07.010

BP (2020). *Statistical Review of World Energy*. Available online at: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (accessed August 28, 2020).

CEADs. (2012). *Emission Inventories for 30 Provinces*. Available online at: https://www.ceads.net/data/province/by_sectoral_accounting/Provincial?#278 (accessed October 10, 2020).

CEADs. (2015). *Emission Inventories for 30 Provinces*. Available online at: https://www.ceads.net/data/province/by_sectoral_accounting/Provincial?#281

Daskalakis, G., Psychoyios, D., and Markellos, R. N. (2009). Modeling CO2 emission allowance prices and derivatives: evidence from the European trading scheme. *J. Banking Finance* 33, 1230–1241. doi: 10.1016/j.jbankfin.2009.01.001

Davis, S. J., and Caldeira, K. (2010). Consumption-based accounting of CO2 emissions. *Proc. Natl. Acad. Sci. U.S.A.* 107, 5687–5692.

Hua, G., Cheng, T. C. E., and Wang, S. (2011). Managing carbon footprints in inventory management. *Int. J. Prod. Econ.* 132, 178–185. doi: 10.1016/j.ijpe.2011.03.024

IPCC (2014). *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*. Geneva: IPCC, 9–21.

Koch, N., Fuss, S., Grosjean, G., and Edenhofer, O. (2014). Causes of the EU ETS price drop: recession, CDM, renewable policies or a bit of everything?—New evidence. *Energy Policy* 73, 676–685. doi: 10.1016/j.enpol.2014.06.024

Kulionis, V., and Wood, R. (2020). Explaining decoupling in high income countries: a structural decomposition analysis of the change in energy footprint from 1970 to 2009. *Energy* 194:116909. doi: 10.1016/j.energy.2020.116909

Leontief, W. (1970). Environmental repercussions and the economic structure: an input-output approach. *Rev. Econ. Stat.* 52, 262–271. doi: 10.2307/1926294

Liang, Q. M., Fan, Y., and Wei, Y. M. (2007). Multi-regional input–output model for regional energy requirements and CO2 emissions in China. *Energy Policy* 35, 1685–1700. doi: 10.1016/j.enpol.2006.04.018

Liu, Y., Lv, Y., and Zhou, M. (2015). Analysis on the influence factors of computing CO2 emission by input-output method. *China Popul. Resour. Environ.* 25, 21–28.

Liu, Y., Meng, B., Hubacek, K., Xue, J., Feng, K., and Gao, Y. (2016). 'Made in China': a reevaluation of embodied CO2 emissions in Chinese exports using firm heterogeneity information. *Appl. Energy* 184, 1106–1113. doi: 10.1016/j.apenergy.2016.06.088

Liu, Z., Guan, D., Wei, W., Davis, S. J., Ciais, P., Bai, J., et al. (2015). Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* 524, 335–338. doi: 10.1038/nature14677

Meng, B., Xue, J., Feng, K., Dabo, G., and Xue, F. (2013). China's inter-regional spillover of carbon emissions and domestic supply chains. *Energy Policy* 61, 1305–1321. doi: 10.1016/j.enpol.2013.05.108

Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y. M., et al. (2017). Chinese CO 2 emission flows have reversed since the global financial crisis. *Nat. Commun.* 8:1712.

Mi, Z., Meng, J., Zheng, H., Yuli, S., Wei, Y. M., and Guan, D. (2018). A multi-regional input-output table mapping China's economic outputs and interdependencies in 2012. *Sci. Data* 5:180155.

Otaki, M. (2013). Emission trading or proportional carbon tax: a quest for more efficacious emission control. *Environ. Syst. Res.* 2, 1–6.

Peters, G. P., and Hertwich, E. G. (2008b). CO2 embodied in international trade with implications for global climate policy. *Environ. Sci. Technol.* 42, 1401–1407. doi: 10.1021/es072023k

Peters, G. P., and Hertwich, E. G. (2008a). Post-Kyoto greenhouse gas inventories: production versus consumption. *Climatic Change* 86, 51–66. doi: 10.1007/s10584-007-9280-1

Shan, Y., Guan, D., Zheng, H., Ou, J., Li, Y., Meng, J., et al. (2018). China CO 2 emission accounts 1997–2015. *Sci. Data* 5, 1–14.

Su, B., and Ang, B. W. (2013). Input–output analysis of CO2 emissions embodied in trade: competitive versus non-competitive imports. *Energy Policy* 56, 83–87. doi: 10.1016/j.enpol.2013.01.041

Wang, A., Feng, Z., and Meng, B. (2017). Measure of carbon emissions and carbon transfers in 30 provinces of China. *J. Q. Tech. Econ.* 8, 89–104.

Wiedmann, T., Wilting, H. C., Lenzen, M., Lutter, S., and Palm, V. (2011). Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input–output analysis. *Ecol. Econ.* 70, 1937–1945. doi: 10.1016/j.ecolecon.2011.06.014

Wu, R., Dai, H., Geng, Y., Xie, Y., Masui, T., and Tian, X. (2016). Achieving China's INDC through carbon cap-and-trade: insights from Shanghai. *Appl. Energy* 184, 1114–1122. doi: 10.1016/j.apenergy.2016.06.011

Yang, F., Yang, M., Xue, B., and Luo, Q. (2018). The effects of China's western development strategy implementation on local ecological economic performance. *J. Clean. Prod.* 202, 925–933. doi: 10.1016/J.JCLEPRO.2018.08.203

Zhang, L., Li, Y., and Jia, Z. (2018). Impact of carbon allowance allocation on power industry in China's carbon trading market: computable general equilibrium based analysis. *Appl. Energy* 229, 814–827. doi: 10.1016/j.apenergy.2018.08.055

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

POLICY AND PRACTICE REVIEWS
published: 06 July 2021
doi: 10.3389/fenrg.2021.707492

De-Coalizing Rural China: A Critical Examination of the Coal to Clean Heating Project from a Policy Process Perspective

Zhanping Hu *

School of Humanities and Social Sciences, North China Electric Power University, Beijing, China

This article critically examines the Coal to Clean Heating Project (CCHP) implemented in rural northern China from a policy process perspective. On the one hand, CCHP is an effective environmental policy that has reduced a large quantity of low quality bulk coal; on the other hand, however, it has created mounting socio-economic and political challenges, pushing the well-intended project into a deep dilemma. Moreover, existent discussions tend to attribute the dilemma to the "inappropriate implementation" of street-level bureaucrats. Through the lens of policy process, this article identifies key features of five critical temporal stages of CCHP: agenda setting, policy formulation, policy implementation, policy evaluation and policy adjustment. It illustrates that the policy process of CCHP has followed a politics-administration-dominated approach characterized by both positive attributes such as rapid resource mobilization and efficient implementation, and negative factors such as deficient policy design, overuse of mandatory instruments, and neglect of social acceptance. The major challenges that CCHP currently faces are identified, and policy implications are proposed based on the insights drawn from the policy process perspective. It concludes by highlighting the complexity of energy transition and the strength of linking energy transition research with a policy process perspective.

Keywords: clean heating, double substitution, coal-to-gas project, coal-to-electricity project, policy process

OPEN ACCESS

Edited by:
Henry Wang,
University of Missouri, United States

Reviewed by:
Aiyuan Tao,
Shanghai Lixin University of Accounting and Finance, China
Ying Chen,
Guangxi University of Finance and Economics, China

Correspondence:
Zhanping Hu
huzhanping2006@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies,
a section of the journal Frontiers in Energy Research

Received: *10 May 2021*
Accepted: *11 June 2021*
Published: *06 July 2021*

Citation:
Hu Z (2021) De-Coalizing Rural China: A Critical Examination of the Coal to Clean Heating Project from a Policy Process Perspective.
Front. Energy Res. 9:707492.
doi: 10.3389/fenrg.2021.707492

INTRODUCTION

The long-standing coal-dominated energy structure has made China the largest coal consumer in the world (Wang and Li, 2016), and also a prominent contributor to the severe air pollution in contemporary China (Ma et al., 2017; Xie et al., 2020). Among multiple patterns of coal usage, civil bulk coal, a type of low quality and unprocessed raw coal, consumed by rural households, was found to be particularly harmful to air quality in northern China (Liu et al., 2016; Zhang et al., 2017; Xie et al., 2020). To tackle the air quality crisis, China initiated an ambitious and arguably the toughest-ever action plan, Air Pollution Prevention and Control Action Plan, in 2013. One critical section of

Abbreviations: BTH, Beijing-Tianjin-Hebei region; CAE, Chinese academy of engineering; CCHP, coal to clean heating project; CTG, coal-to-gas; CTE, coal-to-electricity; MEE, ministry of ecology and environment; MF, ministry of finance; MHURD, ministry of housing and urban-rural development; NEA, national energy administration; NDRC, national development and reform commission; $PM_{2.5}$, particulate matter with an aerodynamic diameter of less than 2.5 microns.

the 2013 Action Plan is CCHP, a state-sponsored energy project aiming to radically transform the coal-dominated heating energy structure to cleaner energies (e.g., natural gas, electricity, centralized heating systems, as well as renewables such as solar) in northern rural China.

Since its first appearance in the 2013 Action Plan, CCHP has been implemented, sporadically at the beginning but intensively since 2017, for eight years in China so far. As of 2020, more than twenty five million rural households have been taken into the mega project (MEE, 2020a). 43 municipal cities from BTH and other key regions of air pollution have been selected as pilot sites for CCHP. The progress appears exceptionally remarkable. As a de facto environmental policy, CCHP has contributed significantly to air quality improvement (Zhang et al., 2019a; Zhang et al., 2020). Li Ganjie, the former Minister of MEE, claimed that the CCHP contributed approximately one third to the improvement of air quality in northern China (Li, 2018). However, despite the encouraging environmental effects, grave challenges have been exposed in recent years, including insufficient and unstable energy supply, unbearable energy costs, and brutal behaviors of street-level bureaucrats in implementation, which have been dragging this mega project into a deep dilemma and uncertainty. Numerous comments and reports from social media and governmental systems regarding the current situation of CCHP center on the dimension of implementation, taking the misbehaviors of local implementers as the major reason for the dilemma (An, 2017; Chu, 2018; Zhao, 2021).

The brutal and "one-size-fits-all" behaviors of street-level bureaucrats surely should be criticized, while overemphasis on it would obscure the flaws of the entire policy system. The persistent exposure of social dissatisfaction and mounting queries about the design of the project since 2017 have pointed to more complicated problems beyond the misbehaviors of local officials. Academic literature has not attended to this issue systematically, although researchers have started to evaluate the effectiveness of the project based on specific locations with different evaluation parameters (Wang et al., 2019a; Barrington-Leigh et al., 2019; Zhang et al., 2019b; Gong et al., 2020; Hu, 2020; Wu et al., 2020; Yan et al., 2020).

Furthermore, energy transition studies in general have mostly focused on specific policy stages or policy output through policy content analysis, and regrettably neglected the critical implication of long-lasting, politically contested policy process (Kern and Rogge, 2018). An explicit consideration of policy process is particularly instrumental to understanding the impacting factors of policy instruments and innovations, the causal link between policy-making and policy implementation, as well as to develop well informed policy recommendations (Grossman, 2015; Thomas, 2016; Kern and Rogge, 2018).

Given that gap, this article, from the lens of policy process, critically examines the evolutionary process of CCHP, and identifies defining features of five critical sub-stages: agenda setting, policy formulation, policy implementation, policy evaluation and policy adjustment. The lens of policy process allows us to challenge the prevailing discussions that attribute the current dilemma to the poor implementation of local bureaucrats. Instead, this study contends that the whole project was built on a poorly articulated and integrated policy framework, and without thorough reflection and adjustment of the whole policy process, the likelihood of achieving successful transition by CCHP remains grossly challenging.

The data utilized in this article stem from three sources. The first source is the policy documents associated with CCHP at different levels of administrations, which can provide valuable information about the policy design and adjustments. For data collection, policy documents from national-level administrations were collected through searching major governmental websites, covering the State Council, MEE, NEA, and NDRC, among others. For local governments, given the vast diversity, Beijing Municipality and Hebei Province, two typical regions for CCHP, were selected as representatives to collect local policy documents. More than fifty policy documents from various administrations associated with CCHP ranging from 2013 to 2020 were collected.

The second source is reports and commentaries from social media, which can provide valuable information about the social feedback and interactions between government and the society during the rollout of CCHP. For official media sources, People's Daily, Xinhua Net, China Energy News, and China Environment News, among others, were consulted; for independent media, Caixin, Beijing News, and Southern Weekly, among others, were consulted. In addition, since 2017 the author has intentionally accumulated news and reports associated with the issue from multiple sources, including social network apps, such as Weibo and Wechat. After phasing out repetitive contents, over one hundred of original reports and commentaries were collected. The third source is peer-reviewed papers and academic reports. The author searched both international and domestic academic databases to acquire a complete literature of CCHP. For international literature, two major databases were searched: Web of Science and Scopus, with key words associated with CCHP, i.e., "coal to gas", "coal to electricity", "coal substitution", "double substitution", "bulk coal control", "clean heating", and "China", ranging from 2013 to 2020. Searching results show that over two hundred articles focus on the technological aspects of heating devices, and only about thirty peer-reviewed English papers that study the policy aspects of CCHP. For domestic literature, the author searched the largest database, China National Knowledge Infrastructure (CNKI), ranging from 2013 to 2020, and acquired more than thirty peer-reviewed papers associated with CCHP. This set of data is also supplemented by a dozen of survey reports published by university researchers and independent NGOs. The author believes these three sets of data are sufficient enough to evaluate the CCHP project in an overall sense. Nonetheless, limitations deserve to be mentioned. CCHP has been implemented in highly heterogeneous contexts across nearly ten provincial level regions and tens of prefecture-level cities. Therefore, local variations, particularly in the stage of policy implementation, must to a varying degree exist, which however are not discussed in this paper.

The article is organized as follows. *Historical Background and Practical Progress of Coal to Clean Heating Project* briefly introduces the overall background and progress of CCHP. *The Policy Process of Coal to Clean Heating Project* provides an

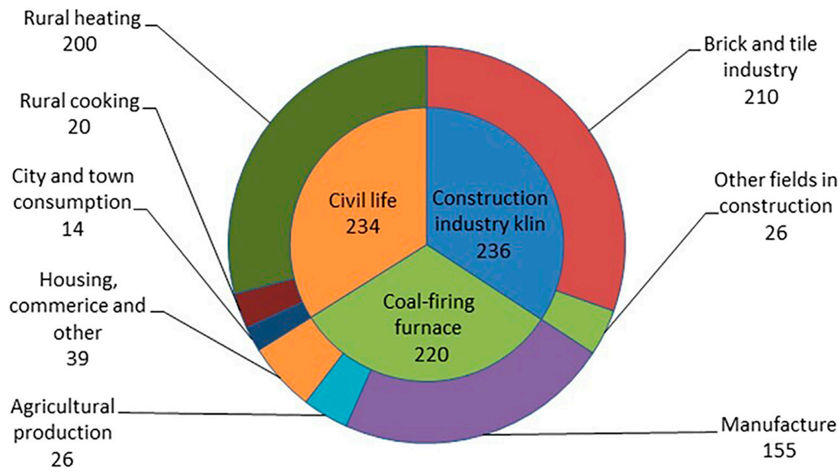

FIGURE 1 | Major sources and constituent structure of Chinese bulk coal (Unit: Million Tonnes). Data Source: Adapted From (He and Li, 2017).

analysis of CCHP from the policy process perspective, according to the five policy stages. Based on the analysis, *Policy Implications: Insights From the Policy Process Perspective* proposes relevant policy implications drawn from the insights of the policy process perspective. *Conclusion* concludes the article with an emphasis of the complexity of energy transitions and a call for linking energy transition research with a policy process perspective.

HISTORICAL BACKGROUND AND PRACTICAL PROGRESS OF COAL TO CLEAN HEATING PROJECT

The Historical Background of Coal to Clean Heating Project

CCHP is derived from the deterioration of air quality in the BTH region since the beginning of the 2010s, when heavy smog provoked mounting and fierce public discontent (Wang, 2013; Aunan et al., 2018). Identifying the causes of and solutions to the heavy air pollution has become the most popular research subject since the severe smog events in 2013 (Wang, 2013; Xu et al., 2013). Among various findings, coal was universally identified as one of the primary causes for the increased level of $PM_{2.5}$—one of the major constituents of smog in northern China (MEE, 2019). Furthermore, among different patterns of coal consumption, bulk coal consumed in winter heating by rural households was found as one direct reason for heavy smog during winter season (MEE, 2019). As estimated, the quantity of civil bulk coal in rural regions amounted to 220 million tonnes in 2015, taking up 94% of national civil bulk coal consumption (He and Li, 2017) (see **Figure 1**). Of the bulk coal consumption for rural civil life, over 90% is used for residential heating. Moreover, rural heating bulk coal was found to contribute 30–50% of $PM_{2.5}$ concentration in northern China during autumn-winter season (Wang Z et al., 2019b).

To improve air quality, bulk coal for rural heating must be reduced significantly (He and Li, 2017). Since 2013, particularly from 2017, an array of national initiatives and policies have been launched to direct, guide, and regulate the implementation of CCHP in northern China, particularly in the BTH and surrounding regions, including Shanxi, Henan and Shaanxi provinces. Correspondingly, multilevel regional and local governments issued numerous regional plans and concrete measures to execute the grand project. In terms of national-level polices, as **Table 1** shows, a comprehensive policy package has been enacted by national-level administrations, including general national plans, sectoral plans from MEE and NEA, *ad hoc* working schemes, and supportive policies. Local governments at different levels were requested to issue corresponding plans and polices. As a result, within a short timeframe, a comprehensive and systematic policy package has been established to promote CCHP (as illustrated by **Figure 2**).

The Progress of Coal to Clean Heating Project in Practice

In practice, it was only until 2017 that CCHP started to be promoted by local governments in an intensive manner. Between 2013 and 2016, most local governments from northern China focused on policy measures such as transportation regulations and coal reduction and replacement in industrial sectors. Only a limited number of cities took efforts to conduct CCHP during this period. Due to its special political position and severity of air pollution, Beijing Municipality pioneered in bringing CCHP into practice. In 2013, Beijing initiated a special action plan in its rural area: “Reduce Coal to Exchange Clean Air”, of which CTE project was an important constituent part. From 2015, Beijing and a few cities from Hebei Province (such as Shijiazhuang and Xingtai) started to initiate CTG pilot projects. Nonetheless, the implementation of CCHP was largely conducted in a sporadic and tentative manner before 2017.

As the assessment year of the 2013 Action Plan, 2017 was a critical time for CCHP. Local governments faced tremendous

TABLE 1 | Summary of major national level policy documents regarding CCHP.

Time	Policy title	Contents regarding CCHP
2013	Air pollution prevention and control action plan.	Enhance the provision of clean energies and control coal consumption. By 2015, build new gas pipes able to convey 150 billion m^3. Promote gas substitution of coal in residential sector. Enhance the energy efficiency of residential properties in Northern China By 2017, the inhalable particulates of BTH and surrounding areas should reduce 25% compared to 2012.
2014	Temporary measures of coal consumption reduction and substitution management in the key regions.	By 2017, Beijing should reduce 12 million tonnes of coal consumption based on the quantity of 2012, Tianjin 10 million, Hebei province 40 million, Shandong province 20 million. The governments of the key regions should formulate concrete coal reduction and substitution action schemes, which should include CCHP. 'Plan firstly, develop secondly', orderly promote 'coal-to-gas' and 'coal-to-electricity' programs.
2016	'Thirteenth five year plan' of energy-saving and emission-reduction comprehensive working scheme.	Transform energy structure, and promote clean energies. Reduce bulk coal usage and promoting coal-to-gas and coal-to-electricity substitution in residential heating.
2016	'Thirteenth five year plan' of ecological and environmental protection.	By 2020, coal consumption is reduced to 58% of overall energy consumption. Promote substitution of bulk coal in northern China, and implement 'coal-to-gas' and 'coal-to-gas' projects in BTH and surround areas.
2016	'Thirteenth five year plan' of energy development.	Take comprehensive measures to reduce bulk coal usage. Promote gas, electricity, cleaner coals and renewables to replace bulk coal. Reform gas price mechanism to reduce gas cost and promote coal-to-gas substitution. Enforce electricity substitution project.
2016	BTH air pollution and control strengthening measures.	Promote rural CTG and CTE projects in BTH region. By the end of October, 2017, all the plain area of Beijing should be de-coalized.
2017	Report on the work of the central government.	Strengthen the efforts of tackling pollution from fire coal, comprehensively addressing bulk coal. Accomplish three million households of double substitution in 2017.
2017	Working scheme of BTH and surrounding area air pollution prevention for 2017.	Take 2 + 26 cities as the first group of CCHP implementation region. Set Beijing, Tianjin, Baoding and Langfang as 'zero coal' area. By the end of October 2017, every city should finish CCHP covering 50,000–100,000 households.
2017	Action scheme of comprehensive governance of autumn and winter air pollution in BTH and surround area (2017–2018).	Beijing, Tianjing and four provinces should finish coal-substitution for 3.55 million rural families by the October of 2017. Take measures to forbid re-ignition of bulk coal in regions already covered by CCHP.
2017	Winter clean heating plan in Northern China (2017–2021).	By 2019, the clean heating rate of northern China should be over 50%, reducing 70 million ton of bulk coal; by 2021, cleaning heating rate of Northern China should be over 70%, reducing 150 million ton of bulk coal. Local governments should promote differential strategies based on specific endowments, and avoid 'one-size-fits-all' approach.
2017	Instructions of clean heating price policy in Northern China.	Promote differential prices. Price subsidies to rural residents. Tax preferences to enterprises that provide heating services to rural residents.
2017	Notice on selecting pilot cities of CCHP supported by central finance in Northern China.	Select pilot cities for clean heating projects. 2 + 26 corridor cities as the key targets. Provide 3 year long financial support for pilot cities at differential scales: one billion Yuan for province-level municipality; 700 million for provincial capital city; 500 million for prefecture-level city.
2017	Notice on conducting well the work of 'coal-to-electricity' to ensure people a warm winter in Northern China.	Take efforts to make sure rural residents have a warm winter. Stabilize the provision of electricity in the rural areas conducting 'coal-to-electricity' switch.
2018	Document No.1 of the central government: Instructions of enforcing the strategy of rural vitalization.	Accelerate construction and upgrade of rural electric grid. Promote coal-replacing programs in Northern rural China.
2018	Three-year action plan of winning Blue Sky protection campaign.	Effectively promote clean heating in Northern China with case-by-case principle. By the winter season of 2020, the BTH and surrounding areas and the pain areas of Fen-Wei River should finish substitution of coal with clean energies. Encourage to improve energy efficiency of rural houses. Expand financial support for CCHP.
2018	Action scheme of comprehensive governance of autumn and winter air pollution in BTH and surrounding area (2018–2019).	Local governments should make a three-year action plan to accomplish policy goal of zero-coal by 2020 in plain villages. Implementing project based on flexible principle, choosing technological approach based on local concrete situation.

(Continued on following page)

TABLE 1 | (*Continued*) Summary of major national level policy documents regarding CCHP.

Time	Policy title	Contents regarding CCHP
2018	Notice on expanding pilot cities of CCHP supported by central finance.	Bring most of 2 + 26 cities, Zhang Jiakou city, cities from Fenwei plain into the range of pilot city program. Provide RMB 500 million subsidy for Zhang Jiakou city, 300 million for cities from Fenwei plain. After three years, the urban clean heating rate amounts to 100%; civil bulk coal in plain area should be generally replaced.
2019	Report on the work of the government (2019).	Significant achievement on coal-to-gas and coal-to-electricity projects in 2018. Continue working on clean heating in Northern China, and meanwhile guarantee people to have warm winter.
2019	Notice on mid-term evaluation of clean heating in Northern China.	Check the progress of local governments on CCHP from 2016. Summarize the experiences and problems in CCHP implementation.
2019	Action scheme of comprehensive governance of autumn and winter air pollution in BTH and surrounding area (2019–2020).	By the end of October, 2019, 2 + 26 cities should finish double substitution of 5.24 million rural families. Before the heating season of 2019, the first trial cities funded by central finance should accomplish the task of double substitution. Promote double substitution in the unit of county or town, instead of scattered villages. Take various efforts to stop re-burning of coal in areas already substituted. Ensure substituted families receive subsidies timely and sufficiently.
2019	Action scheme of strengthening inspection and conducting designated assistance in the key regions of Blue Sky Protection Campaign.	Strengthen the inspection of the implementation of air quality improvement policies. Evaluate both environmental goals and the working process. Conduct comprehensive check and verification of local working progress regarding coal-to-gas and coal-to electricity heating projects.
2020	Action scheme of comprehensive governance of autumn and winter air pollution in BTH and surrounding area, and Fenwei River plain (2020–2021).	Before the heating season of 2020, 7.09 million rural households should be taken into CCHP. In the areas that have been covered by CCHP, local governments should be designated as zero-coal zone. Coal re-burning is strictly forbidden in these areas. Guarantee the supply of natural gas and electricity for clean heating households. Without a trial season, the coal facilities of rural households should not be removed. Provide price support for heating gas and electricity in winter season. Practice differential subsidy policies, focus on poor households in rural areas.

political and administrative pressure to accomplish the environmental targets set by the Plan. Meanwhile, the central government started to offer financial support to enforce CCHP, which provided strong incentives for local governments to grasp the opportunity to rapidly enforce implementation. Driven by multiple factors, local governments have acted very aggressively from 2017, with the achieved quantities significantly exceeding the planned goals, as shown by **Figure 3**. The four-year rollout has taken over 25,000,000 rural households from northern China into CCHP (He and Li, 2020). By the end of 2020, all the plain villages in Beijing have been covered by CCHP. Hebei Province alone has promoted CCHP to approximately eight million rural households by 2020. Among the multiple technological models, CTE and CTG are the two dominant ones, taking up more than 90% (He and Li, 2020).

Besides, the geographical scope of CCHP targeting area has been expanded rapidly. In 2017, BTH and surrounding areas (i.e., Shandong, Shanxi and Henan provinces) were the key regions, and 28 cities i.e., the 2 + 26 air convey corridor cities, from these regions were set as the key cities of clean heating transition. In 2018, Fen-Wei River Plain Area in western China (including 11 cities from Shanxi Province and Shaanxi Province) was taken into the list. Moreover, the central government selected cities for policy experimentation, and the number of pilot cities has kept expanding from 12 in 2017 to 43 in 2019 (He and Li,). The financial support from the central government for pilot cities has also increased dramatically from RMB 7.8 billion in 2017 to 15.2 billion in 2019 (Ministry of Finance (MF), 2020); the financial expenditure from local governments has been much more than that from the central government. From 2017 to 2018, the subsidy funding from local governments for CCHP was up to RMB 55.5 billion, over twice more than that from the central government (He and Li, 2019).

With rapid advance, CCHP has made considerable contribution to bulk coal reduction and air quality amelioration. CCHP facilitated to reduce approximately 100 million tonnes bulk coal by the end of 2019 (MEE, 2020b). Meanwhile, air quality improvement has been well observed (see **Figure 4**). Compared to 2013, the $PM_{2.5}$ concentration of BTH and surrounding areas in 2017 has reduced by 40%, surpassing 25% of the target set by the 2013 Action Plan (Wang et al., 2019a). Besides, observable health effects of reducing indoor pollution created by bulk coal have also been reported (Barrington-Leigh et al., 2019; Wu et al., 2020).

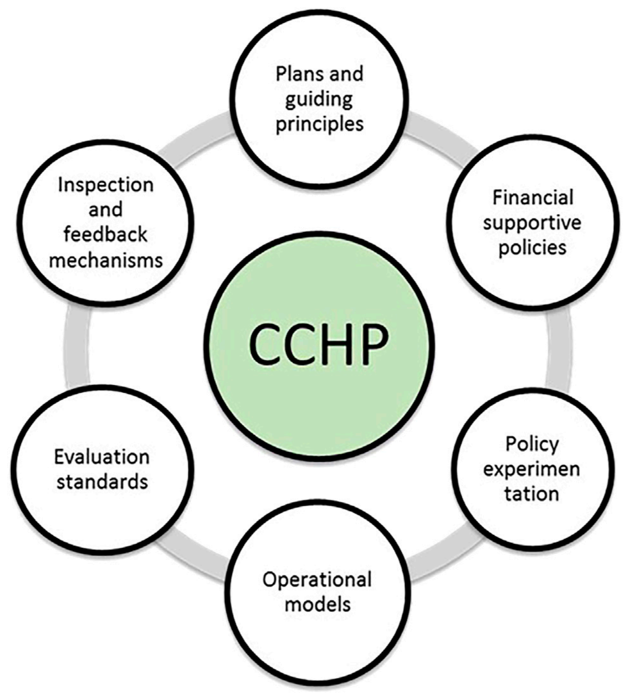

FIGURE 2 | The policy package of CCHP.

However, the rapid progress has been accompanied by numerous problems and doubts since the winter of 2017. Issues about energy security, weak social acceptance, technological immaturity and the most heatedly reported inappropriate implementation by local governments, among others, have been constantly exposed and pushed the mega project into deep dilemma. The project through an incorporation with the framework of policy process will be critically discussed in next section.

THE POLICY PROCESS OF COAL TO CLEAN HEATING PROJECT

Policy process is broadly defined as an analytical framework encompassing different policy stages and driving variables (Sabatier and Weible, 2014). A multiplicity of theoretical frameworks have been developed to understand the complexity of policy processes (Kern and Rogge, 2018). This article does not intend to focus on any specific policy stage or variable from a singular theoretical perspective, but takes the policy process as a systematic framework composed by a couple of interconnected and integral parts (Wu et al., 2010; Kern and Rogge, 2018). Confronted with increasingly complex and challenging socio-political environments, achievement of policy goals entails integrated policy processes that coherently and systematically link different parts of policy processes (Wu et al., 2010). Given that justification, this article examines the features of five key stages of CCHP's policy process: 1) agenda setting, 2) policy formulation, 3) policy implementation, 4) policy evaluation and 5) policy adjustment. This approach illustrates that CCHP has been poorly articulated in the policy process and requires thorough and systematic reconsideration and readjustments. Merely focusing on the implementation section, i.e. blaming the "inappropriate behaviors" of local implementers, offers little help in improving the effectiveness of CCHP in the future.

Agenda Setting

Agenda setting is the initial stage of a typical policy process. At this stage, potential public problems are identified and confirmed, and then attempt to catch political attention, so that specific public policies enter into the agenda list of decision-makers. The agenda setting of China's public policies has followed multiple models contingent upon varied spatiotemporal contexts (Wang et al., 2019b; Yang

FIGURE 3 | The planned goals and achieved quantities of CCHP from 2017 to 2019. Source: adapted from He and Li (2018, He and Li, 2019, He and Li, 2020) and various policy documents and reports.

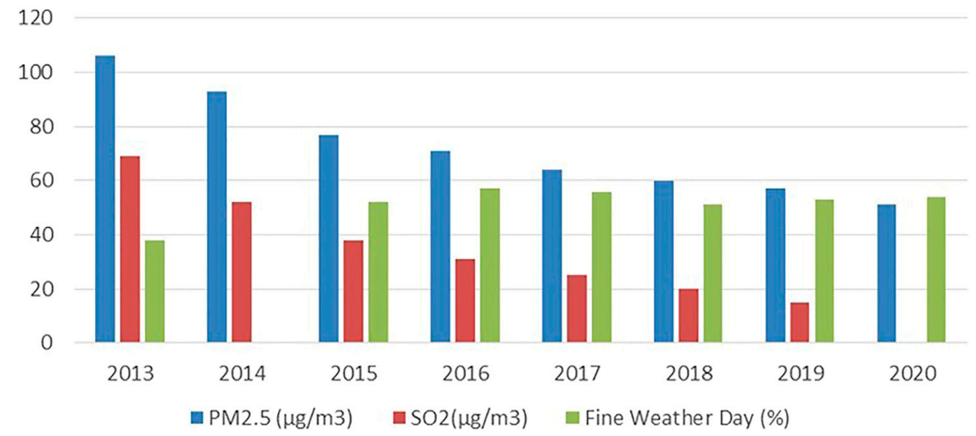

FIGURE 4 | Key indicators of air quality improvement in BTH and Surrounding Areas from 2013 to 2020. Source: adapted from MEE Annual Report (2013–2020).

and Li, 2019; Zhao and Xue, 2017). Wang (2008) argued that public policies in China have taken multiple agenda setting models according to different situations, and currently a popular-pressure model has become increasingly prevalent. In this model, powerful public pressure pushes decision-makers to respond promptly, with solutions quickly formulated and rolled out. The proposal of bulk coal reduction was triggered by air quality crisis in northern China, which was so severe that acute public discontent was produced, ultimately taking air pollution mitigation into the political agenda (Aunan et al., 2018). From 2013, ameliorating air quality as rapidly as possible has become a national imperative which needs to be tackled at all costs (Jin et al., 2016). With support from associated scientific research, replacing coal with clean energies became a logical and plausible roadmap (He and Li, 2017; Wang Z et al., 2019b). In this sense, air pollution mitigation measures are a set of responsive actions to public pressure, and CCHP was taken as an integral part of these actions. One critical issue in the agenda setting of CCHP is an evident mismatch between those who pushed it to political agenda (mostly well-educated middle class from first-tier cities, such as Beijing) and those who are mostly affected by its implementation (e.g. rural residents) (Cao and Hu, 2019; Hu, 2020). The voice of rural residents—a silent and weakly represented social group in China—failed to enter into the agenda setting, which left grave repercussions for subsequent policy processes. To a certain degree, popular pressure can be powerful in prioritizing public agenda, but can also be vague in policy design, which may jeopardize policy effectiveness eventually (Wang, 2008; Zhao and Xue, 2017). As widely found in China, hasty agenda setting driven by political concerns often results in deficient policy design, partial policy goals, short-termism in implementation, and ignorance of deep-seated social problems (Wang, 2008; Wu et al., 2010; Zhao and Xue, 2017). As shown below, the agenda setting of CCHP prioritized environmental concerns over other concerns such as technological suitability, social acceptance, and energy security, among others, which buries "time bombs" for subsequent policy implementation.

Policy Formulation

Policy formulation is the process that how solutions to some public issues are sought and formulated, which results in promulgation of specific forms of policy output (Wu et al., 2010). Here three key aspects of the policy formulation of CCHP are discussed: the first is about how specific technological models, i.e., CTG and CTE, were taken as the major solution; the second asks what were the policy objectives of CCHP and how they were set; and the third presents how policy experimentation, a distinctive model of China's policy process, worked in the policy formulation of CCHP.

Selection of the Dominant Technological Models

As reviewed in *Historical Background and Practical Progress of Coal to Clean Heating Project*, CCHP was not taken as a major measure between 2013 and 2016 by either the central government or local governments. Most regions mainly concentrated on promoting clean briquette and matched stoves to substitute bulk coal (Wei et al., 2016). Yet, the clean briquette substitution strategy achieved disappointing progress, due to poor properties of clean briquette (e.g., high price, difficult to burn), difficulties in controlling bulk coal market, and weak incentives from local governments (Wei et al., 2016; Focus Interview, 2017). In a sense, local governments were waiting for advanced technological models to accomplish the tasks of bulk coal reduction. In the middle of 2016, CAE, the top tier academic institute of engineering in China, conducted a mid-term evaluation of the progress and effectiveness of the 2013 Action Plan. Among various findings, the evaluation report explicitly listed rural civil bulk coal for heating as one of the most prominent factors for severe winter air pollution, which had not been systematically attended to by that time (CAE, 2016). As a result, the report advocated coal-to-electricity and coal-to-gas transition of residential heating as major measures to reduce consumption of civil bulk coal in BTH rural region, in order to achieve the target of the 2013 Action Plan by 2017 (CAE, 2016). The CAE report played a critical role in the formulation of CCHP.

As, Lei Yu, a high-ranking official from MEE, stated, "The mid-term evaluation report helped the central government make the mind. The government provides sufficient administrative resources to promote coal-to-gas and coal-to-electricity, such as financial subsidy, top-down task assignment, among others. It is not just 'encourage' anymore (as before), which made you (local governments) act slowly". (Huang et al., 2017).

What's more, a few rounds of heavy air pollution swept Beijing and surrounding areas in the winter of 2016, which further accelerated the policy formulation of CCHP (Huang et al., 2017). Most importantly, CCHP gained strong and explicit political support at this time. In December, 2016, President Xi Jinping explicitly spoke for CCHP in a high-end meeting,

"Promoting clean heating in northern China matters significantly, which is about to make the people live a warm winter, about the reduction of smog, and is an important section of the revolution of energy production and consumption, as well as the revolution of rural life style. It should be promoted according to the principle of 'enterprises play the major part, government promotes it, and residents can afford it'. Choose gas or electricity based on local conditions, and try best to improve the proportion of clean heating." (Xinhua Net, 2016)

Before long, Premier Li Keqiang listed CTG and CTE projects as a major administrative task in his annual government report in March, 2017. Hereto, driven by strong political and administrative mobilization, scientific justification and external driver from climatic conditions, the "windows of opportunity" for CCHP, particularly CTG and CTE projects, opened. In consequence, from the beginning of 2017, an array of policies from central administrations were intensively issued to enforce CCHP. Aggressive tasks were assigned to local governments to accomplish before the end of October in 2017.

It should be noted that suspicion of the proposed technological models was not absent in the scientific realm, even within CAE itself. Despite scientists in general approve that civil bulk coal is a major contributor to severe air pollution in northern China, they hold different viewpoints regarding technological roadmaps, particularly for technological models in the dispersedly distributed countryside. Doubts were raised in two aspects, mainly regarding the CTG model (Zhang, 2019a; Tao, 2019). Firstly, natural gas should not be taken as clean energy, since its combustion also generates NO_x—a major air pollutant. Secondly, the coal-dominated natural energy endowment of China makes radical coal replacement unrealistic, and heavy reliance on import of natural gas generates high risks of energy security. A more practical approach hence is to improve building insulation and utilize clean briquette (together with advanced stoves) to replace bulk coal in rural areas (Kou, 2017; Tao, 2019). However, these scientific suspicion was marginalized in the policy formulation of CCHP.

Another critical issue is that the temporal gap between policy output and outcome is exceptionally short. Premier Li Keqiang announced the tasks in March 2017, leaving only approximately six months for local governments to put into practice. The short timeframe pressured local governments to accomplish their tasks as quickly as they could. They had few choices but to follow the two models proposed by the central government. Moreover, most local governments at the beginning preferred CTG model among the two due to its attributes of technological maturity, lower costs, and higher feasibility of rapid promotion (Liu et al., 2019). In this process, the public, more specifically the energy enterprises and the recipient communities, were largely excluded in the decision-making of technological model selection.

Setting Policy Objectives

Policy objective setting is an important part in policy formulation. Low-carbon energy policies are frequently situated in a difficult position to satisfy multiple (often conflicting) objectives, including objectives regarding economics (accessibility and affordability), politics (energy security) and environment (emission reduction). In practice, each of these objectives or concerns tends to drive energy policies toward its own direction (Heffron et al., 2018). Energy policies that manage to balance these multiple objectives serve the best option in policy-making (Heffron et al., 2018). Poorly aligned policy objectives frequently lead to policy failure in public policies in general (Wu et al., 2010), and in sustainable transitions in particular (Howes et al., 2017). Although not explicitly stated in the policy documents, CCHP was propagated as a national project with two goals (i.e., environmental and developmental): 1. to ameliorate air pollution in northern China, and 2. to improve the living standards of rural people through accessing clean and affordable energies. However, CCHP was originally nested in the air pollution mitigation framework, and its effectiveness is measured only by three major environmental indicators, i.e., the decreasing quantity of bulk coal, the decline degree of key pollutant density (i.e., $PM_{2.5}$ and SO_2), and the number of reduced heavily polluted days (Wang et al., 2019a). Indicators of well-being and life quality of the recipients were explicitly absent in the policy texts. Namely, the evaluation standards mainly point to the scale of civil bulk coal reduction estimated by the quantity of households that participate in CCHP. The partiality of policy goal setting in this stage induced local governments to concentrate on those environmental indicators, which generated severe consequences as shown in subsequent policy processes.

Conducting Policy Experimentation

Policy experimentation is a distinctive feature of Chinese policy process (Heilmann, 2008; Lo and Broto, 2019). In policy experimentation, pilot projects are initiated to test and evaluate the effectiveness of different policy methods and examine the reactions from the society, before formal policy formulation and implementation (Heilmann, 2008). In light of that, policy experimentation is a valuable strategy of selecting appropriate policy instruments and achieving effective policy outcomes in the context of China's vast socio-economic heterogeneity (Heilmann, 2008). The experimentation model was also adopted in the policy process of CCHP. In 2017, the central government selected 12 cities to conduct cleaning heating pilot projects, and the number was enlarged to 43 in 2019. However, it falls short in two aspects. Firstly, common policy

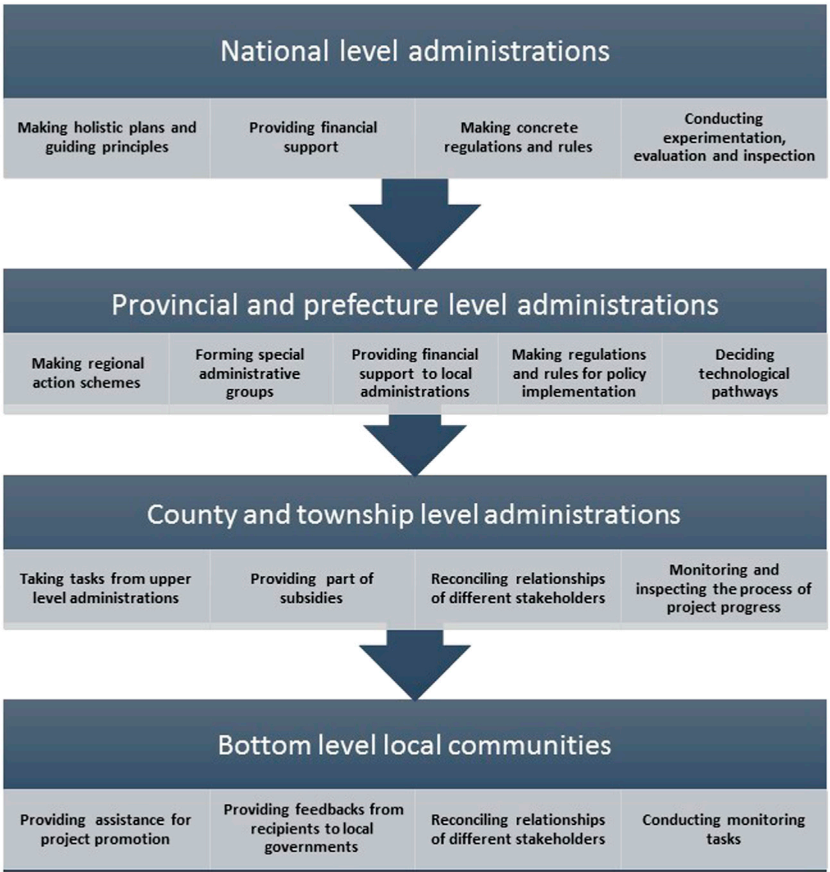

FIGURE 5 | The top-down policy implementation mode of CCHP.

experimentation commences before formal policy formulation and rollout, in order to learn the real effectiveness of different policy designs. In CCHP, however, pilot programs and national-scale promotion were conducted simultaneously, which resulted in ignorance of many social problems generated by CCHP in subsequent implementation. Secondly, the technological roadmaps for pilot cities were basically confined to the two main models proposed by the central government, although the policy texts ostensibly encouraged the pilot cities to explore multiple technological models. Consequently, policy experimentation of CCHP failed to provide real-world feedbacks of different technological models; instead, most pilot cities promoted CCHP blindly and aggressively in order to fulfill administrative tasks and grab financial support.

This section shows that the formulation of CCHP has been mainly driven by political and administrative dynamics, and largely overlooked the societal aspects. The selection of technological models and the policy experimentation were poorly coordinated, which challenges the frequently heard comments that the policy design of CCHP is correct, and problems lie with the implementation at the local level (Li and Feng, 2017; Chu, 2018; Li, 2018).

Policy Implementation

Policy implementation represents a complicated process of putting formulated policies into practice, and involves multiple aspects, such as participant groups, organizational mechanisms, and selection of policy instruments, among others (Stewart et al., 2007). This section focuses on two aspects of the implementation of CCHP: 1. the major approach in terms of organizational mechanisms; and 2. the selection of policy instruments.

Top-Down Administrative Mechanisms

The policy implementation of CCHP took an explicit top-down command-and-control approach by the administrative system (He et al., 2019; Qi and Xiao, 2019). First, the extensive promotion of CCHP was proposed, designed, and driven by the central government. Local governments in general were pushed to implement the policy tasks assigned by the central government. As mentioned above, it was the call from the central government that truly drove local governments to enforce this project. The enforcement pressure was vertically channeled from the central down to the county and township level administrations, as summarized by **Figure 5**. Pressure from every layer of administration would push their lower level

TABLE 2 | Major policy instruments of CCHP as implied by the policy discourse.

Category	Concrete instruments	Major content
Mandatory instruments	● Political mobilization ● Administrative organization ● Regulations	● Take CCHP as a major political task ● Form specific organizational mechanisms for CCHP at both national and local levels ● Set mandatory and regulative action plans within administrative system ● Execute market regulation of civil bulk coal ● Regulate gas and electricity price mechanisms ● Establish environmental inspection institutions ● Establish policy task-evaluation institutions
Mixed instruments	● Subsidy ● Contract ● Financing ● Information and exhortation	● Provide substantial subsidies from the central government to local governments, and from governments to recipients ● Select and subsidize pilot cities for conducting CCHP ● Outsource the project to energy enterprises ● Encourage banks to give loan to market entities related with CCHP ● Support clean heating enterprises to conduct financing ● Encourage state-owned central enterprises to participate in CCHP with supportive performance assessment institutions ● Provide information of different technologies to local governments and rural residents ● Conduct publicity to rural residents about the advantages of clean heating
Voluntary instruments	● Rural residents and communities ● Private enterprises	● Endow rural residents with the right of voluntary option ● Encourage local community to choose viable projects based on local conditions ● Encourage people to report malfeasance of officials via specific channels ● Invite social (private) investments to participate in clean heating

Source: Author's compilation from CCHP policy documents.

administration to add more tasks. In the vertical administrative chain, county level and beneath administrations had little autonomy in the decision-making but simply served as policy executors in order to fulfill the tasks set by upper level administrations. Furthermore, the central government has established stringent inspection institutions since 2013, wherein the responsibility of air quality amelioration was transferred from environmental administrations to local governments, or more specially, to the principal leaders of local governments (Clean Air Asia, 2019). Hence, local leaders hold accountability for the air quality indicators, through mechanisms such as seasonal report, semiannual inquiry, annual accountability, and reinforced inspection, among others. According to the inspection rules, failing or even being slow to meet the targets would negatively impact the evaluation of those local leaders, so that immense pressure was created and transmitted layer by layer down to the local administrations (Clean Air Asia, 2019).

Policy Instruments Dominated by Mandatory Ones

Policy instruments are an integral part of policy implementation, serving as concrete methods in policy execution. Due to extreme complexity, policy instruments have been categorized diversely by scholars based on different criteria. This article adopts the widely used classification according to mandatory degree, which groups policy instruments into three major types: mandatory, mixed and voluntary instruments (Doren and Phidd, 1992; Howlett and Remash, 1995). A combination of multiple instruments were supposed to be taken to enforce CCHP, as shown by the policy design from the central government (see **Table 2**). The mandatory instruments manifest in three aspects. First, political mobilization is a decisive instrument adopted by all levels of administrations to enforce CCHP. In the policy discourse, the political significance of CCHP was explicitly and repeatedly stressed, whereby this project was constructed as a grand political task. Policy documents, work reports, and social media commentaries constantly quoted President Xi's speech on clean heating to accentuate the political significance of CCHP. Second, as discussed above, the central government designed specific organizational mechanisms to implement CCHP. A range of ministry-level administrations, such as NDRC, MEE, NAE, MHURD and MF, among others, were organized into an *ad hoc* leading group, with clear function divisions and coordinated institutions. Correspondingly, local governments were required to establish specific organizational entities and mechanisms to promote CCHP (Song et al., 2019). **Figure 6** shows a typical organizational approach that local governments adopt. To be clear, **Figure 6** takes Beijing City as an exemplar, and various policy documents and governmental websites show that other provinces followed a similar approach. This highly centralized administrative mechanism can efficiently mobilize various resources to implement the project. Third, various administrative regulations were issued to enforce CCHP, including administrative tasks, rules and arrangements of evaluation and inspection, and energy price regulations, among others.

For mixed policy instruments, four aspects can be observed in CCHP. The first, also the foremost, is substantial subsidies from various levels of administrations to project recipients. The amount of ultimate subsides is contingent on the financial ability of local governments. In general, Beijing and Tianjin, the two wealthiest municipalities in northern China, provide

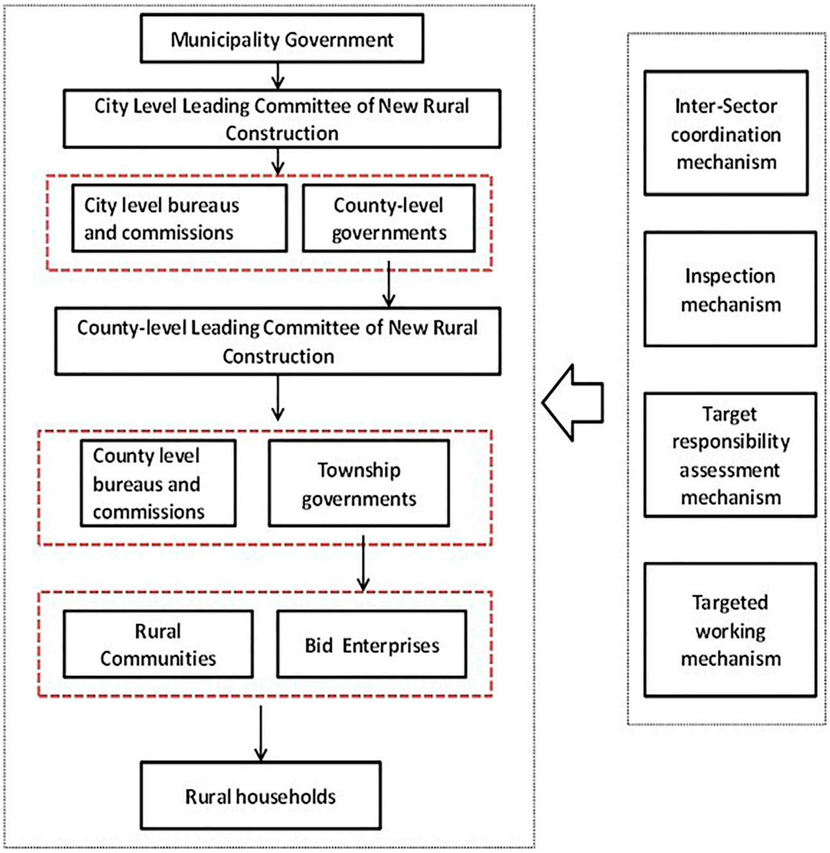

FIGURE 6 | The organizational mechanism for CCHP of Beijing City. Data source: adapted from CCHP related policy documents of Beijing (Beijing, 2018).

the most generous subsidies for their CCHP recipients. Less wealthy regions, such as Hebei and Shanxi Provinces, often provide a lower level of subsidies. Second, contracting out the project to qualified energy enterprises through open bidding is the main tool of executing CCHP. Third, local governments are encouraged to help enterprises to acquire financing in CCHP. State-owned central energy enterprises are encouraged to participate in clean heating. Fourth, apart from economic incentives, information provision and exhortation are also important instruments. Concrete technological roadmaps and details are provided to local governments, participant enterprises and recipients. Publicity is taken as a necessary method to pursue social acceptance from rural recipients.

Voluntary instruments are not explicitly emphasized, but all the policy documents highlight that the implementation of CCHP should respect the willingness of recipients, take local concrete conditions into account, and most importantly, ensure the affordability as the core principle of promotion. Besides, private investments are encouraged to participate in CCHP.

In practice, the instrument pluralism by design, however, was translated into a monism dominated by the mandatory ones. The proposed policy model featured by coordinated cooperation among stakeholders (market-government-recipient) was translated into a "government dominance" model, featured by strong irrationality, short-termism, inflexibility and blindness. Local governments took stern measures to remove the obstacles in CCHP promotion. For example, many local governments frequently adopted mandatory methods to shut down local bulk coal markets. Rural recipients were left with very limited choices, and even forced to accept CCHP (Wang et al., 2018; Hu, 2020). It was reported repeatedly that local residents were forced to remove stoves and take gas or electricity (MEE, 2018). Preliminary planning and investigation on the availability of energy supply, local natural endowments, and local economy levels were neglected in the implementation process, which directly caused the supply shortage of natural gas in 2017. To summarize, the implementation of CCHP took a sweeping campaign-style manner, featured by rapid and extraordinary mobilization of political and administrative resources, and non-deliberative enforcement.

Policy Evaluation

Policy evaluation is a crucial section of policy process, during which specific evaluation bodies assess the outcome, efficacy and process of specific policies according to specific standards and procedures (Wu et al., 2010). Policy evaluation provides feedbacks for policymakers and implementers to examine policy effectiveness and make subsequent adjustments. The evaluation of CCHP has been provided by multiple bodies through both formal and informal channels. The first, which

TABLE 3 | Evaluations of CCHP on environmental and socio-economic aspects by academics.

Studies	Environmental aspect	Socio-economic aspect	Research region	Projects	Methods
Zhao et al. (2019)	1. 30% contribution to provincial pollution control	1. Higher energy efficiency and more financial subsidy than bulk coal	Hebei province	CTG	Simulation
	2. Coal-to-gas performs better than coal-to-electricity	2. Low cost of CCHP can be achieved with subsidies		CTE	Field tests
Chen and Chen, (2019)	1. 33% contribution to national total scattered coal reduction during 2015–2020	1. Health and climate benefits equivalent to 3% of GDP in the 28 major northern cities	28 key cities of CCHP	CTG	Simulation
	2. Considerable air pollutants reductions	2. Heavy financial burden for local governments 3. CTE will be a more promising model than CTG 4. Financial pressure for poor people from poor cities		CTE	
Lin and Jia, (2019)	1. CTE project is effective in reducing SO_2 and NOx emission than CO_2 emissions	1. High costs of promotion and operation	Northern China	CTE	Simulation
	2. CTE plays a positive role in adjusting the energy structure	2. Governmental subsidies are necessary			
	3. The positive impact on energy structure is not as significant as other energy policies 4. The environmental effect of coal to electricity is significant	3. Marketization of electricity prices is an effective mechanism to sustain CTE			
Barrington-Leigh et al. (2019)	1. Successfully removed bulk coal in targeted villages	1. Higher level of well-being brought by CTE	Beijing	CTE	Quasi-field experiment
	2. Significantly better in-door air quality	2. Cost of higher expenditure can be traded off by the benefits of increased health, comfort and convenience 3. Benefits vary according to income levels 4. Poor households need more subsidies			Survey
Zhang et al. (2019c)	1. Significantly improve air quality	1. Will bring significant health effects by avoiding 22.2 thousand cases of premature death and 607.8 thousand morbidity cases.	BTH	CTE	Modeling
	2. PM2.5 concentration in the three regions can be reduced by 6–15 μg/m³ in 2020	2. Will bring RMB18.73–19.87 billion social net benefits for BTH			Simulation
Wang Z et al. (2019b)	1. Clean energy, particularly electricity has become the dominant energy for heating in study area	1. Income level is highly associated with adoption of clean heating practices	Henan province	CTE	Indoor survey (1,030 households)
		2. CTG is more effective in practice transition than CTE project due to lower costs. 3. Inflexibility of implementation obstructed recipients' adoption 4. Poor infrastructure in rural areas is a barrier for the promotion of CCHP		CTG	
Huang, et al. (2019)	1. CTG in the case village reduced 25.66t SO_2, 1.76t CO_2, generating significant environmental effects	1. Low income families face pressure of increased heating costs	Shandong province	CTG	Indoor survey (*N* = 388)
	2. CTG has energy-saving effects, saving 86.03t coal equivalent energy per winter season	2. After coal-to-gas project, the life satisfaction of recipients increased			
Yun, et al. (2018)		1. Higher level of life satisfaction 2. Heating costs increased 3. Some places suffered gas shortage in 2017 4. Costs of CTE are higher than CTG	Hebei province	CTG CTE	Indoor survey (*n* = 150)
Liu, (2017)		1. With subsides, heating cost is about 3% of family income 2. For low income families, the proportion could reach to 32.4% 3. Heavy financial pressure for local governments	Beijing	CTG	Modeling
Du et al., 2018	1. CTG produces the most environmental benefits for Beijing, the least for Hebei	1. The economic cost of CTG is higher than CTE in Beijing, Tianjin and Hebei	Beijing Tianjin	CTG	Simulation
	2. For CTE, Beijing and Hebei receive no significant environmental benefits		Hebei	CTE	
Li and Chen, (2019)	1. Insignificant impact on reduction of CO_2			CTG	Modeling

(Continued on following page)

TABLE 3 | (*Continued*) Evaluations of CCHP on environmental and socio-economic aspects by academics.

Studies	Environmental aspect	Socio-economic aspect	Research region	Projects	Methods
	2. Insignificant impact on energy consumption per unit of GDP	1. CTG and CTE have not significantly increased the quantity of gas provision and electricity consumption	41 cities from northern China	CTE	
Wu, et al. (2018)		1. 24–65% of rural recipients did not use the heating devices; the electricity consumption quantity of 11–26% of recipients was zero	Beijing, Tianjing, Hebei and Henan	CTE	Case study
		2. Subsidies took 30–70% of heating electricity costs			Secondary dataset from grid enterprises
		3. Low profitability of rural coal-to-electricity projects could not attract private capital investment			
Yan et al. (2019)	1. Significantly reduce PM2.5 in Beijing, Tianjin and Hebei 2. Beijing and Tianjin achieve much more environmental effects than Hebei.	1. Significant health benefits for Beijing, Tianjin and Hebei 2. Beijing will achieve the largest health benefits, with Hebei second, and Tianjin third	Beijing, Tianjin and Hebei	CTE	Simulation modeling
Song, et al. (2019)	1. The PM2.5 of 12 pilot cities in 2017 has declined about 30% compared to 2016, some cities more than 40%	1. Some cities face heavy financial pressure	12 pilot cities from northern China	CTE	Fieldwork
	2. All 12 pilot cities accomplished the PM2.5 reduction tasks set by MEE	2. Gas prices rose up due to increased gas demand 3. Poor rural grid infrastructure restrained the promotion of CTE 4. Expenditure of CTG recipients increased RMB874 after subsidy, that of CTE RMB1333. 5. Majority of rural recipients fell into energy poverty after CCHP		CTG	Secondary data
Meng et al. (2019)	1. More than 60% of households will remove solid fuels by 2021 in northern China	1. Significantly improve indoor air quality	28 key cities in northern China	CTE	Survey-based modeling
	2. CCHP will significantly reduce PM2.5 intensity	2. Rural women benefit more than rural men		CTG	
		3. Exposure reduction comes more from improved indoor air quality than ambient air quality 4. Financial burden as a major constraint			
Xie, et al. (2019)	1. Bulk coal was significantly reduced after CCHP	1. CTE and CTG significantly increased heating costs	Beijing	CTE	Indoor survey (N = 3949)
	2. Environmental benefits are greater than economic cost	2. CTE and CTG improved subjective satisfaction of rural recipients		CTG	
		3. Mandatory promotion harmed well-being of recipients		CTCC	
		4. Universal subsidy led to energy inequality for heating			
Xu and Ge, (2020)		1. Overall satisfaction of residents regarding CTG is medium 2. Residents are satisfied with the heating level; but not satisfied with the subsidy amount	Hebei	CTE	Indoor survey (N = 908)
Wang et al. (2020)	1. CTG and CTE contributed to 60% of total PM2.5 reduction in winter 2017 in northern China 2. The gas shortage triggered by blind promotion of CTG in 2017 indirectly contributed 15% upsurge of PM2.5 in Southern China		2 + 26 cities in northern China	CTG and CTE	Simulation
Zhang et al. (2020)	1. CCHP can effectively reduce pollutant emissions in northern China		35 pilot cities in northern China	CTG, CTEetc.	Daily monitored panel data
Yan et al. (2020)		1. The CTG project nearly doubled the heating expenditure of rural recipients 2. Contemporary compensation standards are insufficient to cover the increased cost brought by the CTG project 3. The low income level of rural households is the main barrier to clean energy transition	One county in Shanxi province	CTG	Survey (n = 374)

(Continued on following page)

TABLE 3 | (*Continued*) Evaluations of CCHP on environmental and socio-economic aspects by academics.

Studies	Environmental aspect	Socio-economic aspect	Research region	Projects	Methods
Wu, et al. (2020)	1. Coal in CTE targeted area was effectively reduced. 2. Indoor and outdoor air quality were improved due to the CTE implementation	1. Households involved in CTE received poor heating experience 2. High heating costs brought by CTE are unbearable for rural poor households. 3. Clean coal program is more viable for rural households	Beijing rural villages	CTE and clean coal	Survey (N = 3949)
Gong et al. (2020)		1. Majority of rural households are willing to pay clean heating less than RMB 1000 2. Financial support from government is critical to the success of clean heating project	Hebi city, Henan province	CTE	Survey (N = 324)

is informal but arguably the most influential and consequential, was the 2017 winter "gas shortage" crisis exposed by social media. Due to the aggressive promotion without considering gas provision, in the heating season of 2017, the supply of natural gas was in significant shortage across northern China (Huang et al., 2017; Shu and Shen, 2018). It was estimated that the national demand of gas increased by 33 billion m^3 in 2017, with a growth of 17%, which was partly attributed by CCHP (Chen and Zhu, 2018). The increased gas demand for heating in Hebei Province, where 2.31 million rural residents participated in CTG project in 2017, reached 2.5 billion m^3, and 25% of the demanded gas was in shortage (Chen and Zhu, 2018). An official report from MEE revealed that 426 thousand families from 1,208 villages or communities faced insufficient gas supply in the winter of 2017 (Du, 2017). The majority of these impacted groups were in low-level or even "zero" heating status (Zhu, 2017). This phenomenon was exposed by social media and quickly became a heated focusing event. Ministry-level administrations made quick responses to address the social crisis, including suspending the rollout of CTG and reconciling gas provision to satisfy the demand of civil heating. Apart from the gas shortage event, problems of poor affordability, delay of subsidies, public security concerns were also widely reported by social media (Zhou et al., 2018).

Another source of policy feedback comes from the administrative system itself. One featured action was the middle-term evaluation of CCHP pilot cities conducted by four ministry-level administrations in 2019. The report has not been formally published as yet, so that we can only learn from an NEA official who revealed a few brief conclusions on an international conference (Zhang, 2019b). First of all, the environmental goals of CCHP have been well accomplished. Also, clean heating markets and industries have achieved significant developments driven by the extensive promotion of CCHP. Moreover, residents are generally satisfied with the environmental and health effects brought by CCHP. Meanwhile, a multiplicity of problems are identified in evaluation, including the inflexibility of technological choices, poor affordability, and high rate of coal re-burning, among others. Besides the national-level evaluation, a few provincial-level governments, e.g., Hebei Province and Shanxi Province, conducted local investigation and evaluation of CCHP as well, with similar problems being found.

The third strand of feedback is from academia, as summarized by **Table 3**. Two major findings can be drawn from these studies. The first is that CCHP has been an effective tool in controlling civil bulk coal, and remarkably ameliorated air pollution and improved indoor air quality. The environmental effects generated by CCHP provide powerful justification for the continuous promotion of CCHP. The second finding is that CCHP caused many socio-economic problems, which may push the project into deep uncertainty. The two most prominent issues are poor affordability and heavy reliance on external subsidies. Therefore, how to build a sustainable pathway for CCHP is the most pressing issue for the policymakers.

Table 4 summarizes the multiple challenges that CCHP faces identified by the feedbacks from multiple sources. For an overall evaluation, besides the environmental effects, the challenges can be roughly grouped into two dimensions. The first concerns with the poor affordability of the technological models, revealing weak social legitimacy of CCHP. The unbearable expenditure of CTG and CTE is the foremost barrier for this mega project. The majority of CCHP recipients are rural residents, whose income level is generally low. Even rural residents from Beijing, the wealthiest region that CCHP targeted, also widely report difficulties in paying the surged heating costs (Xie et al., 2019). As estimated by researchers, the energy cost of CTG is approximately 3 times as high as that of bulk coal heating, and CTE 4 times of bulk coal (He and Li, 2018). Even with subsidies, the cost of new heating systems is still significantly higher than former bulk coal based heating systems (He and Li, 2018; Li, 2018). In average, the rural per capita net income of the CCHP key regions range from RMB 10,000 to 18,000, and the willingness-to-pay for winter heating is less than RMB 2,000 (He and Li, 2018). According to a survey covering 975 participants from four provinces, 32% of CCHP rural recipients paid more than RMB 2,000 per heating season after deducting subsidies, out of whom 30% paid between RMB 2,000–5,000 (He and Li, 2019).

For rural residents, the increased energy costs leads to heavy dependence on subsidies. Surveys show that the majority of rural

TABLE 4 | The challenges of CCHP identified by governments, social media and intellectuals.

Dimension	Problems identified
Economic	● Significantly high economic costs, even after subsidies ● Costs of coal to electricity higher than that of coal-to-gas ● Uncertainties of receiving subsidies in due course ● High risk of increasing gas price after installation ● Coal prices were uplifted due to restrict prohibition
Technological	● Safety concerns, potential danger of gas leaking, fire and explosion ● Accidents of gas explosion and leaking happened in many areas ● Low energy efficiency of rural houses ● Poor installation ● Low quality of facilities and instruments ● Poor provision of after-installation services ● Poor stability of gas provision in some regions ● Unmatched upgradation of power grids
Social	● Operational difficulties for rural elderly ● No time for acceptance and adaption ● Lack of alternatives for the disadvantageous ● High rate of coal re-burning ● Potential danger of low heating or 'zero' heating for poor people ● Inequality of heating gap between the rich and the poor ● Widespread public concerns of sustainability of CCHP in poor areas
Governmental	● Financial pressure to subsidize the project ● Poor transparency in selecting qualified energy enterprises. ● Default on project funding from local governments ● Excessively restrict on coal usage ● Poor coordination among sectors at both central and local levels ● Rapid and blind promotion leads to resource waste and public discontentment ● Fake reports toward upper level administrations ● Low flexibility of subsidy standard from the central government toward pilot cities ● Low flexibility of subsidy standard from local government toward different levels of residents ● High changeability of policies

residents express that they will return to former heating practices if subsidies stop (Liu et al., 2019). He and Li (2019) also found from a survey (n = 1,635) that 43% of CCHP recipients said they would use coal again if subsidies stopped. Of the 43% participants, 99% are CTG and CTE recipients. Unsurprisingly, the poor affordability leads to high rate of returning to coal in practice. A survey reported by MEE in 2019 shows that in Baoding, a municipal city in Hebei province, over a third (36.1%) of rural CCHP families returned to burn bulk coal (Zhang, 2019b). In consequence, the major governors of Baoding were criticized through circulating a notice by MEE because of poor monitoring work on bulk coal re-burning (Zhang, 2019b).

The second major challenge is associated with governance dilemma. Heavy subsidy placed heavy financial pressure on local governments. Particularly for the local governments from less wealthy regions, the financial pressure can be insurmountable (Li, 2018). More worrying is a consensus that CCHP subsidies will eventually reduce to zero in subsequent years. Retreat of subsidies in poor regions are very likely to create severe energy poverty in winter. In this sense, local governments face immense pressure of keeping the sustainability of CCHP, which could end with profound policy failure if no coordinated efforts are invested. In addition, policy flexibility has been a persistent challenge for CCHP (Liu et al., 2019; He and Li, 2019). Although policy documents from national administrations reiterate the request of flexibility principle in implementing CCHP in the first place, local governments rarely followed in practice, as shown in the next subsection.

Policy Adjustments

In typical policy processes, policymakers make changes to address obstacles and improve policy effectiveness. Alongside the promotion of CCHP, a few adjustments can be identified driven by the feedbacks from multiple sources. First, the 2017 gas shortage crisis made the central government slow down the promotion pace of CCHP in 2018. A variety of national-level administrations issued policy notices to curb the "runaway" behavior of local governments, which was regarded as a "calm period" after the 2017 fad (He and Li, 2019; National Energy Administration (NEA), 2018; Li et al., 2019). For example, Hebei Province conducted CCHP for 2.55 million rural households in 2017, and reduced to 1.8 million in 2018 (He and Li, 2019). Second, the central government explicitly expanded the range of technological models. In 2017 and before, technological choices were dominated by CTG and CTE, with very limited efforts taken to promote alternative models. From 2018, more technological choices were explicitly encouraged by the central government.

The policy documents before 2018 stated the selection principle of technological roadmaps as "choosing (coal to) gas or (coal to) electricity according to local conditions", which was adjusted into "choosing gas, electricity, clean briquette, geotherm based on local conditions" after 2018. Clean briquette has been re-framed as a major model of heating energy transition since then. Renewable energy heating technologies such as biomass and solar heating have been particularly stressed by national-level administrations. In the middle of 2019, NEA issued an opinion soliciting draft and wished to resolve the problems occurred in the promotion of CTG and CTE projects. The draft explicitly proposed to balance different clean heating technological models, and give priority to biomass heating in rural regions. Third, national-level administrations tended to balance the two policy goals of CCHP, and urge local governments to follow the principle of "ensuring residents live a warm winter." But, the policy evaluation standards remain unchanged.

Despite the adjustments from the national-level administrations, local governments seemed reluctant to follow in practice. CTG and CTE have remained the major technological models in implementation; the promotion tasks have even increased consistently after 2018 (see **Figure 1**). A latest policy document reveals that in the year of 2020, local governments planned to take over seven million rural households into CCHP, which is significantly higher than the five million task of 2019 (MEE, 2021). After 2017, mounting focusing events have kept exposing the coercive and one-size-fits-all implementation behavior of local implementers. Nonetheless, local governments still rush to increase coverage scale, with insufficient consideration regarding long-term project sustainability. Overall, the policy adjustments so far have shown marked limitations, and have not touched upon the major challenges of CCHP, leaving the mega project still in deep uncertainty.

POLICY IMPLICATIONS: INSIGHTS FROM THE POLICY PROCESS PERSPECTIVE

The above critical examination of five policy stages of CCHP has revealed key features of energy policy process in contemporary China, and identified manifold challenges that CCHP currently faces. Thorough readjustments beyond merely accentuating adjustments in the domain of local implementation are of necessity, if the well-intended project is to achieve ultimate success. Well-aligned policy process is a prerequisite for policy success (Wu et al., 2010). Based on the analysis of this article, a few policy implications illuminated by the policy process perspective can be drawn as follows.

Aligning Policy Objectives and Policy Evaluation

First of all, conflicting policy objectives have been identified as a significant reason for policy failure in sustainable transition (Kraft and Kamieniecki, 2012; Howes et al., 2017). Although environmental improvement and the well-being of impacted groups do not necessarily disaccord with each other, they render huge divergence in policy practices. Pursuing one often means sacrificing the other. For CCHP, the two objectives should be better aligned in future, not only in policy discourse, but also in concrete and operational policy instruments. For example, the institutions of evaluation and inspection regarding CCHP should go beyond the scale and speed of project promotion, but be geared to indicators associated with well-being, such as satisfaction of recipients, operational sustainability, etc. Besides, a balanced emphasis on well-being requires a concerted readjustment in policy evaluation. Contemporary policy evaluation of CCHP conducted by the administrative system is mainly guided by indicators associated with task accomplishment, energy provision and price stability, financial management and environmental targets, which primarily focuses on the techno-economic dimension of the project and systematically overlooks the social well-being aspects. Future evaluation efforts should pursue more inclusive and balanced standards. For instance, indicators associated with residents' satisfaction regarding project installation, heating effect and post-installation services should be incorporated into future evaluation criteria. Moreover, the overall governance structure of CCHP has functioned to overemphasize environmental concerns, which should be adjusted in the future. In the rollout of CCHP heretofore, environmental administrations at multiple levels have played a central role in the policy initiation, implementation and evaluation, which inevitably caused prioritization of environmental goals over others. Regrettably, administrations that represent rural communities and residents, such as ministry and bureaus of agricultural and rural affairs, have not engaged in the rollout of CCHP since the beginning. Future adjustments should consider incorporating Ministry of Agricultural and Rural Affairs and its vertical branches into the governance structure of CCHP, which can generate a better balance between environmental concerns and farmers' welfare.

Lastly, from a pragmatic viewpoint, the pursuit of environmental goals should be based on properly designed and well-practiced compensation schemes, to avoid loss of social welfare caused by environmental projects. For CCHP, numerous studies have revealed the poor affordability of the dominant technological models, and also found poor effectiveness of current subsidy policies. Hence, in the future, subsidy policies and other measures should be reevaluated and readjusted, to fully realize their restorative potential for rural recipients' welfare. To a great degree, practicing restorative justice is crucial to achieve balance between environmental goals and social welfare improvement (Hu, 2020). .

Making Policy Experimentation Better Inform Policy Formulation

The policy experimentation in CCHP so far has offered little assistance in formulating well-fitted policy designs. In future, major revisions of policy experimentation are essential to release its potential in testing different technological models, identifying challenges, and preparing more practicable policies for subsequent extension in a broader scope. In so doing, the central government should take a flexible and tolerant approach to encouraging pilot cities to innovate and try out different technological models based on local backgrounds. Corresponding incentive arrangements should be designed to encourage local officials to innovate and practice suitable models. Moreover, the cooperation between R&D and multi-level governments and enterprises should be further strengthened to offer local practitioners more selections of technological models.

Forging Flexible Governance Mechanisms in Implementation

Prior CCHP policy processes were featured by evident ossification, with limited flexibility in dealing with highly heterogeneous local conditions. Major reasons include excessive emphasis on political significance and harsh administrative inspection and evaluation. In future, no effort should be spared to explore flexible governing mechanisms. First, national-level administrations should be aware that energy transition is a long-term process filled with numerous relapses, frustrations, and even failures, and in most cases it cannot be completed in a compulsively confined time range (Sovacool, 2016). Therefore, top-level policymakers should be patient with the progress of energy transition. In policy design, top-level administrations should incorporate the flexibility and toleration principles into concrete policy documents and practical strategies. Besides, substantial incentives in accordance with the principles should be provided to local governments who seek innovative models catering to local conditions. Second, as the major implementation body, county and township level administrations should be substantially empowered, enabling them to actively participate in the designing and executing CCHP based on concrete local conditions (Liu et al., 2019). Provincial and prefecture level administrations should restrain their roles more as supporters and monitors and less as commanders. A balanced relationship among the central, middle and street level administrations is of great necessity.

Practicing Public Participation Throughout the Policy Process

Effective public participation can significantly improve the social acceptance of energy policies. The policy processes of CCHP have witnessed insufficient public participation (Hu, 2020). To a great degree, the challenges that CCHP currently face can be seen as an outcome of deficit public participation. Long-term operational sustainability entails meaningful participation from rural recipients, scientific experts (both natural and social scientists), and various social organizations, which should be integrated into various stages of the policy process. Specifically, meaningful participation from rural recipients can provide genuine feedbacks regarding viable technological roadmaps, effective policies, among others. Admittedly, formidable obstacles have long existed in realizing rural residents' genuine participation in policy processes in China. In most cases, rural residents serve as passive policy receivers, instead of active participants (Hu, 2020), and improving this remains a grave challenge. One possible approach to overcoming this challenge is to enhance local governance efficacy, especially village self-governance organization. In contemporary rural China, village self-governed organizations (*Cun wei hui*) serve as the most important institution that connects rural residents with upper-level administrations. Although they are established as a self-governed autonomous organization, the vast majority of these organizations, however, have become a de facto agent of the township-level governments, and therefore largely lost the mission of representing the will of rural residents. In the future, village self-governance organizations should be empowered by both institution reform and policy practice, which can potentially improve the participation of rural residents in policy process. For instance, technological models in CCHP are vital in determining the operational cost and the acceptability of local residents. Therefore, selection of local technological models should take a deliberative approach, value opinions of local village cadres and common residents, and avoid blunt top-down enforcement. Besides, informal voluntary social organizations in rural villages, such as elderly associations, women associations and various types of voluntary groups, can also be highly contributive to public participation. Fostering these social organizations and encouraging them to engage in policy design, implementation, monitoring and evaluation may significantly improve the policy outcome.

Another pathway can be giving more attention to direct opinions and appeals from rural residents from various channels, such as online appeal platforms. Local governments should exert timely responsiveness toward the direct appeals from rural residents, and this will form a virtuous circle of effective participation and good policy outcome. Ultimately, improving participation of rural residents entails systematic efforts, which goes beyond the governance system of CCHP, but core principles remain similar: on the one hand, to mobilize and empower local organizations, either formal or informal, and on the other, to improve the responsiveness of local administrations.

In addition, suggestions from scientists working in different fields (both natural and social sciences) can help form a holistic approach which embodies techno-economic, social, cultural and political justifications of CCHP. The design and evaluation of CCHP so far have been dominated by natural scientists, who stress heavily on the environmental and techno-economic aspects, while social scientists who are more qualified to provide advice on socio-political aspects are distinctly marginalized in the project. In the future, balanced expertise should be pursued in the process of policy consultation. Moreover, various social organizations may well serve as a link between mass society and governmental bodies, and should be encouraged to participate in the policy process of CCHP. Ultimately, how to build effective mechanisms to incorporate meaningful public participation is a great test for all level administrations in China. Failing to do so may lead this well-intended project to profound failure.

CONCLUSION

Reduction of civil bulk coal is not only a pivotal strategy for contemporary China, but also an imperative for the whole world. The rapid promotion of CCHP epitomizes the forceful resolution of the Chinese government in addressing mounting environmental crises. Different from existing studies that mostly focus on specific parts of the policy process, the article examines this mega project from a policy process perspective. It shows that although with only a four-year intensive rollout, CCHP has generated significant environmental, social, economic and even political consequences. A comprehensive policy package has been efficiently formulated to promote clean heating energy transition in northern rural China. Marked environmental effects have been achieved, while formidable challenges have surfaced as well and driven the mega project into a deep dilemma. Attributing the contemporary dilemma to implementation failure at the local level offers little help in improving the effectiveness of CCHP. An examination of the policy process of CCHP provides a holistic understanding of this mega project. CCHP originated from a poorly articulated policy framework, and was propelled more by political momentum and less by socio-economic concerns. The policy design, which placed excessive emphasis on environmental imperative (driven by political concerns) and proposed reckless technological models, forced local practitioners to implement it in an ossified manner and neglect the socio-economic conditions of the recipients. The politics and administration oriented approach and severe deficit of public participation are salient features of the implementation process, and also major reasons for the contemporary dilemma. Although policy feedbacks to a great degree have informed the policy system of the multiple challenges, existent policy adjustments have shown limited potential to tackle these obstacles. Policy recommendations inspired from the policy process perspective are discussed in detail, which mainly stress four aspects: realignment of complex policy goals and policy evaluation, policy experimentation, implementation flexibility and public participation.

Lastly, as a final summary, the policy process of CCHP illustrates that massive political, institutional and material resources do not guarantee a smooth and effective energy transition, no matter how ample the resources are. Energy transition is not just a technological change from coal to another energy type, but a systematic and complex process, involving multi-scale, multi-level, and multifaceted political and socio-economic dimensions. The multidimensionality of energy transition necessitates well aligned and integrated policy process, which requires researchers to look beyond individual policy stages and incorporate a holistic policy process framework in energy policy analysis (Kern and Rogge, 2018).

AUTHOR CONTRIBUTIONS

ZH: framing the article, collecting data and literatures, and writing the article.

FUNDING

This work is supported by the Fundamental Research Funds for the Central Universities (JB2018078).

REFERENCES

An, P. (2017). *Promoting Clean Heating Should Adopt 'flexible' Principle*. Available at: http://www.xinhuanet.com/politics/2017-12/11/c_1122093890.htm (Assessed November 6, 2019).

Aunan, K., Hansen, M. H., and Wang, S. (2018). Introduction: Air Pollution in China. *China Q.* 234, 279–298. doi:10.1017/S0305741017001369

Barrington-Leigh, C., Baumgartner, J., Carter, E., Robinson, B. E., Tao, S., and Zhang, Y. (2019). An Evaluation of Air Quality, Home Heating and Well being under Beijing's Programme to Eliminate Household Coal Use, *Nat. Energ.*, 4, 416–423. doi:10.1038/s41560-019-0386-2

Beijing (2018). *Guidance Opinion on Winter Clean Heating Work in Rural Regions*. Available at: http://www.beijing.gov.cn/zfxxgk/110019/zcxwj23/201805/18/content_46bd64f74de94c6db8050431496a18ca.shtml (Assessed November 6, 2019).

Cao, J., and Hu, B. (2019). Research on the Interest Compensation Way of the Policy of "Coal to Gas and Coal to Electricity, *Heat. Refrigeration (In Chinese)*, 5, 36–39.

Chen, H., and Chen, W. (2019). Potential Impact of Shifting Coal to Gas and Electricity for Building Sectors in 28 Major Northern Cities of China. *Appl. Energ.* 236, 1049–1061. doi:10.1016/j.apenergy.2018.12.051

Chen, Z., and Zhu, M. (2018). Heating Gas Demand Prediction of Hebei Residents after 'Coal-to-Gas' Project: Based on Big Sample Survey Data of Rural Family Energy Consumption. *Chin. Price (in Chinese)* 7, 64–66.

Chinese Academy of Engineering (CAE) (2016). *Mid-term Evaluation Report of the Implementation of Air Pollution Prevention Action Plan*. Published version: http://www.cae.cn/cae/html/main/col96/2016-07/05/20160705161134200910514_1.html (Assessed November 6, 2019).

Chu, B. (2018). *Discarding "One-size-fits-all" Approach, and Demonstrating Governance Precision19th December*. Beijing: People's Daily. Available at: http://opinion.people.com.cn/n1/2018/1219/c1003-30474919.html (Assessed November 6, 2019).

Clean Air Asia (2019). *China Air 2019: Air Pollution Prevention and Control Progress in Chinese Cities*. Available at: http://allaboutair.cn/a/reports/2019/1126/565.html (Accessed December 3, 2019).

Doren, G. B., and Phidd, R. W. (1992). Canadian Public Policy: Ideas, Structure, Process. second edition. Scarborough: Nelson Canada.

Du, X., Feng, X., Wang, M., Zhao, M., and Liang, Q. (2018). Cost-benefit Analysis of Integrated Coal Treatment towards Clean Heating in Beijing-Tianjin-Hebei Region.*Environ. Sustainable Dev.* 43(6). 135–141. (in Chinese). doi:10.3969/j.issn.1673-288X.2018.06.032

Du, X. (2017). *Ministry of Ecology and Environment Conducted Special Inspection on winter Heating Guarantee for 2+26 Cities from Beijing-Tianjin-Hebei and Surrounding Region*. 25th December, 2017 Available at: http://epaper.cenews.com.cn/html/1/2017-12/25/01B/2017122501B_pdf.pdf 25. (Accessed November 6, 2019).

Focus Interview (2017). *Why Does Not Clean Briquette "Burn"? 22th May*. Available at: http://tv.cntv.cn/video/C10326/5e01275a9bd549b98fc7162ec325035f?from=groupmessage&isappinstalled=1 (Accessed November 6, 2019).

Gong, Y., Cai, B.-f., and Sun, Y. (2020). Perceived Fiscal Subsidy Predicts Rural Residential Acceptance of Clean Heating: Evidence from an Indoor-Survey in a Pilot City in China. *Energy Policy* 144, 111687. doi:10.1016/j.enpol.2020.111687

Grossman, P. Z. (2015). Energy Shocks, Crises and the Policy Process: a Review of Theory and Application. *Energy Policy* 77, 56–69. doi:10.1016/j.enpol.2014.11.031

He, K., and Li, X. (2017). *A Research Report of the Comprehensive Governance of China's Bulk Coal*. Available at: http://coalcap.nrdc.cn/datum/info?id=68&type=1 (Accessed November 6, 2019).

He, K., and Li, X. (2018). *A Research Report of the Comprehensive Governance of China's Bulk Coal*. Available at: http://coalcap.nrdc.cn/datum/info?id=68&type=1 (Accessed November 6, 2019).

He, K., and Li, X. (2019). *A Research Report of the Comprehensive Governance of China's Bulk Coal*. Available at: http://coalcap.nrdc.cn/datum/info?id=68&type=1 (Assessed December 10, 2019).

He, K., and Li, X. (2020). *A Research Report of the Comprehensive Governance of China's Bulk Coal*. Available at: http://coalcap.nrdc.cn/datum/info?id=105&type=1 (Accessed December 2, 2020).

He, W., Zhang, W., Wang, S., Chai, F., Li, H., Zhang, J., et al. (2019). Effects and Improvement Suggestions on Air Pollution Joint Prevention and Control Mechanism in Beijing-Tianjin-Hebei Region. *Res. Environ. Sci. (In Chinese)* 10, 1696–1703.

Heffron, R. J., McCauley, D., and de Rubens, G. Z. (2018). Balancing the Energy Trilemma through the Energy Justice Metric. *Appl. Energ.* 229, 1191–1201. doi:10.1016/j.apenergy.2018.08.073

Heilmann, S. (2008). Policy Experimentation in China's Economic Rise. *St Comp. Int. Dev.* 43, 1–26. doi:10.1007/s12116-007-9014-4

Howes, M., Wortley, L., Potts, R., Dedekorkut-Howes, A., Serrao-Neumann, S., Davidson, J., et al. (2017). Environmental Sustainability: A Case of Policy Implementation Failure?. *sustainability* 9 (165), 1–17. doi:10.3390/su9020165

Howlett, M., and Remash, M. (1995). *Studying Public Policy: Policy Cycle and Policy Subsystem*. New York: Oxford University Press.

Hu, Z. (2020). When Energy Justice Encounters Authoritarian Environmentalism: The Case of Clean Heating Energy Transitions in Rural China *Energy Res. Soc. Sci.*, 70, 10177. doi:10.1016/j.erss.2020.101771

Huang, K., Zhou, C., Zhou, T., Li, R., and Wu, X. (2017). *Drive for Clean Air Creates 'Chaos,' Leaves Thousands Shivering*. December: Caixin. 11th. Available at: https://www.caixinglobal.com/2017-12-11/drive-for-clean-air-creates-chaos-leaves-thousands-shivering-101183499.html?sourceEntityId=101182801 (Accessed November 6, 2019).

Huang, S., Chen, B., Luo, S., and Yuan, R. (2019). The Case Study and Analysis of 'Coal to Gas' Project in Rural Areas of Jinan-Based on the Research of Xianggaocun. *City Gas (in Chinese)* 533, 38–42. doi:10.3969/j.issn.1671-5152.2019.07.008

Jin, Y., Andersson, H., and Zhang, S. (2016). Air Pollution Control Policies in China: a Retrospective and Prospects. *Ijerph* 13, 1219. doi:10.3390/ijerph13121219

Kern, F., and Rogge, K. S. (2018). Harnessing Theories of the Policy Process for Analysing the Politics of Sustainability Transitions: A Critical Survey. *Environ. Innovation Societal Transitions* 27, 102–117. doi:10.1016/j.eist.2017.11.001

Kou, J. (2017). *Governing Bulk Coal Pollution, Thoughts Should Be Expanded*. Beijing: People's Daily. (Accessed December 9, 2017).

Kraft, M. E., and Kamieniecki, S. (2012). *The Oxford Handbook of U.S. Environmental Policy*. Oxford: Oxford University Press. doi:10.1093/oxfordhb/9780199744671.013.0031

Li, S., and Chen, M. (2019). The Impact of 'Coal-to-Gas' and 'Coal-to-Electricity' Policies on Green Development. *Res. Financial Econ. Issues (in Chinese)* 7, 49–56.

Li, J., and Feng, X. (2017). *Collectively Promote 'Coal to Gas' to Become a Moral Project for the People*. Beijing: China Environment News 19th December. Available at: http://epaper.cenews.com.cn/html/2017-12/19/content_68320.htm (Accessed November 6, 2019).

Li, H., Fu, G., and Wu, S. (2019). *Clean Heating: From a Priority of Clean Energy to a Balance with Well-Being*. Beijing: China Energy News 4th, November Available at: http://paper.people.com.cn/zgnyb/html/2019-11/04/content_1954350.htm (Accessed November 8, 2019).

Li, G. (2018). *Coal-to Gas and Coal-to-Electricity Contribute Significantly to the Governance of PM2.5*. Available at: http://www.chinanews.com/gn/2018/03-19/8470974.shtml (Accessed November 6, 2019).

Lin, B., and Jia, Z. (2019). Economic, Energy and Environmental Impact of Coal-to-Electricity Policy in China: A Dynamic Recursive CGE Study. *Sci. Total Environ.* 698, 134241. doi:10.1016/j.scitotenv.2019.134241

Liu, J., Mauzerall, D. L., Chen, Q., Zhang, Q., Song, Y., Peng, W., et al. (2016). Air Pollutant Emissions from Chinese Households: a Major and Underappreciated Ambient Pollution Source. *Proc. Natl. Acad. Sci. U.S.A.* 113 (28), 7756–7761. doi:10.1073/pnas.1604537113

Liu, G., Xue, C., Ren, Y., Wan, W., Zhang, W., Xu, Y., et al. (2019). *A Study of Winter Heating of Typical Northern Rural Regions of China*. Available at: http://www.allaboutair.cn/a/reports/2019/1031/564.html (Accessed December 3, 2019).

Liu, Y. (2017). Analysis of Affordability on Residents Heating with Coal to Gas: a Case Study in Urban and Rural of Beijing. *Int. Pet. Econ. (in Chinese)* 25 (6), 45–50.

Lo, K., and Castán Broto, V. (2019). Co-benefits, Contradictions, and Multi-Level Governance of Low-Carbon Experimentation: Leveraging Solar Energy for Sustainable Development in China. *Glob. Environ. Change* 59, 101993. doi:10.1016/j.gloenvcha.2019.101993

Ma, Q., Cai, S., Wang, S., Zhao, B., Martin, R. V., Brauer, M., et al. (2017). Impacts of Coal Burning on Ambient PM2.5 Pollution in China. *Atmos. Chem. Phys.* 17, 4477–4491. doi:10.5194/acp-17-4477-2017

MEE (2018). *Yingze District, Taiyuan City Controlled Coal by Coercion, and People Cannot Have a Warm Winter*. Beijing: Available at: http://www.mee.gov.cn/xxgk2018/xxgk/xxgk15/201811/t20181116_674178.html (Accessed November 6, 2019).

MEE (2019). *Three Major Impacting Elements Are Found to Contribute to Air Pollution*. Xinhua News Agency. 11th March. doi:10.1515/9789048544936 Available at: http://www.gov.cn/xinwen/2019-03/11/content_5372975.htm (Assessed November 6, 2019).

MEE (2020a). *Ministry of Ecology and Environment Press Conference in December*. Available at: http://www.mee.gov.cn/xxgk2018/xxgk/xxgk15/202012/t20201229_815398.html (Accessed January 1, 2020).

MEE (2020b). Action Scheme of Comprehensive Governance of Autumn and Winter Air Pollution in BTH and Surrounding Area, and Fenwei River plain (2020–2021). Available at: http://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/202011/t20201103_806152.html (Accessed January 1, 2021).

MEE (2021). *China's Environmental Quality Report (2013-2019)*. Available at: http://www.mee.gov.cn/hjzl/sthjzk/zghjzkgb/ (Assessed January 20, 2021).

Meng, W., Zhong, Q., Chen, Y., Shen, H., Yun, X., Smith, K. R., et al. (2019). Energy and Air Pollution Benefits of Household Fuel Policies in Northern China. *Proc. Natl. Acad. Sci. U.S.A.* 116 (34), 16773–16780. doi:10.1073/pnas.1904182116

Ministry of Finance (MF). (2020). *Notice on Distributing the Central Fund of Air Pollution Control in Advance*. Available at: http://zyhj.mof.gov.cn/gjz/zjfp/201911/t20191115_3423099.htm (Assessed 6 November 2019).

National Energy Administration (NEA) (2018). *National Energy Administration Notice on Conducting Well the 2018-2019 Winter Heating Work*. Available at: http://www.gov.cn/xinwen/2018-12/15/content_5349109.htm (Accessed November 9, 2019).

Qi, J., and Xiao, J. (2019). The Interpretation of Administrative Law of the Calling off of the "Coal to Gas" Project. *J. Huazhong Univ. Sci. Tech. (Social Sci. Edition)* 33 (4), 82–92.

Sabatier, P. A., and Weible, C. M. (2014). *Theories of the Policy Process*. 3rd ed. Boulder, CO: Westview Press.

Shu, L., and Shen, X. (2018). How to Solve the Crisis of Gas Famine?. *Caijing Mag.* 518 (1). Available at: http://magazine.caijing.com.cn/20180108/4390458.shtml (Assessed November 6, 2019).

Song, L., He, J., Wu, J., Xu, Y., Cheng, L., Wang, Z., et al. (2019). Study on the Implementation Evaluation of Clean Heating Pilot City in Northern China. *Environ. Prot. (in Chinese)* 47 (9), 64–68.

Sovacool, B. K. (2016). How Long Will it Take? Conceptualizing the Temporal Dynamics of Energy Transitions. *Energ. Res. Soc. Sci.* 13, 202–215. doi:10.1016/j.erss.2015.12.020

Stewart, J. J., Hedge, D. M., and Lester, J. P. (2007). *Public Policy: An Evolutionary Approach*. 3rd edition. Boston: Thomson Wadsworth.

Tao, G. (2019). *Six Years of Tackling Smog*. Available at: http://www.chplaza.com.cn/article-2867-1.html (Accessed November 6, 2019).

Thomas, S. (2016). The Hinkley Point Decision: an Analysis of the Policy Process. *Energy Policy* 96, 421–431. doi:10.1016/j.enpol.2016.06.021

Wang, Q., and Li, R. (2016). Journey to Burning Half of Global Coal: Trajectory and Drivers of China's Coal Use. *Renew. Sustain. Energ. Rev.* 58, 341–346. doi:10.1016/j.rser.2015.12.104

Wang, S., Su, H., Chen, C., Tao, W., Streets, D. G., Lu, Z., et al. (2020). Natural Gas Shortages during the "Coal-To-Gas" Transition in China Have Caused a Large

Redistribution of Air Pollution in winter 2017. *Proc. Natl. Acad. Sci. U.S.A.* 117, 31018–31025. doi:10.1073/pnas.2007513117
Wang, Y., Zhang, S., and Hao, J. (2019a). Air Pollution Control in China: Progress, Challenges and Future Pathways. *Res. Environ. Sci. (in Chinese)* 32 (10), 1755–1762.
Wang, Z., Li, C., Cui, C., Liu, H., and Cai, B. (2019b). Cleaner Heating Choices in Northern Rural China: Household Factors and the Dual Substitution Policy. *J. Environ. Manage.* 249, 109433–109437. doi:10.1016/j.jenvman.2019.109433
Wang, S. (2008). Changing Models of China's Policy Agenda Setting. *Mod. China* 34 (1), 56–87. doi:10.1177/0097700407308169
Wang, Q. (2013). China's Citizens Must Act to Save Their Environment. *Nature* 497, 159. doi:10.1038/497159a
Wei, G., Cui, G., and Song, Y. (2016). Discussion on the Control of Coal Pollution in Beijing, Tianjin, Hebei. *Environmental Protection (In Chinese)* 6, 28–30.
Wu, X., Ramesh, M., Howlett, M., and Fritzen, S. (2010). *The Public Policy Primer: Managing the Policy Process*. London: Routledge.
Wu, L., Wu, D., Yan, X., Zhang, J., Zhao, B., and Zhang, Z. (2018). Performance Analysis of Rural "Coal to Electricity"in Beijing-Tianjin-Hebei. *Power Demand Side Manage. (in Chinese)* 20 (4), 36–41. doi:10.3969/j.issn.1009-1831.2018.04.008
Wu, S., Zheng, X., Khanna, N., and Feng, W. (2020). Fighting Coal - Effectiveness of Coal-Replacement Programs for Residential Heating in China: Empirical Findings from a Household Survey. *Energ. Sustain. Dev.* 55, 170–180. doi:10.1016/j.esd.2020.02.002
Xie, L., Chang, Y., and Lan, Y. (2019). The Effectiveness and Cost-Benefit Analysis of Clean Heating Program in Beijing. *China Environ. Manage. (in Chinese)* 3, 87–93.
Xie, X., Ai, H., and Deng, Z. (2020). Impacts of the Scattered Coal Consumption on PM2.5 Pollution in China. *J. Clean. Prod.* 245, 118922. doi:10.1016/j.jclepro.2019.118922
Xinhua Net (2016). *Meeting of the Leading Group for Financial and Economic Affairs: Adopting Clean Energies, Enhancing the Proportion of Clean Energies* 21st, December. Available at: http://finance.china.com.cn/news/gnjj/20161221/4037342.shtml> (Accessed November 6, 2019).
Xu, S., and Ge, J. (2020). Sustainable Shifting from Coal to Gas in North China: an Analysis of Resident Satisfaction. *Energy Policy* 138, 111296. doi:10.1016/j.enpol.2020.111296
Xu, P., Chen, Y., and Ye, X. (2013). Haze, Air Pollution, and Health in China. *The Lancet* 382, 2067. doi:10.1016/S0140-6736(13)62693-8
Yan, Z., Jin, L., Chen, X., Wang, H., Tang, Q., Wang, L., et al. (2019). Assessment of Air Pollutants Emission Reduction Potential and Health Benefits for 'Residential Heating Coal Changing to Electricity' in the Beijing-Tianjin-Hebei Region. *Res. Environ. Sci. (in Chinese)* 32 (1), 95–103. doi:10.13198/j.issn.1001-6929.2018.10.16
Yan, Y., Jiao, W., Wang, K., Huang, Y., Chen, J., and Han, Q. (2020). Coal-to-Gas Heating Compensation Standard and Willingness to Make Clean Energy Choices in Typical Rural Areas of Northern China. *Energy Policy* 145, 111698. doi:10.1016/j.enpol.2020.111698
Yang, H., and Li, P. (2019). Reform and Evolution of China's Policy Agenda. *Henan Soc. Sci. (In Chinese)* 27 (4), 10–15.
Yun, Y., Shao, Z., and Yao, D. (2018). Comparative Analysis on Operation Cost of Coal to Gas and Coal to Electricity in Hebei Province in Winter. *Reg. Heat. (in Chinese)* 4, 79–82.
Zhang, Z., Wang, W., Cheng, M., Liu, S., Xu, J., He, Y., et al. (2017). The Contribution of Residential Coal Combustion to PM 2.5 Pollution over China's Beijing-Tianjin-Hebei Region in Winter. *Atmos.Environ* 159, 147–161. doi:10.1016/j.atmosenv.2017.03.054
Zhang, X., Dai, H., Jin, Y., and Zhang, S. (2019a). Evaluation of Health and Economics Benefits from "Coal to Electricity" Policy in the Residential Sector in the Jing-Jin-Ji Region. *J. Peking Univ. (Natural Sciences)* 55 (2), 367–376.
Zhang, X., Jin, Y., Dai, H., Xie, Y., and Zhang, S. (2019b). Health and Economic Benefits of Cleaner Residential Heating in the Beijing-Tianjin-Hebei Region in China. *Energy Policy* 127, 165–178. doi:10.1016/j.enpol.2018.12.008
Zhang, Q., Zheng, Y., Tong, D., Shao, M., Wang, S., Zhang, Y., et al. (2019c). Drivers of Improved PM2.5 air Quality in China from 2013 to 2017. *Proc. Natl. Acad. Sci. U.S.A.* 116 (49), 24463–24469. doi:10.1073/pnas.1907956116
Zhang, Y., Li, W., and Wu, F. (2020). Does Energy Transition Improve Air Quality? Evidence Derived from China's Winter Clean Heating Pilot (WCHP) Project. *Energy* 206, 118130. doi:10.1016/j.energy.2020.118130
Zhang, J. (2019a). *Fellow of CEA Xie Ke Chang: We Need a Coal Revolution, but Not to Revolutionize Coal*. The Paper. 24th October, 2019. Available at: https://www.thepaper.cn/newsDetail_forward_4751896 (Accessed November 6, 2019).
Zhang, J. (2019b). *Deputy Direction of Electricity Department of NEA: Rural Clean Heating Is a New Thing, and it Brings Heavy Tasks*. The Paper. 28th August, 2019. Available at: https://www.thepaper.cn/newsDetail_forward_4273433 (Accessed November 6, 2019).
Zhao, J., and Xue, L. (2017). The Response-Oriented Agenda-Setting Process—The Analysis Based on the Cases of Public Policy Transition in China. *Cass J. Polit. Sci. (in Chinese)* 3, 42–51.
Zhao, N., Zhang, Y., Li, B., Hao, J., Chen, D., Zhou, Y., et al. (2019). Natural Gas and Electricity: Two Perspective Technologies of Substituting Coal-Burning Stoves for Rural Heating and Cooking in Hebei Province of China. *Energy Sci Eng* 7, 120–131. doi:10.1002/ese3.263
Zhao, Y. (2021). *Village Officials Coercively Removed Villagers' Heating Stoves? the Fact Tests the Wisdom of Local Governance*. China Comment. Available at: http://www.banyuetan.org/jrt/detail/20210111/1000200033134991610189451759780661_1.html (Accessed January 25, 2021).
Zhou, L., Dai, W., Wan, S., and Ren, Q. (2018). *Plans to Move Households to Clean Energy Face Challenges Again this winter*. Beijing: Cainxin. Available at: https://www.caixinglobal.com/2018-11-08/plans-to-move-households-to-clean-energy-faces-challenges-again-this-winter-101344637.html (Assessed November 6, 2019).
Zhu, H. (2017). *Rural Primary Schools in Quyang County Cannot Access heating China Youth Daily*. 5th December Available at: http://zqb.cyol.com/html/2017-12/05/nw.D110000zgqnb_20171205_6-03.htm (Assessed November 6, 2019).

Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 15 July 2021
doi: 10.3389/fenrg.2021.694338

Phased Impacts of China's Dual-Credit Policy on R&D

Xu Li and Qing Y. Xiong*

School of Business, Central South University, Changsha, China

As a sustainability policy in emerging markets, the dual-credit policy was implemented in China to promote automakers expanding investment in research and development, and ultimately achieve the energy-saving and emission-reduction goals of the auto industry. We regard the dual-credit policy as a quasi-natural experiment, use the difference-in-difference model to divide Chinese automakers into an experimental group (the passenger vehicle group) and a control group (the commercial vehicle group), and analyze the impacts of the dual-credit policy in the brewing period (2014–2016) and the implementation period on the scale, intensity, and structure of research and development investment. We found that the dual-credit policy has significantly promoted the research and development investment of automakers, and the heterogeneity of automakers has a moderating effect on the policy effects. In addition, we also found that there are certain differences in the significance and stability of the effects of the dual-credit policy during the brewing period and the implementation period. Finally, we presented some management insights into the response to the dual-credit policy.

Keywords: dual-credit policy, new energy vehicles, R&D investment, difference-in-difference model, industrial policy

OPEN ACCESS

Edited by:
Chan Wang,
Guangdong University of Finance and Economics, China

Reviewed by:
Ehsan Rasoulinezhad,
University of Tehran, Iran
Vidya C T,
Center for Economic and Social Studies (CESS), India

****Correspondence:***
Xu Li
36848663@qq.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *13 April 2021*
Accepted: *10 June 2021*
Published: *15 July 2021*

Citation:
Li X and Xiong QY (2021) Phased Impacts of China's Dual-Credit Policy on R&D. Front. Energy Res. 9:694338. doi: 10.3389/fenrg.2021.694338

INTRODUCTION

Since 2015, China has become the world's largest producer and marketer of new energy vehicles (NEVs)[1] for six consecutive years,[2] but there is still a lack of major breakthroughs in the key-core technologies of NEVs (Wang, et al., 2020). One of the important reasons is the excessive dependence of automakers on government subsidies, and the lack of driving force and pressure for technology's research and development (Wen and Huang, 2020; Yan and Huang, 2020). Therefore, how to use the nonsubsidized policy to continue the cultivation function of industrial policy, enhance the power and pressure of R&D and innovation of automakers, and establish a long-term mechanism for energy-saving and NEV management are the top priorities of policy-makers in industrial policy design (Ministry of industry and information technology of the people's Republic of China, 2017; Fernandez, et al., 2018).

Drawing lessons from the Zero Emission Vehicle Mandate (ZEVM) in California and European Union Emission Trading Scheme (EUETS), China planned originally in 2014 and officially rolled out the "Parallel Administrative Measures for Passenger Vehicle Corporate Average Fuel Consumption and New Energy Vehicle Credits" (the dual-credit policy for short) in September 2017. Among them, the Corporate Average Fuel Consumption Credit (CAFCC) focuses on examining the energy-saving and

[1]New energy vehicles refer to vehicles with new technologies and new structures that use unconventional vehicle fuels as power sources. In China, new energy vehicles mainly refer to hybrid electric vehicle (HEV), battery electric vehicle (BEV), extended-range electric vehicles (EREV), and fuel cell battery electric vehicle (FCBEV).
[2]Source: https://www.marklines.com

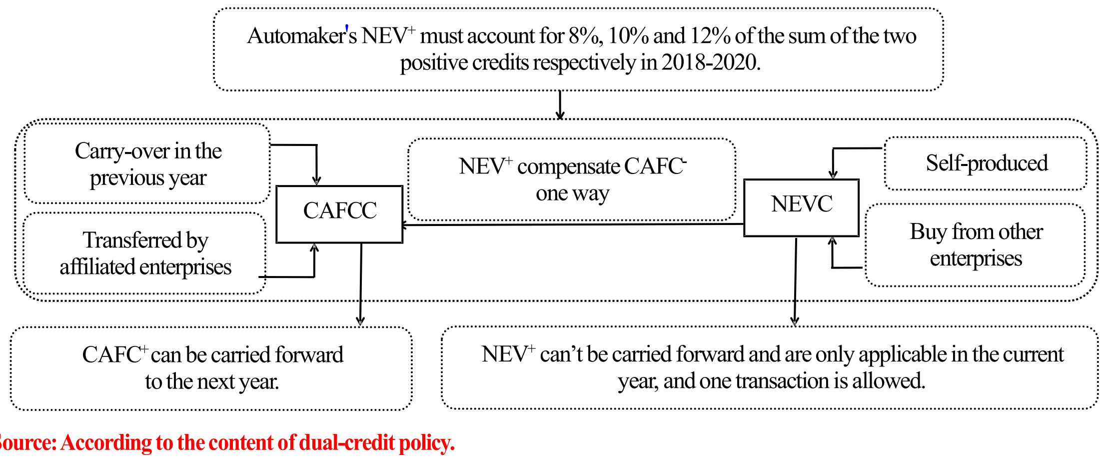

FIGURE 1 | Operation mechanism of the dual-credit policy for Chinese automakers.

efficiency-enhancing level of traditional automobile. The New Energy Vehicle Credit (NEVC) focus on the assessment of NEV's energy-saving emission reduction level. The policy stipulates that the CAFC-negative credits ($CAFC^{-}$) must be offset, and the ways of compensation include the CAFC-positive credits ($CAFC^{+}$) carry-over in the previous year, $CAFC^{+}$ transferred by affiliated enterprises, or own NEV-positive credits (NEV^{+}) or NEV^{+} from other automaker. These rules will force automakers to expand R&D investment in the short term and achieve $CAFC^{+}$ assessment standards through energy-saving and efficiency-enhancing technologies. At the same time, automaker's NEV^{+} must account for 8, 10, and 12% of the sum of the two positive credits, respectively, in 2018–2020, which can be earned by producing or buying. In the long run, these rules can incentivize automakers to expand investment in R&D of NEV in order to seek competitive advantage and profit from point trading. China expects to build a management mechanism of "two integral parallel management, two types of vehicle-coordinated development" by implementing the dual-credit policy (**Figure 1**). Credit policy, an effective policy instrument, is used widely in the administration of public affairs such as environmental protection (John, 2008), household registration management (Xie, 2014), and social services (Qian et al., 2017). Nevertheless, this is a new exploration for China's auto industry to introduce such policy. It is still to be proven by the academia whether it is effective for automakers to expand R&D investment.

There are two shortcomings in previous studies. First, China's dual-credit policy was formulated based on learning from the ZEVM and EUETS, but its contents and quotas were different. There are also differences in NEV technologies and market in China and other countries, so some existing results of ZEVM may not be perfectly suitable for China. In addition, the impacts of an industrial policy often have a pre-diffusion period. Actively picking up policy signals and pre-acting are common in modern enterprise operation (Sierzchula et al., 2012; Cherif and Hasanov, 2019). Actually, the dual-credit policy exerted a considerable impact starting from the brewing period, but existing research gave more weight to its impacts in the implementation period than to those in the brewing period.

In summary, this study focuses on the following issues in the context of China's dual-credit policy. 1) Does the dual-credit policy encourage automakers to expand R&D investment? What are the characteristics of the scale, intensity, and structure of R&D investment? 2) In the context of the dual-credit policy, does corporate heterogeneity have a moderating influence on policy effects? 3) In the different periods of the dual-credit policy, do the policy effects have phased characteristics?

The main contributions are as follows. 1) In terms of research design, existing researches mainly use theoretical analysis rather than data simulation to study the dual-credit policy (*Literature Review* Section). However, we regard the dual-credit policy as a quasi-natural experiment, using the DID model to gain some new insights. 2) In terms of research content, on the basis of the scale and intensity of R&D investment, we have added discussions on the structure of R&D investment. In addition, we divide the impact of the dual-point policy into the brewing period and the implementation period, and compare the phased characteristics of the policy effects at different periods (*Did Result* Section). 3) In terms of research conclusions, we found that the automakers took the initiative to respond during the brewing period and make arrangements in advance. This is different from some conclusions of existing researches, which provides new insights for academic researchers and policy-makers (*Conclusion* Section).

The rest of this article is structured as follows. The *Literature Review and Theoretical Analysis* section conducts the literature review and formulates the research hypotheses; *The Model and Methods* section provides a detailed description of the design of this study; the *Empirical Analysis* section derives the empirical results; and the *Conclusion and Policy Implications* section summarizes the full article and draws relevant policy implications.

LITERATURE REVIEW AND THEORETICAL ANALYSIS

Literature Review

1) Nonsubsidized policies in the NEV industry

Our research background is related to nonsubsidized policies, which have become a popular topic in the field of the NEV industry in recent years. Scholars generally believe that nonsubsidized policies, including infrastructure policies (Andrenacci et al., 2016), commercial demonstration (Barton and Schütte, 2017; Li et al., 2019a), government procurement policies (Xiong and Li, 2019), and right-of-way priority policies (Langbroeket al., 2016), have a positive effect on the development of the NEV industry and corporate innovation. Our study also explores nonsubsidized policies in the NEV industry (i.e., China), but the difference is that we focus on the impact of technical standard policy (i.e., the dual-credit policy) on R&D in the NEV industry.

2) Credit policy in the NEV industry

Many literatures explore the ZEVM in the NEV industry. Some scholars believe that the ZEVM has a positive effect in promoting the innovation of NEVs, such as reducing R&D costs (Majumdar, 2005), increasing R&D investment and patents (Stokes and Breetz, 2018), restraining free-riding (Sykes and Axsen, 2017), and mass production (Melton et al., 2016).

Furthermore, some scholars noticed the problems in its implementation, such as "picking the wrong winner" (Nordhaus, 2011), market failure (Weber and Rohracher, 2012), weakening the effects of other policies (Rubal et al., 2019), and increasing carbon emissions in the short term (William et al., 2020).

Our study also explores the credit policy (i.e., the dual-credit policy) in the NEV industry. The difference is that we divide the dual-credit policy into the brewing period and the implementation period, and theoretically analyze the mechanism of action in different periods.

3) The dual-credit policy

Existing research on the dual-credit policy can be divided into two levels. At the micro level, researchers mainly focused on the changes in automakers' corporate decision-making. Cheng and Mu (2018) discussed the optimal pricing, production, and internally negotiated prices under the three strategies of insufficient credits, surplus credits, and credit balance. Zheng et al. (2019) used a three-stage game model to analyze the impact of positive credit prices on the R&D investment of automakers. Li et al. (2020) discussed optimizing production of NEVs with across-chain cooperation under the dual-credit policy. Tang et al. (2020) analyzed the influence of NEV^+ threshold on the optimal decision-making of automakers. Li and Xiong (2021) used the PVAR model to analyze business and environmental performances of automakers. Ma et al. (2021) analyzed the fuel economy, production, and coordination of conventional automotive supply chains under the dual-credit policy.

At the macro level, it focuses on the trend of the EV sales and industry profits (Ou et al., 2018), the market share of different vehicles (Wang et al., 2019), implications for private motorization rate and battery market (Hsieh et al., 2020), and greenhouse gas consequences (He, et al., 2020).

All of the aforementioned literature mainly adopted data simulation methods or pure theoretical analysis, and few empirical analyses using micro data have been conducted. We extended the dimension of R&D structure based on established dimensions, which included R&D scale and R&D intensity. As far as we know, there has been no research studying the multidimensional characteristics of R&D under industrial policy. Our study considers these changes to better predict and explain the impact of the dual-credit policy.

Theoretical Analysis and Assumptions

The theory of innovation deemed that technological coercion standards will bring more constraints and cost to enterprises, but opportunities are given for them to keep original values or create new ones, so R&D investment and technological innovation can be swelled (Oliver and Holzinger, 2008). Moreover, industrial policy has a more positive effect on enterprises' R&D investment in strategic emerging industries than on those in general industries (Yülek et al., 2020).

1) The dual-credit policy greatly affects the investment from the brewing period to the implementation period and presents fresh characteristics in the scale, intensity, and structure of R&D.

First of all, the mandatory regulatory characteristics of the dual-credit policy in the short term can be effective automakers' R&D investment and technological innovation (Haščič et al., 2009). So far, China's auto industry has performed mediocre in innovation, especially in key-core technologies such as batteries, electric drive systems, and power control systems, which needs to be supplemented (Xie and Zeng, 2019). The policy requires automakers to sell enough NEVs every year to earn credits accounting for 8, 10, and 12% in 2018–2020, respectively. Emission requirements of conventional auto can be met, and NEV^+ surplus can be earned only through widening the R&D scale and technological innovation. Meanwhile, the compulsory designs of "independent accounting and differentiated calculation" strengthen the motives of materializing benefits of automakers *via* technological innovation (Sykes and Axsen, 2017); standards may give stronger incentives than permits (Wesseling, et al., 2014).

Second, credits that use rules of "free trade and one-way offset" are substitutes and link with the subsidized policy in favor of enhancing long-term anticipation of automakers' R&D innovation profits. Tradable NEV^+ is essentially a class of pollution rights trading providing long-term incentives to passenger car enterprises through market mechanisms to compensate enterprises' energy-saving and emission reduction behaviors (Tsakiris et al., 2018). On the one hand, credit calculation and offset rules are not only the law enforcement basis for government to impose penalties but also the policy basis for manufacturers to earn NEV government subsidies after phasing out the NEV subsidy. They are now the government compensation of automakers' R&D innovation and step-by-step replacement of the subsidized policy. On the other hand, NEV credit surplus can be used to make up for the high R&D investment *via* market transaction. It aims to indemnify automakers' R&D innovation through market and connect the original subsidized policy. Consequently, the incentivized characteristic of the dual-credit policy is propitious for intensifying their R&D investment (Wang et al., 2019).

In addition, environmental regulation and technological innovation policies are integrated into the dual-credit policy, alleviating difficulties for automakers' selections between up-to-standard and R&D investment. Policy regulation and technological innovation promote and interact with each other (Guo et al., 2017). For one thing, the credit evaluation system signaled new regulatory assessments to automakers, so those with sound technological foundation will opt to comply with demands by widening R&D investment, notably the scale of developers, and expanding leading edges *via* self-innovation. For another, the offset credits boost the capital input of some automakers with weak technological ground. In the short run, their credits will be hit through technological cooperation among enterprises, establishment of affiliated enterprises, or credit trade, and the R&D structure may be changed by the growth of capital. More development of automakers and upgrading transformation in the auto industry are made by these two innovation strategies.

Based on above theoretical analysis, the research hypothesis, "H1 Under the dual-credit policy, automakers invest R&D more," is proposed to consist of the following three parts:

H1a: Under the dual-credit policy, automakers enlarge their R&D scale,

H1b: Under the dual-credit policy, automakers intensify their R&D intensity,

H1c: Under the dual-credit policy, automakers adjust their R&D structure.

2) China's automakers are greatly heterogeneous in market orientation, enterprise scale, and profitability, so the moderation effect is reflected in motivating the dual-credit policy to some extent.

First of all, passenger vehicles (PVs) and commercial vehicles (CVs) are two types of market orientation for China's automakers (Xiong and Li, 2019). The dual-credit policy evaluates PVs directly, but the Ministry of Industry and Information Technology (MIIT) held seminars many times on the credit policy of CVs, suggesting that those automakers may not be excluded. At present, the PV makers are facing more pressure on the credit assessment, and the time is urgent and the task is heavy. Therefore, the promotion effect of the dual-credit policy on the scale and intensity of PV makers' R&D will be more obvious. Otherwise, PV makers are facing more complex types of consumers, richer models, and more difficulty to develop. Therefore, under the dual-credit policy, the adjustment and optimization of the R&D structure of PV makers will be more obvious.

Second, an enterprise scale is an important internal characteristic that affects R&D. The larger the scale of the automakers, the more NEV^+ and $CAFC^+$ required for the assessment of compliance, and the greater the difficulty of technological innovation. Therefore, small-scale automakers with limited innovation resources and R&D talents tend to concentrate on breakthrough innovation of key technologies, which is an important growth mechanism for latecomers to achieve industrial breakthrough. Large-scale automakers have certain advantages in the R&D scale and tend to carry out global innovation of common technology from the perspective of long-term interests, and their R&D changes will be more significant (Liu, 2019).

Furthermore, enterprise profitability affects the sustainability of R&D investment (Dimitropoulos, 2020). The R&D of automotive belongs to knowledge and capital intensive risk investment. The profitability and profit level of automakers determine the frequency and intensity of their innovation activities. Therefore, under the dual-credit policy, the higher the degree of profitability, the more obvious the growth of their R&D investment.

With the theoretical analysis given above, the research hypothesis, "H2 automakers' heterogeneity exerts a moderation impact on the dual-credit policy incentives," is proposed to compose of the following three sections:

H2a: Under the dual-credit policy, PV makers are motivated more than CV ones,

H2b: Under the dual-credit policy, larger automakers are inspired more than smaller ones,

H2c: Under the dual-credit policy, automakers with better profitability are encouraged more than poorer ones.

3) In order to make up for the disadvantages of the subsidized policy, China began to formulate the dual-credit policy in 2014. The MIIT began to organize government officials, experts, and scholars to learn and discuss ZEVM and other policies. At the same time, it publicly solicited opinions and suggestions from the society, released industrial policy reform signals through various ways, induced automakers to respond positively, and made a layout in advance. In 2017, the dual-credit policy was officially released, and some of the rules were revised every year (**Table 1**). Therefore, it is necessary to divide the dual-credit policy into the brewing period (2014–2016) and the implementation period (2017–2019) to study its phased impact on the R&D investment of automakers.

The relationship between the research hypotheses proposed in this study is shown in **Figure 2**.

THE MODEL AND METHODS

Samples and Date

At present, the dual-credit policy assesses automakers with annual production and sales of more than 30,000 passenger vehicles, and listed companies are the focus of the assessment. At the same time, considering the continuity and availability of data, we selected 20 China automakers' listed companies as our sample.[3] Among them, 15 automakers which mainly provide PVs are direct objects of the dual-credit policy, and another five automakers that sold CVs are potential objects. Hence,

[3]Every listed company actually includes multiple automakers. For example, the SAIC Group includes Shanghai Volkswagen, Shanghai GM, and SAIC-GM-Wuling, and the GAC Group includes GAC Honda, GAC Toyota, and GAC Mitsubishi.

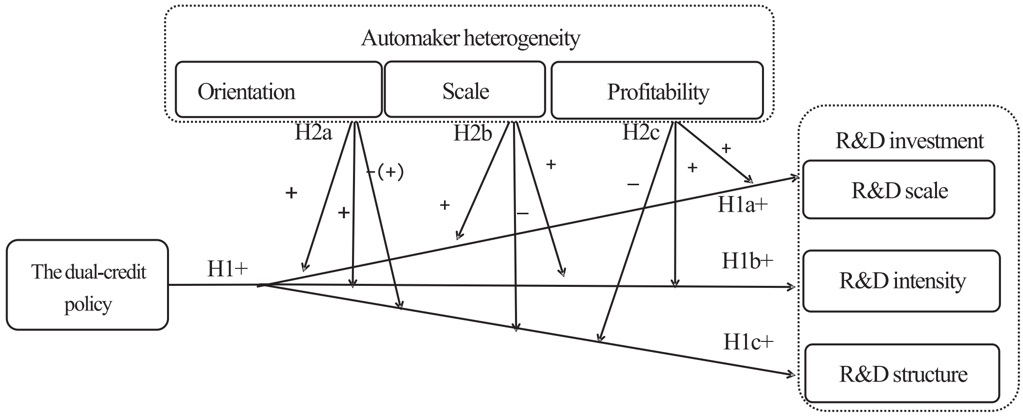

FIGURE 2 | Relationship of research hypothesis.

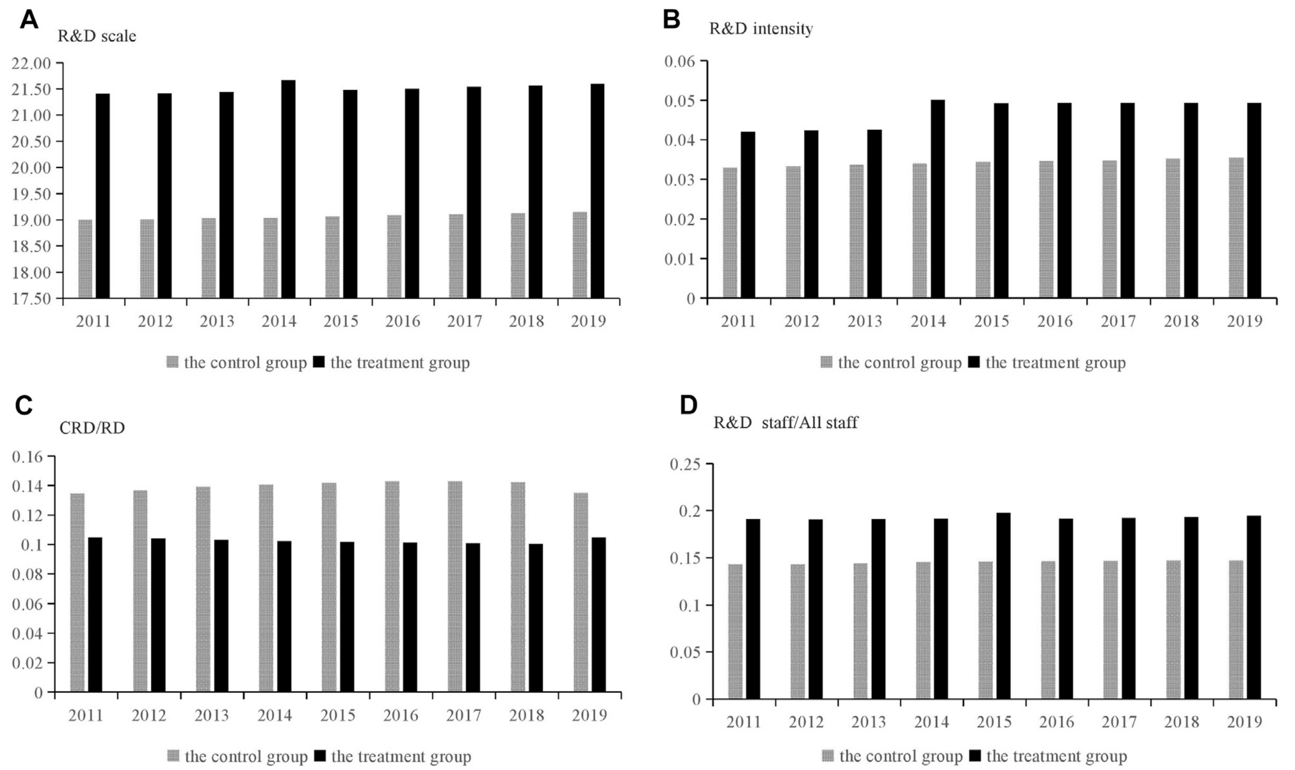

FIGURE 3 | Annual statistics of the average R&D investment of the T-group and the C-group.

according to **Table 2**, this research dissevers these samples as the T-group (PV makers) and the C-group (CV makers).

According to **Figure 3**, we can find that in 2014 (the year of rolling out the dual-credit policy), the maximum difference of the R&D scale mean value between the T-group and the C-group reaches to 2.63 log units, indicating that the dual-credit policy boosted the R&D scale of PV makers more. The maximum difference of the R&D intensity mean value between the T-group and the C-group automakers reached 1.6% in 2014. In the R&D structure of PV makers, the capitalization ratio (CRD/RD) mean value starts to decrease in general with a clear adjustment direction, and the difference between it and the R&D staff ratio (RDS/AS) mean value of CV makers narrows quickly since 2014 and reaches the minimum of about 5.2%, showing that the enactment and implementation of the dual-credit policy is propitious to promote PV makers' R&D

investment, and credit trade motivates them to enlarge the R&D scale and intensity, and upgrade the R&D structure at the same time.

Model and Variable

The DID model is based on the idea of natural science research, which treats policies as natural experiments or quasi-experiments outside the economic system, and effectively controls the *ex ante* differences between the research objects through modeling, to separate the real results of policy influences effectively (Ashenfelter and Card, 1985; Yi et al., 2020). It can avoid the endogeneity of explanatory variables (such as policies), especially in the case of using panel data, which not only use the exogeneity of explanatory variables but also control the influence of unobservable overall factors that change over time, and finally get unbiased estimation of policy effects.

Under the dual-credit policy, the impacts on R&D are described as follows:

$$Y_{it} = \beta_0 + \beta_1 Exami_{it} + \beta_2 Time_{it} + \beta_3 Did_{it} + \beta_4 Moderator_{it} + \beta_5 Control_{it} + \varepsilon_{it}, \tag{1}$$

where Y_{it} represents the R&D of automakers, β_1 controls the difference between the T-group and the C-group, β_2 controls the common impact of time on the T-group and the C-group, β_3 reflects the effect of the dual-credit policy in promoting automakers' R&D, i means different automakers, and t means different years. The value of $Exami_{it}$ is 1 or 0, which represents the T-group and the C-group. The value of $Time_{it}$ is 1 or 0, which represents the postimpact (2014–2019) and pre-impact (2011–2013) of the dual-credit policy, respectively. $Moderator_{it}$ represents moderating variables, that is, automaker heterogeneity. $Control_{it}$ represents control variables, that is, subsidized policies. β_4 and β_5, respectively, represent the regression coefficients. ε_{it} means the random error term (See **Table 3**).

Robust Test

1) Correlation test. In order to eliminate the correlation between correlated variables and error terms, an endogeneity test is necessary. The results manifest that the correlation coefficient between the R&D scale and dummy variables ($Exami_{it}$ and $Time_{it}$) evaluating the dual-credit policy is 0.208 ($p < 0.05$) and 0.224 ($p < 0.05$), respectively; between the R&D scale and profitability is 0.652 ($p < 0.01$) and 0.374 ($p < 0.01$), respectively; and between the R&D scale and Subs is −0.505 ($p < 0.01$). High correlation did not exist among other control variables. The VIF of all variables is far smaller than the upper limit of 10. The correlation between R&D intensity, the R&D structure, and other major variables holds the similar feature. Thus, regression results are not intervened by collinearity.

2) Parallel trend test. The interaction term between the dummy variable year of the generation year and the dummy variable treat of the T-group is added to the model 2) for regression (M and N represent the number of periods before and after the policy, respectively), and then the coefficient β_j of the interaction term $treat_i \times year_j$ is measured. It is the difference between the T-group and the C-group in $period_j$. Specifically, β_0 is the current effect of the dual-credit policy, β_{-3}–β_{-1} are the effects of 2011–2013 before the dual-credit policy is brewed, and $\beta1$–$\beta5$ are after the release of the dual-credit policy signal in 2015–2019. The first period (2013) before the release of the dual-credit policy signal was selected as the model's benchmark group. The results show (taking the R&D scale as an example) that the coefficients β_{-3}–β_{-1} are not significantly different from 0, indicating that there is no significant difference between the T-group and the C-group in the one-to-three period before the dual-credit policy. The T-group and the C-group are comparable before the brewing period of the dual-credit policy, and the parallel trend assumption is established.

$$Y_{it} = \alpha + \sum_{M}^{N} \beta_j treat_i \times year_j + \lambda_i + \nu_i + \xi_{it}. \tag{2}$$

3) DID-PSM test. In order to eliminate the selection bias caused by the different initial conditions between the T-group and the C-group, the propensity matching method is used for testing (taking the R&D scale as an example). As a reference, first perform a univariate regression; the policy effect is 1.4905 ($p < 0.01$) and $R^2 = 0.1379$, that is, the impact of the dual-credit policy can explain 13.78% of the change in the R&D scale by the sample enterprise. Further introducing covariates for multiple regression, the Did_{it} is 0.6515 ($p < 0.1$), market orientation ($p < 0.01$), the enterprise scale ($p < 0.05$), and subsidies ($p < 0.1$) are all significant, and tax preference is not significant.

The data are randomly sorted for propensity score matching. Since the sample size is not large, matching with replacement is performed, and parallel is allowed. The $\log_{it}$ regression results show that the estimated ATT is 0.2036, and the t value is less than 1.96, which is not significant. The regression results of sample estimations after matching procedure are consistent with that before matching. Among the total 180 observations, 19 in the C-group are not in the common value range (off support), two in the T-group are not in the common value range (off support), and the remaining observations are in the common value range (on support).

Further examine whether the matching results balance the data well. The results show that the standard deviation of most variables after matching is less than 10%, the deviation of tax preference variables is 11.2%, and the results of most t-tests do not reject the null hypothesis that there is no systematic difference between the T-group and the C-group. It shows that most observations are within the common value range, so only a small number of samples will be lost when propensity score matching is performed.

EMPIRICAL ANALYSIS

DID Result

From the perspective of policy effects, as shown in **Table 4**, the R&D investment is markedly boosted by the dual-credit policy with more obvious growth of scale than that of intensity. The Did_{it} of the R&D scale and R&D intensity is 0.4031 ($p < 0.05$) and 0.013 ($p < 0.05$), respectively, meaning that comparing the T-group with the C-group after implementing the dual-credit policy, the R&D scale, which grows more, increased by 40.31%

TABLE 1 | Main policy signals in different stages of the dual-credit policy.

	Year	Policy signals	Enterprise behaviour
Brewing period	2014	(1) The MIIT organizes officials, experts, and scholars to study ZEVM and EUETS. (2) China established the China–U.S. NEV policy laboratory	Representatives of automakers (BYD, BAIC, BMW, Ford, and Nissan) participated in the signing ceremony of the China-US NEVs policy laboratory and received the signal of the dual-credit policy
	2015	(1) The MIIT solicits suggestions from the public for the dual-credit policy (2) The management measures for CAFC (draft) was issued	With the production and sales of NEVs exceeding 330,000, China has become the world's largest market.
	2016	(1) The MIIT announced the first round draft of the dual-credit policy (2) The Chinese government notified the WTO of the dual-credit policy	Some countries and automakers have put forward requests for lowering the credit assessment standard and delaying implementation
Implementation period	2017	The MIIT officially promulgated the dual-credit policy	In order to respond to the credit assessment, foreign automakers have begun to establish NEV joint ventures
	2018	The MIIT provides automakers with a one-year buffer period to calculate credits but does not require compliance assessment (it was originally required to reach 8% in 2018)	CAFC drops to 5.8 L/100 km, and the ratio of NEV^+ is as high as 17%, far exceeding the 8% set value
	2019	The assessment standard is adjusted to be 14, 16, and 18% of NEV^+ in 2021–2023. Compared with 2017, the calculation methods of NEVC and CAFCC have also undergone many changes	(1) The product structure of automakers has been significantly adjusted (2) The top ten NEV^+ are all Chinese-independent brand automakers

on average and R&D intensity by 1.31%. It proves that the dual-credit policy has indeed promoted the growth of the R&D scale and intensity of PV makers. The reason may be that the incentive mechanism of the dual-credit policy improves the innovation expectation and motivation of PV makers. At the same time, the dual-credit policy has released a strong signal of the adjustment of China's auto industry to NEVs, which can also lead the capital market to favor the NEV industry and expand the financing channels and the scale of NEVs on the whole. However, the incentive of R&D intensity is relatively weaker. There are two kinds of possible reasons. First, automakers' revenues in the current period rose faster than their R&D scale in 2011–2019: the rapid growth period of China's auto consumers. In consequence, the dual-credit policy incentives were dissolved to some extent. Second, R&D intensity might be suppressed by positive externalities of innovation spillovers in part. Empirical results verify the H1a and H1b in H1 hypothesis.

We have an interesting finding in the R&D structure of PV makers, which shows the characteristics of "valuing capital more than talents." As model I and II document in **Table 4**, the Did_{it} of the capitalization ratio (CRD/RD) and the R&D staff ratio (RDS/AS) is 0.0840 (p < 0.05) and -0.0054 (p < 0.05), respectively. The results show that after the release of the dual-credit policy signals, the R&D structure of the T-Group has been adjusted more significantly than that of the C-Group. Specifically, the capitalization ratio increased by 8.4%, while the R&D staff ratio decreased by 0.54%. It indicates that under the dual-credit policy, PV makers need to have the independent production capacity of NEVs in order to meet the requirements of the mandatory proportion rule of NEV^+ so as to ensure that they can produce NEV^+ and avoid punishment or reduce the cost of purchasing credits (Li, et al., 2019b). As a result, the adjustment of PV makers' R&D structure is biased toward capital, and the growth level is even much higher than that of the R&D intensity (1.31%) in the short term. Comparatively speaking, the RDS/AS declined slightly, reflecting the characteristic that the PV makers' R&D structure is inclined to capital. It may also be due to the rapid growth of China's automobile market demand, and automakers have a larger increase in the number of employees in production, sales, and other links, leading to a relative decrease in the R&D staff ratio. The empirical results confirm the hypothesis of H1C in H1.

From the perspective of enterprise heterogeneity, such as the market orientation, enterprise scale, and profitability, has a more obvious role in regulating the effect of policy for PV makers. **Table 4** shows that the Did_{it} of market orientation (*Mo*) is 0.3858 (p < 0.1), 0.0084, −0.0296, and 0.0058, respectively, and the result reveals that under the dual-credit policy, automakers targeting the PV orientation are direct subject to policy regulations and are under great pressure for assessment. They urgently need to improve the energy-saving technology of traditional fuel vehicles and the emission reduction technology of NEVs. Therefore, the R&D investment has increased significantly. The Did_{it} of the enterprise scale (scale) is 0.6422 (p < 0.001), 0.0012, 0.0039, and 0.0126 (p < 0.1); it may be that automakers with scale advantages have stronger innovation motives to pursue monopoly advantages and profits; therefore, the performance of expanding the R&D scale and increasing the R&D staff is the most obvious. The Did_{it} of profitability (*Roe*) is 1.9156 (p < 0.01), −0.0107, 0.0274 (p < 0.1), and −0.0056; it shows that automakers with high profitability are more sustainable in increasing R&D investment, which can support a substantial increase in the scale of R&D investment and a continuous increase in the capitalization ratio. The above results indicate that the three factors have a significant positive moderating effect on the scale of R&D investment; among which, the moderating effect of profitability is the most obvious, and the moderating effect of the enterprise scale is the most significant.

After adding a cross-term between the dual-credit policy and the enterprise scale (scale), the coefficients are in negative values and show prominent statistical significance at the 10% level, suggesting that the policy effect becomes feebler if an automaker becomes larger. Affected by the

TABLE 2 | Basic information on the research samples(stock code).

T-group: PV makers	C-group: CV makers
BYD (002,594); Dongfeng Motor (600,006); Foton Motor (600,166); GAC group (601,238); Haima Motor (000,572); JAC Motor (600,418); Lifan Motor. (601,777); SAIC Group (600,104); FAW sedan (000,800); Chang'an Motor (000,625); Chang chen Motor (601,633); Jiang ling Automobile (000,550); Zhong tai Automobile (000,980); Geely Automobile (00,175)	Anhui Ankai Automobile Co. Ltd. (000,868) Xiamen King Long Motor Group Co. Ltd. (600,686) Yangzhou Yaxing Motor Coach Co. Ltd. (600,213) Zhengzhou Yutong Bus Co. Ltd. (600,066) Zhongtong Bus Holding Co. Ltd. (000,957)

TABLE 3 | Variables and index selections.

Variable type	Variable name	Variable description and calculation method
Explained variables	R&D scale	(Current period) R&D investment (natural logarithm)
	R&D intensity	(Current period) R&D investment/(current period) revenues capitalized R&D investment/R&D investment
	R&D structure	R&D staff/all staff
Explain variable	Did_{it}	A cross-term between sample groups and evaluation time; $i = 0$ for commercial vehicles; $i = 1$ for passenger vehicles; $t = 0$ for before the dual-credit policy effect; $t = 1$ for after the dual-credit policy effect
Moderating variables	Enterprise scale	Ending total assets (natural logarithm)
	Profitability	Return on equity (last period)
	Market orientation	1 for passenger vehicles; 0 for commercial vehicles
Control variables	Subs	Government subsidies/revenues (last period)
	Tax preference	(Taxes payments—refunds of taxes)/revenues (last period)

regulation of the mandatory proportion of NEV^+, large-scale automakers have a large output of traditional auto and require a large number of NEV^+, which will make it difficult for $CAFC^+$ to meet the target. The adjustment speed of large-scale automakers is relatively slow, and the effect of the dual-credit policy is slightly insignificant. The Did_{it} increases visibly after adding a quadratic term of scale, up by 13.65% ($p < 0.1$) in the R&D scale and 0.1% ($p < 0.1$) in R&D intensity, showing positive correlations to them. This suggests that a positive U-shaped relation has emerged between R&D investment and the enterprise scale. As for possible grounds, on the one hand, samples are listed companies with large scale, and the overall relationship between the enterprise scale and R&D investment tends to be U-shaped; on the other hand, there are differences in the innovation strategies of automakers, that is, smaller ones focus on key technology, while larger automakers pursue generic technology, no matter what kind of innovation strategy requires automakers to expand R&D investment. Empirical results verify the H2a, H2b, and H2c in H2 hypothesis.

Phased Characteristics

The self-interested strategic responses of different automakers will cause differences in the significance and stability of the policy effects (Wang et al., 2017; Li and Xiong, 2021). Therefore, in order to better provide empirical evidences for policy optimization, we divided the dual-credit policy into the brewing period (2014–2016) and the implementation period (2017–2019), and explored its phased effects.

During the brewing period, the dual-credit policy has a significant and stable effect on the R&D scale, and it has a stable effect on the R&D intensity and the capitalization ratio. **Table 5** and **Figure 4** demonstrate that compared to the brewing period ago, the Did_{it} of the R&D scale and intensity are both greater than 0; the R&D scale grows without a lag period, and the R&D intensity lags by two periods. With higher R^2 values, the model has good fit. It shows that the reform signal of the dual-credit policy has indeed significantly promoted the expansion of R&D investment made by automakers and has the most obvious effect on the R&D scale. There has been no significant change in the capitalization ratio and so as the R&D staff ratio. The reasons may be that the adjustment of the capitalization ratio is relatively slow, or the automakers are still waiting for the revision of the dual-credit policy.

With the release of policy signals, the average growth rates of the R&D scale, intensity, and the capitalization ratio were 15.87, 1.36, and 0.17%, respectively. The Did_{it} of the R&D scale and intensity is relatively stable and that of the R&D staff ratio is unstable. It shows that the policy signal release mechanism can indeed stabilize the expectations of PV makers and encourage automakers to make arrangements in advance. However, the changes in the R&D structure are not significant, which may be related to the fact that the effects of the dual-credit policy need time to accumulate before it becomes apparent.

During the implementation period, the dual-credit policy has a significant and stable effect on the R&D scale, intensity, and the capitalization ratio. **Table 5** and **Figure 4** show that the Did_{it} is significant in all dimensions at the 10% level; among which, the R&D scale and the capitalization ratio increased by 8.14 and 2.67%, respectively, annually, significantly higher than those of the brewing period. It demonstrates that with the formal implementation of the dual-credit policy and the approaching of the credit assessment date, the pressure and motivation of PV

TABLE 4 | DID results of the dual-credit policy.

—	R&D scale (model I)		R&D intensity (model II)		R&D structure			
					CRD/RD (model III)		RDS/AS (model IV)	
Did_{it}	4,031* (0.3997)	3,199* (0.4269)	0131* (0.0067)	0146* (0.0070)	0840* (0.0076)	0888** (0.0331)	−0.0054* (0.0285)	−0.0055* (0.0286)
Mo	3,858* (0.2460)	1772 (0.2255)	0084 (0.0076)	0120* (0.0085)	−0.0296 (0.02828)	−0.0176 (0.0304)	0058 (0.0274)	0055 (0.0286)
Scale	6,422*** (0.0562)	−2.0502* (0.8386)	0012 (0.0008)	0477** (0.0174)	0039 (0.0037)	1582* (0.0635)	0126* (0.0055)	0092 (0.1022)
Scale*Policy*	—	−0.0042* (0.0035)	—	−0.0028* (0.0020)	—	—	—	—
Scale2	—	0607** (0.0191)	—	0010* (0.0004)	—	−0.0034* (0.0014)	—	0000 (0.0023)
Roe	1.9156** (0.6844)	8,847 (0.7740)	−0.0107 (0.0083)	0070 (0.0120)	0274* (0.0392)	0866 (0.0553)	−0.0056 (0.0414)	−0.0069 (0.0481)
Subs	1595* (0.0688)	0888 (0.0688)	−0.0011 (0.0010)	0000 (0.0009)	−0.0016 (0.0043)	0024 (0.0044)	0001 (0.0023)	0000 (0.0030)
Taxp	8,743 (2.4388)	2.2654 (2.4189)	−0.2156* (0.1276)	−0.2396* (0.1312)	−1.4371** (0.4343)	−1.5168** (0.4410)	1.0743*** (0.2450)	1.076*** (0.2486)
Constant	1.3777 (1.6396)	32.5116** (9.5757)	0302 (0.0348)	−0.5081** (0.1899)	1,064 (0.1281)	−1.6786* (0.7154)	−0.1630 (0.1374)	−0.1238 (1.1312)
Fixed effects	Control	—	—	—	—	—	—	—
Year	Control	—	—	—	—	—	—	—
Samples	180	—	—	—	—	—	—	—
Within-R^2	0.6354	0.6646	0.6066	0.6313	0.6563	0.6760	0.6800	0.6800
Prob〉F	0.0000	0.0000	0.0015	0.0001	0.0000	0.0000	0.0000	0.0000

*Note: *, **, *** represent the significance level of 10, 5, and 1%, respectively; ( ) is the standard deviation.*

makers' technology research and development are further enhanced. Under the dual-roles of compulsion and incentive, the PV makers' R&D investment growth and the R&D structure adjustment are more obvious. Compared with 2018, the Did_{it} of the R&D scale and the capitalization ratio in 2019 increased by 24.22 and 7.37%, respectively. Although the Did_{it} of the R&D staff ratio is less than 0, the growth trend has already appeared. In summary, compared with the brewing period, the policy effects of all dimensions of R&D investment have increased to a certain extent, and the development trend is relatively clear. This manifests that with the gradual strengthening of policy signals and the approaching of credit assessment, the dual-credit policy has become more stable in promoting the expansion of R&D investment.

CONCLUSION AND POLICY IMPLICATIONS

Conclusion

We regard China' dual-credit policy as a quasi-natural experiment using the DID model to divide Chinese automakers into an experimental group and a control group, and analyzed the phased impacts on the scale, intensity, and the structure of R&D in the brewing period and the implementation period.

We have reached some main conclusions about the dual-credit policy. First, the policy has encouraged automakers to expand the R&D scale and intensity, and promoted the adjustment of the R&D investment structure to "valuing capital more than talents." It indicates that automakers have begun to actively respond after the release of policy signals. These conclusions are different from the "negative" behaviors of some automakers under the ZEVM, such as delaying the implementation of policies through litigation and political lobbying, or demanding to reduce the credit assessment criteria (Collantes and Sperling, 2008). Second, the heterogeneity of automakers' scale, profitability, and market orientation has obvious moderating effects on policy effects. This is partly consistent with the research conclusion of Xiong et al. (2018). There is a U-shaped relationship between the enterprise scale and the R&D investment, which is inconsistent with the inverted U-shaped relationship theory of modern enterprise R&D tendency (Hu and Li, 2014). This shows that big automakers and small ones have their own advantages in promoting R&D innovation. Third, the effect of China's dual-credit policy has phase characteristics. During the brewing period, the dual-credit policy has a significant and stable effect on the R&D scale, R&D intensity, and the capitalization ratio. During the implementation period, the dual-credit policy has a significant and stable effect on the R&D scale, intensity, and the capitalization ratio. The policy effects of various dimensions of the R&D investment show shock adjustments, but the trend of change is basically determined.

Policy Implications

Our research provides important management insights and policy implications as shown below.

Policy-makers in China: 1) Policy-makers need 2consider promoting the transition from accounting to compensation for

TABLE 5 | Results of the characteristics of the dual-credit policy effect in different periods.

	Brewing period			Implementation period		
	2013/2014	2013/2015	2013/2016	2013/2017	2013/2018	2013/2019
R&D scale	1,592* (0.438)	1,581* (0.426)	1,588* (0.516)	1,751* (0.459)	1,609* (0.540)	4,031* (0.3997)
Within-R2	0.947	0.943	0.907	0.905	0.923	0.6354
R&D intensity	0151 (0.012)	0131 (0.012)	0127* (0.013)	0046* (0.013)	0313* (0.023)	0131* (0.0067)
Within-R2	0.456	0.314	0.295	0.288	0.330	0.6066
CRD/RD	0032 (0.0160)	0023 (0.0115)	−0.0005 (0.0085)	0014 (0.0062)	0103* (0.0055)	0840* (0.0076)
Within-R2	0.617	0.619	0.544	0.569	0.632	0.6563
RDS/AS	−0.0288 (0.045)	0042* (0.040)	−0.0235* (0.043)	−0.0125* (0.043)	−0.0133* (0.055)	−0.0054 (0.0285)
Within-R2	0.236	0.423	0.422	0.452	0.635	0.680

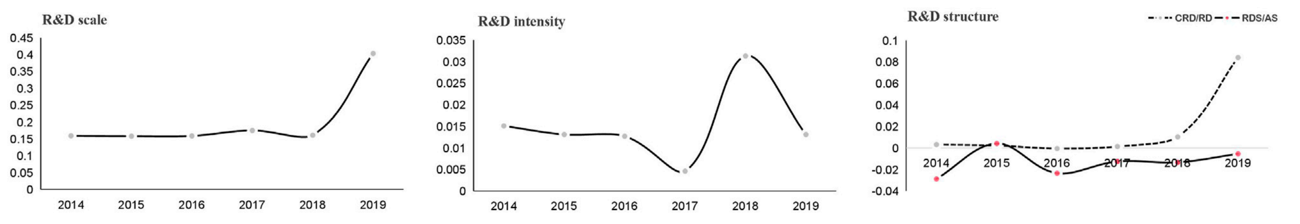

FIGURE 4 | A trend chart of the dual-credit policy effect in different periods.

credit assessment. It has been concluded that the dual-credit policy has significantly promoted the R&D investment of automakers. In order to strengthen the effect of the policy, it is possible to further force automakers to expand R&D investment through the implementation of the credit compensation rules. At the same time, it is necessary to improve the credit trading platform and management system. 2) Policy-makers need to consider adjusting the calculation rules of credits and the scope of assessment objects. It has been concluded that automaker heterogeneity has a significant moderating effect on policy effects. In order to have a wider coverage of the policy effects, more automakers need to be included in the assessment scope. At the same time, taking into account the diversity of NEVs, it is necessary to implement classified guidance and key management for different automakers through flexible credit accounting rules.

Other emerging markets: The dual-credit policy provides important references and practical value to emerging markets facing the same problems. Combined with our conclusions, emerging markets can consider implementing the credit policy in phases, releasing signals to automakers during the brewing period, guiding them to make arrangements in advance, changing from passive compliance to proactiveness, and creating a good industrial foundation for the realization of policy goals during the implementation period.

Future studies: In the future, our research may be further optimized, such as analyzing the difference in the effects on conventional automakers and NEV automakers, which will facilitate more precise policy implementation. In addition, we also need to consider the impact of the revision itself on the effect of the dual-credit policy, which will make the model more complex and bring challenges to the optimization solution. The corresponding research results will help to optimize the dual-credit policy. Finally, some global uncertainties such as the COVID-19 will bring a lot of impacts to our research topics. The income and profits of some automakers may have significantly decreased, and the supply–demand ratio of credits will be tightened in 2021, which will affect the stability and continuity of R&D investment. We also need to consider to control these structural breakpoints or exogenous shocks in the empirical model.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

XL contributed to conception and design of the study, wrote the first draft of the manuscript. Thanks to Professor QX for his contribution to the revision of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

REFERENCES

Andrenacci, N., Ragona, R., and Valenti, G. (2016). A Demand-Side Approach to the Optimal Deployment of Electric Vehicle Charging Stations in Metropolitan Areas. *Appl. Energ.* 182, 39–46. doi:10.1016/j.apenergy.2016.07.137

Ashenfelter, O., and Card, D. (1985). Using the Longitudinal Structure of Earnings to Estimate the Effect of Training Programs. *Rev. Econ. Stat.* 67 (4), 648–660. doi:10.2307/1924810

Barton, B., and Schütte, P. (2017). Electric Vehicle Law and Policy: a Comparative Analysis. *J. Energ. Nat. Resour. L.* 35 (2), 147–170. doi:10.1080/02646811.2017.1262087

Cheng, Y. W., and Mu, D. (2018). Optimal Production Decision of Vehicle Manufacturer Based on Double-Score System. *Syst. Engineering-Theory Pract.* 38 (11), 2817–2830. doi:10.12011/1000-6788(2018)11-2817-14

Cherif, R., and Hasanov, F. (2019). The Return of the Policy that Shall Not Be Named: Principles of Industrial Policy. *IMF Working Pap.* 19 (74), 1–79. doi:10.5089/9781498305402.001

Collantes, G., and Sperling, D. (2008). The Origin of California's Zero Emission Vehicle Mandate. *Transport. Res.* 42 (10), 1302–1313. doi:10.1016/j.tra.2008.05.007

Dimitropoulos, P. E. (2020). R &D Investments and Profitability during the Crisis: Evidence from Greece. *R&D Manag.* 50 (5), 587–598. doi:10.1111/radm.12424

Fernández Fernández, Y., Fernández López, M. A., and Olmedillas Blanco, B. (2018). Innovation for Sustainability: The Impact of R&D Spending on CO2 Emissions. *J. Clean. Prod.* 172 (4), 3459–3467. doi:10.1016/j.jclepro.2017.11.001

Guo, L. L., Qu, Y., and Tseng, M.-L. (2017). The Interaction Effects of Environmental Regulation and Technological Innovation on Regional green Growth Performance. *J. Clean. Prod.* 162 (20), 894–902. doi:10.1016/j.jclepro.2017.05.210

Haščič, I., Vries, F. D., Johnstone, N., and Medhi, N. (2009). Effects of Environmental Policy on the Type of Innovation: The Case of Automotive Emission-Control Technologies. *OECD J. Econom. Stud.* 2009 (1), 1–18. doi:10.1787/eco_studies-v2009-art2-en

He, X., Ou, S., Gan, Y., Lu, Z., Przesmitzki, S. V., Bouchard, J. L., et al. (2020). Greenhouse Gas Consequences of the China Dual Credit Policy. *Nat. Commun.* 11 (1), 5214. doi:10.1038/s41467-020-19036-w

Hsieh, I.-Y. L., Pan, M. S., and Green, W. H. (2020). Transition to Electric Vehicles in china: Implications for Private Motorization Rate and Battery Market. *Energy Policy* 144, 111654. doi:10.1016/j.enpol.2020.111654

Hu, Y. M., and Li, Y. (2014). The Development and Review of Schumpeter Hypothesis Theory-Based on Enterprise Scale, Market Power and R&D Investment. *Rev. Economy Manag.* 30 (005), 107–113. doi:10.13962/j.cnki.37-1486/f.2014.05.016

John, A. M. (2008). How Carbon Credits Could Drive the Emergence of Renewable Energies. *Energy Policy* 36 (10), 3633–3639. doi:10.1016/j.enpol.2008.05.033

Langbroek, J. H. M., Franklin, J. P., and Susilo, Y. O. (2016). The Effect of Policy Incentives on Electric Vehicle Adoption. *Energy Policy* 94, 94–103. doi:10.1016/j.enpol.2016.03.050

Li, G. D., Luo, R. Q., and Gu, Y. F. (2019a). Government's Promotion Policies and the Demand of New-Energy Vehicles: Evidence from Shanghai. *China Ind. Econ.* 4, 42–61. doi:10.19581/j.cnki.ciejournal.2019.04.003

Li, J., Ku, Y., Yu, Y., Liu, C., and Zhou, Y. (2020). Optimizing Production of New Energy Vehicles with Across-Chain Cooperation under china's Dual Credit Policy. *Energy* 194, 116832. doi:10.1016/j.energy.2019.116832

Li, X., and Xiong, Y. (2021). Characteristics of the Impact of Corporate Average Fuel Consumption-New Energy Vehicle Credits (CAFC-NEV) Mandate on the New Energy Vehicle Industry: From the Perspective of Business and Environmental Performances. *Resour. Sci.* 43 (1), 1–11. doi:10.18402/resci.2021.01.01

Li, Y., Zhang, Q., Li, H., Tang, Y., and Liu, B. (2019b). The Impact of Dual-Credit Scheme on the Development of the New Energy Vehicle Industry. *Energ. Proced.* 158, 4311–4317. doi:10.1016/j.egypro.2019.01.792

Liu, C. D. (2019). Impact of R&D Investment on Firm Performance of Single champion Firms in Manufacturing Industry-Based on Heterogeneity Threshold Effects of Firm Size. *R&D Manag.* 31 (01), 39–49.

Ma, H., Lou, G., Fan, T., Chan, H. K., and Chung, S. H. (2021). Conventional Automotive Supply Chains under china's Dual-Credit Policy: Fuel Economy, Production and Coordination. *Energy Policy* 151 (4), 112166. doi:10.1016/j.enpol.2021.112166

Majumdar, S. R. (2005). A Prospect Theory Analysis of California's Initiatives in Implementation of its Zero Emission Vehicles (ZEV) Mandate1. *Rev. Pol. Res.* 22 (2), 157–169. doi:10.1111/j.1541-1338.2005.00127.x

Melton, N., Axsen, J., and Sperling, D. (2016). Moving beyond Alternative Fuel Hype to Decarbonize Transportation. *Nat. Energ.* 1 (3), 16013. doi:10.1038/nenergy.2016.13

Ministry of industry and information technology of the people's Republic of China (2017). Measures for parallel management of average fuel consumption and NEV credits of passenger automakers. Available at: http://www.gov.cn/xinwen/2017-09/28/content_5228217.htm

Nordhaus, W. (2011). Designing a Friendly Space for Technological Change to Slow Global Warming. *Energ. Econ.* 33 (4), 665–673. doi:10.1016/j.eneco.2010.08.005

Oliver, C., and Holzinger, I. (2008). The Effectiveness of Strategic Political Management: A Dynamic Capabilities Framework. *Amr* 33 (2), 496–520. doi:10.5465/amr.2008.31193538

Ou, S., Lin, Z., Qi, L., Li, J., He, X., and Przesmitzki, S. (2018). The Dual-Credit Policy: Quantifying the Policy Impact on Plug-In Electric Vehicle Sales and Industry Profits in China. *Energy Policy* 121, 597–610. doi:10.1016/j.enpol.2018.06.017

Qian, X. Y., Hu, Q., and Su, D. R. (2017). Public Service Right, Residential Permit point Sand Measurement on Rural Migrant Citizenization. *China Econ. Stud.* 9 (05), 47–57.

Rubal, D., Kenneth, W., and Rebecca, L. (2019). Understanding Potential for Battery Electric Vehicle Adoption Using Large-Scale Consumer Profile Data. *Energ. Rep.* 5, 515–524. doi:10.1016/j.egyr.2019.04.013

Sierzchula, W., Bakker, S., Maat, K., and van Wee, B. (2012). Technological Diversity of Emerging Eco-Innovations: A Case Study of the Automobile Industry. *J. Clean. Prod.* 37, 211–220. doi:10.1016/j.jclepro.2012.07.011

Stokes, L. C., and Breetz, H. L. (2018). Politics in the U.S. Energy Transition: Case Studies of Solar, Wind, Biofuels and Electric Vehicles Policy. *Energy Policy* 113, 76–86. doi:10.1016/j.enpol.2017.10.057

Sykes, M., and Axsen, J. (2017). No Free Ride to Zero-Emissions: Simulating a Region's Need to Implement its Own Zero-Emissions Vehicle (ZEV) Mandate to Achieve 2050 GHG Targets. *Energy Policy* 110, 447–460. doi:10.1016/j.enpol.2017.08.031

Tang, J. H., Yang, F., and Xu, J. W. (2020). Optimization of Manufacturing Decision-Making for Automobile Companies Considering the Drivers of Both Sides of Supply and Demand under the Dual-Credit Policy. *Syst. Eng.* (4), 59–68.

Tsakiris, N., Hatzipanayotou, P., and Michael, M. S. (2018). The Efficiency of Decentralized Environmental Policies under Global Pollution and Tradable Emission Permits. *J. Public Econ. Theor.* 20 (4), 541–556. doi:10.1111/jpet.12296

Wang, L. X., Chen, X. G., and Yao, X. L. (2017). Industrial Enterprises'response to Environmental Regulation Policy in China. *China Soft Sci.* 10, 143–152.

Wang, N., Fang, T., and Liu, X. (2019). Research on the Impact of Double Points Policy on China's Auto Market and Policy Evolution. *China Soft Sci.* 1, 203–215.

Wang, Z. P., Yuan, C. G., and Li, X. Y. (2020). An Analysis on Challenge and Development Trend of Safety Management Technologies for Traction Battery in New Energy Vehicles. *Automotive Eng.* 317 (12), 15–29. doi:10.3969/j.issn.1002-9753.2017.10.014

Weber, K. M., and Rohracher, H. (2012). Legitimizing Research, Technology and Innovation Policies for Transformative Change. *Res. Pol.* 41 (6), 1037–1047. doi:10.1016/j.respol.2011.10.015

Wen, G. R., and Huang, J. Q. (2020). Research on the Impact of Government Subsidies on R&D and Innovation Capacity of High-Tech Industries. *East China Econ. Manag.* 34 (7), 9–17. doi:10.19629/j.cnki.34-1014/f.200213013

Wesseling, J. H., Farla, J. C. M., Sperling, D., and Hekkert, M. P. (2014). Car Manufacturers' Changing Political Strategies on the ZEV Mandate. *Transportation Res. D: Transport Environ.* 33, 196–209. doi:10.1016/j.trd.2014.06.006

William, H., Jonn, A., and Erik, K. (2020). How to Slash Greenhouse Gas Emissions in the Freight Sector Policy Insights from a Technology-Adoption Model of Canada. *Energy Policy* 137, 111093. doi:10.1016/j.enpol.2019.111093

Xie, B. F. (2014). Residence Points System: Another "patch" of Household Registration Reform? Characteristics, Problems and Countermeasures of Shanghai Residence Points System. *Popul. Res.* 38 (01), 90–97.

Xie, W. H., and Zeng, D. C. (2019). Empirical Study on Competitiveness Evaluation of New Energy Automobile Industry in Guangdong Province Based on the New Diamond Model. *Sci. Technol. Manag. Res.* 039 (009), 56–61. doi:10.3969/j.issn.1000-7695.2019.09.009

Xiong, Y. Q., and Li, X. L. (2019). Analysis of the Roles and Differences of the Supply and Demand Side Policies of NEV Industry in Heterogeneous Markets. *Stud. Sci. Sci.* 4, 597–606.

Xiong, Y. Q., Fan, S. W., and Liu, X. Y. (2018). The Difference of Fiscal Subsidies for NEVs and R&D Investment Intensity of the Manufacturers: An Analysis Based on the Heterogeneity of the Manufacturer's Strategic Decision. *Sci. Sci. Manag. S.T.* 6, 72–83.

Yan, X. C., and Huang, G. T. (2020). Government Subsidies, Enterprise Economic and Innovation Performance, and Overcapacity: An Empirical Research Based on Strategic Emerging Industries. *Nankai Econ. Stud.* (01), 176–198.

Yi, L., Bai, N., Yang, L., Li, Z., and Wang, F. (2020). Evaluation on the Effectiveness of China's Pilot Carbon Market Policy. *J. Clean. Prod.* 246 (10), 1–10. doi:10.1016/j.jclepro.2019.119039

Yülek, M. A., Lee, K. H., Kim, J., and Park, D. (2020). State Capacity and the Role of Industrial Policy in Automobile Industry: A Comparative Analysis of turkey and South Korea. *J. Industry, Competition Trade* 20, 307–331. doi:10.1007/s10842-019-00327-y

Zheng, J. C., Zhao, H., and Li, Z. G. (2019). A Research on NEV Industry R&D Subsidy under the Policy of "double Credits. *Sci. Res. Manag.* 40 (02), 126–133.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 16 July 2021
doi: 10.3389/fenrg.2021.686561

Effects of Fiscal Decentralization on Garbage Classifications

Qiuzhuo Ma[1], Diejun Huang[2]*, Hua Li[3], Yimei Hu[4], Krishna P. Paudel[5], Sijin Zhang[1] and Jianfeng Zhang[1]

[1]Business School, Guangdong University of Foreign Studies, Guangzhou, China, [2]Institute of Geography and Tourism, Guangdong University of Finance and Economics, Guangzhou, China, [3]College of Economics and Management, South China Agricultural University, Guangzhou, China, [4]Aalborg University Business School, Aalborg University, Aalborg, Denmark, [5]LSU Agricultural Center, Louisiana State University, Baton Rouge, LA, United States

China has been promoting garbage classification in its rural areas, yet it lacks financial appropriation and fiscal decentralization to support waste processing projects. Though the existing literature has suggested fiscal decentralization strategies between different local government levels, few of the studies ascertain garbage classification efficiency from a quantitative perspective. To bridge the gap, this study examines the optimal fiscal decentralization strategies for garbage classification. It uses an optimization model while considering decision makers' requirements regarding the fund allocation amounts at different government levels and the classification ratios in villages as constraints and decisions, respectively. A three-stage heuristic algorithm is applied to determine optimal landfill locations and efficient classification ratios for the garbage processing system in rural China, with an analytical discussion on the propositions and properties of the model. Our analytical results suggest that 1) the theoretically optimal solution is conditionally achievable, 2) the applied algorithm can achieve the optimal solution faster when the relationship between governance costs and classification ratios reaches some mathematical conditions, and 3) there is always a potential for increasing the retained funds between different government levels or for reducing the total appropriation from the county government. The numerical experiment on a primary dataset from 12 towns and 143 villages in the Pingyuan county of Guangdong province, China, does not only affirm the qualitative results, but it also provides insights into the difficulties encountered during the implementation of the garbage classification policy in China's rural areas.

Keywords: garbage classification, fiscal decentralization, quantitative analysis, optimization, rural area

OPEN ACCESS

Edited by:
Chan Wang,
Guangdong University of Finance and Economics, China

Reviewed by:
Chuanbin Zhou,
Chinese Academy of Sciences (CAS), China
Ramesh Ghimire,
University of Georgia, United States

****Correspondence:***
Diejun Huang
diejunhuang@gdufe.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *27 March 2021*
Accepted: *03 June 2021*
Published: *16 July 2021*

Citation:
Ma Q, Huang D, Li H, Hu Y, P. Paudel K, Zhang S and Zhang J (2021) Effects of Fiscal Decentralization on Garbage Classifications. Front. Energy Res. 9:686561. doi: 10.3389/fenrg.2021.686561

INTRODUCTION

Under a typical multilevel governance structure, local governments in China—villages, towns and counties—are always authorized specific rights and responsibilities during a garbage processing project. For instance, the village committee is always responsible for hiring cleaning staff to classify and deliver the garbage from each household to the transfer station in town. The town government then transports the waste from the transfer station in town to further treatment sites such as refuse landfills. Efficient allocations of funds between each of two local government levels—that is, fiscal decentralization—are critical to garbage processing efficiency, as well as ensuring consistency between administrative power and financial rights.

However, due to information asymmetry, it is difficult for the central government to design any efficient fiscal decentralization plan to guide subordinate local government levels under a "top-down" scheme. When the supervision costs between each of two different government levels are abnormally high, the fiscal allocation is inefficient. Previous studies have explored factors critical to the financial sustainability of waste management systems (Bartolacci et al., 2018), conceptually proposed specific fiscal decentralization strategies to solve grassroots problems (Gregorio et al., 2019) and evaluated the application of fiscal decentralization principles in practical contexts (Zegras et al., 2013). However, the quantitative examination of the efficiency of decentralization strategies remains scant in the literature.

Considering that garbage classification at the grassroots government level will have a "bottom-top" impact on the fiscal decentralization strategy of the governments at higher levels, inefficient garbage classification at the village level may cause serious financial efficiency and environmental sustainability problems at the town and county levels. For instance, the deregulated classification may lead to a large number of garbage abuses in a village, which will further undermine the local environmental quality. In contrast, an overly strict requirement [1] may lead to excessively high costs for the entire garbage governance system. It could lead to the community surpassing landfill capacity in a relatively short time. Therefore, we argue that an optimized garbage classification ratio not only improves fiscal decentralization through different government levels but also helps to achieve the sustainability goal.

This study optimizes the fiscal decentralization strategy for processing local garbage taking garbage classification as a decision variable. The whole problem is modeled as a location-allocation network, in which the landfill location is also optimized. The requirements of fund flow in this network through different government levels are treated as constraints for the optimization model. Our key findings show that it is possible to improve the fiscal usage efficiency between government levels. We specifically show the impact of garbage production scale on classification decisions and the impact of such decisions on the size of fiscal appropriations.

The remainder of this paper is structured as follows: *Literature Review* reviews the related literature from three aspects: garbage collection, fiscal decentralization and garbage processing optimization. *Setting* describes the research problem by specifying the authorities and financial constraints through different government levels. Model, analytical discussion and algorithm development are presented in *Modeling and Analysis*. *Numerical Experiment* presents the quantitative experiment and optimization solutions. *Conclusion* concludes the paper.

LITERATURE REVIEW

The study aims to optimize fiscal decentralization efficiency in garbage processing under a multilevel government structure. Three strands of relevant literature—garbage classification, multilevel governance and operational optimization—are reviewed in this section. Then gaps in the existing literature are identified.

Garbage Classification

Previous studies have discussed different garbage classification methods. For instance, Nie et al. (2018) propose a new Decision Support System on a specific classification method in Shanghai, China. Idowu et al. (2019) address an identifiable and comprehensive academic evaluation of the value of landfill sites on garbage classification. Li et al. (2019) carry out field investigations, questionnaire interviews and factor analysis in the rural area of Hangzhou, China, to detect the efficiency of some new garbage classification methods. The authors compare four methods, including a "2 + T" source method (biodegradable waste, other waste and toxic waste) and three types of source classification and resourcing treatment patterns. Garbage classification, as an end-of-pipe (EOP) treatment, always happens before garbage collection at farm households. Yet landfill classification refers to any waste management system that processes waste before discarding it into the environment (Dutt and King, 2014). Dutt and King (2014) conduct an empirical study to test the contribution of EOP treatment to improve the waste reduction process. Using EOP treatment was found to increase information about process problems and hence could help practitioners identify the root cause of insufficient capacity and facilitate the source reduction of processed waste.

Besides proposing garbage classification methods, researchers have also tried to improve classification efficiency. According to Nguyen et al. (2015), trust, personal perception, moral norms, perceived difficulties and reciprocity are critical factors that explain residents' intentions in garbage classification separation. Gundupalli et al. (2017) review the automated sorting techniques, including sensors and actuators, and found their contribution to improving garbage processing efficiency. Boonrod et al. (2015) investigate how to design management mechanisms for increasing garbage classification efficiency, and they identified that an economic incentive mechanism, e.g., the community business mechanism, performed best, as it increased separation efficiency by about 58%. According to our pilot experiment, however, higher garbage classification intensity does not necessarily bring about cost reductions, especially for the whole system, since different levels of garbage separation intensity in villages may cause different governance and transportation costs throughout the fiscal decentralization chain.

Through our investigation in the rural areas of Southern China, we find that local garbage is always recommended to be sorted into four classes: organic perishable garbage, hazardous waste, inert trash and others. Most of these types, in terms of classification method, are sorted at the source instead of treatment patterns. In addition to choosing the appropriate classification method, this study suggests that an efficient fiscal decentralization strategy is a critical factor in the successful implementation of rural domestic waste classification and resource management.

[1]For instance, like in the metropolitan areas of China, garbage is required to be classified before processing.

Fiscal Decentralization

Gregorio et al. (2019) propose a theoretical framework that combines institutional and policy network approaches to the study of multilevel governance of the climate change problem. These authors provide valuable information with which to identify the institutional framework among different government levels. In line with their framework, which highlights the institutional environment, we focus mostly on fiscal institutions and the efficiency of fiscal decentralization through different government levels. According to Oates (1999), pp. (1120), fiscal decentralization, which is also called fiscal federalism, refers to understanding which functions and instruments are best centralized and which are best placed in the sphere of decentralized levels of government. Fiscal decentralization efficiency and environmental performance are evaluation criteria in rural China. Zhang et al. (2017) point out that fiscal decentralization hurts efficiency (Zhang et al., 2017). Zegras et al. (2013) examine Portugal's metropolitan transportation sector from the fiscal federalist's perspective in light of the country's decentralization efforts and new relevant legislation. Several problems are identified within the local metropolitan transportation system, such as a lack of direct user fees, prices that inadequately reflect costs and a heavy reliance on central government subsidies for public transportation investments and operations. In the rural China, garbage disposal processing is always launched by the higher government level, and undertaken by the subordinates, with structurally spent cost through different levels. However, we found that, based on our spot investigation, the cost may not be entirely come from the higher government levels. The villagers for example, are often charged with the garbage disposal fees.

Optimization in Garbage Processing

Anwar et al. (2018) solve a location problem to identify the configuration of a municipal solid waste (MSW) management system. Balaman and Selim (2014) use mixed-integer programming in the network design model to determine the most appropriate locations for biogas plants and biomass stores. Badran and El-Haggar (2006) use a mixed-integer programming model to solve a waste management problem and discussed the selection strategy for the locations of multiple garbage collection stations at different geographical locations. Tavares et al. (2011) use the spatial multicriteria evaluation method to examine the optimal location of an MSW incineration plant. Since these studies have not considered classification at the endpoint of the garbage processing network, no allocation optimization needs to be implemented. Considering waste transportation and the location problem, Srivastava and Nema (2012) use a fuzzy parametric programming model to address the location-allocation problem for urban waste management. Apart from the studies mentioned above, topics related to the application of multilevel governance in optimization can be found in the operational management literature as well. For instance, Levaggi et al. (2018) construct an N-region network programming model to address a systematic garbage disposal problem. In this model, waste mobility is allowed between nodes, and its effect on the solution was discussed under both centralized and decentralized decision models. In Ma et al. (2018), the authors also used a network optimization method for waste processing issues. In their study, a case from Louisiana, United States, is used, and monetary constraints are considered through different players in the network.

The literature on garbage classification mostly focuses on the classification methods that may improve operational efficiency, the factors that impact the classification behavior/intention and the mechanism design that may increase the policy efficiency (Gundupalli et al., 2017; Nie et al., 2018; Li et al., 2019). Some existing research has discussed the impact of end-of-pipe treatments, such as landfill, on garbage reduction efficiency through the whole process. A few studies have explored the intrinsic connection between end-of-pipe garbage treatment and fiscal decentralization efficiency, incorporating all decision makers in the modeling process. We provide theoretical decision-making suggestions on fiscal decentralization as well as simulate the outcome of the EOP garbage treatment, rather than addressing ex-post discussions on the EOP impact on the participants' decision quality.

Though some studies have discussed the impact of fiscal decentralization on policy efficiency (Zhang et al., 2017), the regional economy (Gregorio et al., 2019) and some public-service departments (Zegras et al., 2013), few of them, however, have scrutinized the impact of fiscal decentralization efficiency on waste management and garbage processing. The optimization literature usually focuses on the application of related programming or computing methodologies, and few studies integrate the network programming technique with any practical garbage classification problems in specific areas.

We quantitatively optimize fund allocation efficiency through different players within a logistics network. Our study is the first attempt to apply an operational method to a rural garbage processing problem under a multilevel governance mechanism.

SETTING

We consider a multilevel governance framework that consists of the issues of "collection-and-classification in the village, transportation in town and processing in the county" (CAV-TT-PC). To determine an efficient fiscal decentralization strategy that starts from garbage classification within the grassroots government, our study builds a location-allocation optimization network, treating the location of the landfill and classification ratio as the decision variables. To approach the local garbage logistics network, a second-order conic programming model is applied, based on the above two decision variables. To specify the other issues, along with these decision variables and the corresponding constraints on fiscal expenditures at each government level, we make the following assumptions.

Assumptions

(1) The garbage production of each village household and the location of the town's transfer station are known.

(2) Only the classified garbage needs to be processed at the refuse landfill in the county. The rest is assumed to be disposed of by local households.
(3) The governance cost related to the classification work is the function of the classification ratio. Such information will then be specified in the quantitative experiment.
(4) The cost of garbage collection from each farm household and the transfer of garbage to the transfer station is constant.
(5) The number of refuse landfills in the county is predetermined as being equal to one.
(6) None of the government levels will accept a negative flow of funds.

In addition to assumption (2), we actually imply another assumption here that the disposal process of the garbage is indifferent to classified waste types. In the reality, different garbage disposal processes are often placed together, in order to avoid pollution to the villages. Besides, there is limited available location to position the processing site in the rural area. For theoretical discussion, we social researchers are always lack of specific data regarding of the benefits and cost of classifying out different garbage types. Based on the above, the distance from the origin to the processing site is accordingly assumed to be equal to that between the origin to the landfill in the county. That is, the distance will be indifferent to the classification result.

Stoeva and Alriksson (2017) state that policies and legislation and people's attitudes could be important factors that affect garbage processing efficiency. In our paper, however, these conditions are implicitly assumed to be satisfied. The local farm households in our area of investigation are always found to have good intentions regarding garbage classification and to follow the guidance of the local government. Thus, in this paper, the implementation quality is assumed to be guaranteed by the incentive mechanism from local governance and the household's behavior. Although we find from the citations from Dutt and King (2014) that many authors approached the garbage governance problem from the perspective of process quality management, we are mostly interested in process efficiency. In the following subsection, to-be-decided variables that are determined by the authorities at each government level are specified under a CAV-TT-PC framework.

Decision Units and the Variables to be Decided

Village Committee

(1) Classification ratio

The village committee determines the classification ratio during garbage collection.

(2) Amount of retained funds

In addition to the funds used for classifying and collecting domestic garbage, the village committee has to decide on the amount of funds to be retained from the amount allotted by the town government level.

Town Government

(1) Funds allocated to villages

These funds are used by the town government to support the garbage classification and processing work and to cover the governance cost in villages.

(2) Amount of retained funds

The town government has to decide on the amount to be retained from the amount allocated by the county government.

County Government

The county government should choose the refuse landfill location while making a plan for the appropriations budget. These two aspects, in practice, jointly influence the total costs of the garbage processing network and the strategies for fund allocation through to subordinate levels. In other words, the county government must consider the location problem that would be created by different landfill locations, as well as the size of the appropriation that comes from the higher government level. The appropriation will always be treated as both an incentive/authority and a constraint/responsibility for the local government during a garbage processing project. Although the total amount of the allocated appropriation from the central government is closely related to the specific authorities and affairs in the subordinate government levels, few studies have explored the potential of improving fund allocation efficiency within grassroots governance.

Following the implementation of a location strategy, waste transportation routes from the transfer stations to the landfill site will also be optimized. This change, as stated in Peri et al. (2018), will then mitigate the total logistics cost of the whole system. Further modification of the network will be carried out by optimizing the classification of the garbage from each village.

We do not address the location problem for the transfer station in town for two reasons. First, the delivery cost from each farm household to the transfer station is independent of the station's location, since the salary paid to the cleaning staff is only dependent on the weight of the delivered garbage. Second, the distances from farm households to the transfer station are much smaller than the distance from a transfer station to the landfill in the county. Thus, the transportation cost between farm households to transfer stations has little impact on the total cost. In the following subsection, the requirements of the fund allocation strategy at each government level, superior and subordinate, are specified.

Financial Requirements of Decision Units

Based on the discussion in *Decision units and the variables to be decided*, the following specifies the requirements from different government levels that can be used as the constraints in programming:

From the village committee's perspective, its net fiscal revenue from processing rural garbage is equal to the difference between the garbage processing cost and the funds received from the town government. The processing cost in the equation equals the sum of the collection costs and

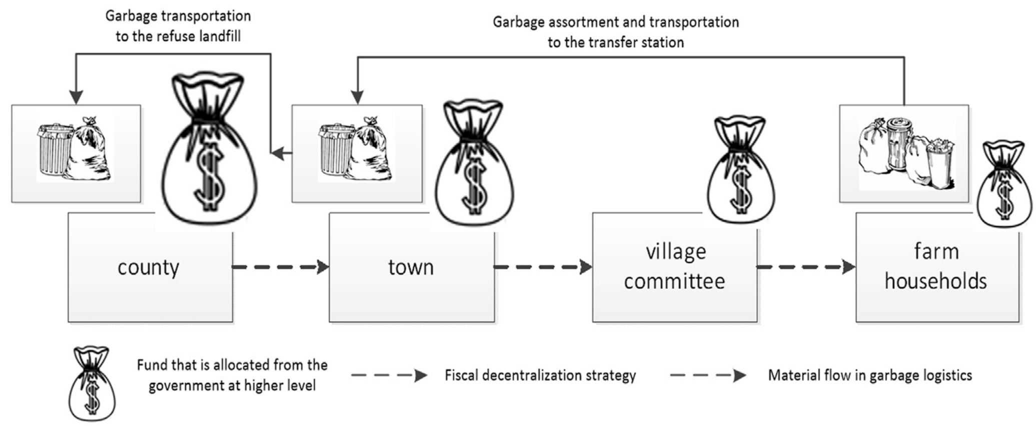

FIGURE 1 | The procedures of garbage processing and final decentralization. Notes: The above figure takes one village as an example. Otherwise, the amount of garbage transported to the landfill (i.e., from right to left) would cumulatively increase.

classification-related governance costs. Collection costs are usually paid to the local cleaning staff, while officers always undertake the classification related governance costs at the grassroots government level.

$$\begin{aligned}&\textit{net fiscal revenue of village committee in garbage processing}\\&\quad= \textit{allocated funding from town} - \textit{garbage collection cost}\\&\qquad- \textit{governance cost} \ldots\ldots \end{aligned} \tag{1}$$

In equation **Eq. 1**, the cost is generally specified by the village committee itself. The correlation of the garbage processing expenditure, classification-related governance cost and processed garbage volume mainly reflect the fiscal decentralization efficiency between the local and the superior government levels.

Similarly, the net fiscal revenue of the town government—consisting of the funds allocated by the county government, the allocations to village committees and the expenditures for garbage transportation—is listed by equation **Eq. 2** as follows:

$$\begin{aligned}&\textit{net fiscal revenue of town government in garbage processing}\\&\quad= \textit{allocated funds from county} - \textit{funding allocation to villages}\\&\qquad-\textit{transportation cost} \ldots \end{aligned} \tag{2}$$

The net fiscal revenue of the county government is derived by subtracting the allocation funds and transportation costs that occur in the town from the funds received from the central government level. Accordingly, the following equation **Eq. 3** is derived:

$$\begin{aligned}&\textit{net fiscal revenue of county government in garbage processing}\\&\quad= \textit{allocated funds from the central government}\\&\qquad-\textit{allocation to town} - \textit{transportation cost} \ldots \end{aligned} \tag{3}$$

According to assumption (6), the net fiscal revenue for the county, town and village governments should be nonnegative. If each local government level has a requirement on the minimum funds to be retained, the lower bound should be considered in the constraint as well.

Integrating *Decision units and the variables to be decided* and *Financial requirements of decision units*, the following argument is proposed. Although the operational analysis of the garbage processing system is derived from a bottom-up approach, the optimized location of the landfill site in the county and the classification ratio in the village are conducted within the fiscal decentralization strategy that is implemented under a top-down approach. This statement can be graphically depicted in **Figure 1**, in which the size of the money bag represents the amount of the allocated funds received by the local government. In contrast, the variation in the size represents the outcome of fiscal decentralization through different government levels. For instance, the town's money bag is bigger than the village's, since the town government needs to use a part of the funds to transport the garbage from the transfer station to the landfill site before the funds are allocated to the village committee. The reduced size of the garbage bags, in the direction opposite to that of the fiscal decentralization, denotes the outcome of garbage classification. That is, for example, why the town holds less garbage than the household does.

MODELING AND ANALYSIS

Based on the above discussion, we first build an operational optimization model, then derive the analytical properties and, after that, put forward some propositions for the model.

Notations

All the relevant parameters and variables discussed in this study are listed as follows:

Index	
i	Index for the village such that $i = \{1, 2, \ldots, n_j\}$, where n_j denotes the largest indexed village in town j
j	Index for the town such that $j = \{1, 2, \ldots, m\}$, where m denotes the largest indexed town
Decision variables	
α_{ij}	Ratio of garbage classification in household j in town i
V_{ij}	Funds allocated by town j to village i
H_{ij}	Funds retained in village i of town j
W_j	Funds allocated by county to town j
M_j	Funds retained in town j from W_j
$\boldsymbol{R}$	Location of the to-build refuse landfill, such that $\boldsymbol{R} = \{R_1, R_2\}$**,** where the two elements represent the latitude and longitude, respectively[2]
Parameters	
s	Unit wage of the cleaning staff in the village
h_{ij}	Garbage production in village i in town j
r_j	Coordinate of the transfer station in town j
n_{ij}	Population of village i in town j
$\boldsymbol{T}_j$	Location of a transfer station in town j, which is already known
u	Marginal cost of transportation from the town to the refuse landfill
A	Financial budget fixed by the county government
γ	Coefficient that associates the governance cost with the assorted garbage volume
C	Annual garbage processing capacity of the landfill in the county

Modeling	**The programming model, which is denoted by (QP), is shown as follows:**	
$\min_{\boldsymbol{r}\in\boldsymbol{L}} G(\boldsymbol{r}, \alpha_{ij}) = u\sum_{j=1}^{m} D_j \sum_{i=1}^{n_j} \alpha_{ij}h_{ij}$ Subject to		
Capacity constraint	$C \geq \sum_{j=1}^{m}\sum_{i=1}^{n_j} \alpha_{ij}h_{ij}$	(1)
Fund flow constraint1	$W_j - M_j - \sum_{i=1}^{n_j} V_{ij} \geq uD_j \sum_{i=1}^{n_j} \alpha_{ij}h_{ij},\ i = \{1, 2, \ldots, n_j\},\ j = \{1, 2, \ldots, m\}$	(2)
Fund flow constraint2	$V_{ij} - H_{ij} \geq s\alpha_{ij}h_{ij} + f(\alpha_{ij}, h_{ij}),\ i = \{1, 2, \ldots, n_j\},\ j = \{1, 2, \ldots, m\}$	(3)
Appropriation constraint	$A \geq \sum_{j=1}^{m} W_j$	(4)
Coefficient constraint	$0 \leq \alpha_0 < \alpha_{ij} \leq \overline{\alpha} < 1$	(5)
Variable constraint and nonnegativity constraint	$\boldsymbol{R} \in \mathcal{L};\ V_{ij}, H_{ij}, M_j, W_j \geq 0$	(6)

The objective function minimizes the total cost, which is the sum of the product between the distance and the assorted garbage from each village. D_j denotes the distance from the landfill position in the county to the transfer station in the town. Mathematically, we have $D_j = \left\| r_j - \boldsymbol{R}_2 \right\|$ where $\| \cdot \|$ denotes the norm, with its subscript denoting the degree. Constraint (1) ensures the delivered garbage will not exceed the annual processing capacity (*capacity* for abbreviation) of the landfill; constraints (2) and (3) guarantee the fund flows through the town government and village committees are nonnegative, respectively. Note that the right term of (2) is a ton-kilometer cost that follows the pricing convention of the logistics industry, taking the product of the marginal transportation rate with the product of weight and distance. In the right first term of constraint (3), the collection cost of the cleaning staff relates to the assorted volume of the household garbage. In the second, the **function** between the garbage classification and the corresponding governance cost is described as a **general form** of the decision variable α_{ij}, as well as the parameter h_{ij}. The generalization of this function will have little impact on our analytical discussion. The specific form will be later addressed in the numerical experiment section. Constraint (4) says that the total planned funds over all the towns cannot exceed the appropriation from the county government, and the salary for the cleaning staff in the village is not lower than a lower bound. Such a lower bound always comes from the requirement of the local government or the labor law. The classification ratio is limited by constraint (5), in which α_0 and $\overline{\alpha}$ are the lower and upper bounds, respectively. The two boundaries, naturally, are to be restrained between zero and one to comply with reality. We use $\leq$ after 0 since we consider the extreme case that no garbage is transported from the household; constraint (6) makes sure that all the decision variables are nonnegative.

Remark 1

In the objective, α_{ij} is used as a classification variable that can be determined by the grassroots government level. Then the problem can be solved through a location-allocation algorithm scheme that was proposed by Cooper (1963) and extended by Wu et al. (2015) and Ma et al. (2018). Related pseudocodes are listed in Algorithm 1 in **Supplementary Appendix A**. Our version in the current paper is closer to that used by Cooper (1963) and Wu et al. (2015), since Ma et al. (2018) considered a multiobjective scenario.

Proposition 1

The problem equals a location-allocation problem.

Proof of Proposition 1

The proof is evident since we can treat $\alpha_{ij}h_{ij}$ as a decision variable, e.g., v_{ij} that concerns the delivered garbage value from village j of town i, determined by the decision of the classification ratio. Then (QP) can be reformulated to $\sum_{j=1}^{m} D_j Q_j$ where $Q_j = \sum_{i=1}^{n_j} v_{ij}$ that represents a total delivered garbage volume from town j. So far, a standard location-allocation problem is constructed, and the proposition is proved. ■

Proposition 2

Following the scheme that requires D_j and α to be alternately determined, (QP) is convex programming during each iteration round, given $f(\alpha_{ij}, h_{ij})$ is convex.

Proof of Proposition 2

Based on **Proposition 1**, the objective is convex to α given a fixed $\boldsymbol{r}$—since the function is of a linear form, and convex to $\boldsymbol{r}$ given a fixed α_{ij}—because the function is of a second-order conic form. Then we need to prove that all the constraints are convex: constraint (1) is convex due to its linearity; according to the algorithm scheme, constraint (2) is convex; if $f(\alpha_{ij}, h_{ij})$ is convex, then constraint (3) is convex. Thus, the proposition can be proved. ■

Remark 2

It can be found from the above that, given that the other conditions are unchanged, the relationship between the governance cost and garbage classification ratio affects the algorithm's effectiveness and efficiency. Exploration of the specific form of such a relationship and its impact on optimization analysis can be left as an interesting problem for future research.

Proposition 3

The three-stage heuristic algorithm by Cooper (1963), Wu et al. (2015) or Ma et al. (2018) is valid in the current problem for searching the locally optimal solution for programming (QP) in terms of both its decision variables $\boldsymbol{r}$ and α_{ij}.

Proof of Proposition 3

To prove this proposition, we have to prove that $G(\boldsymbol{r}^{t+2},\alpha_{ij}^{t+1}) \le G(\boldsymbol{r}^{t},\alpha_{ij}^{t+1})$ and $G(\boldsymbol{r}^{t+1},\alpha_{ij}^{t+2}) \le G(\boldsymbol{r}^{t+1},\alpha_{ij}^{t})$, $0 \le t \le t_{\max}$, where $t$and $t_{\max}$ denote the iteration and predetermined maximum iteration times.

Since $G(\boldsymbol{r}^{t+2},\alpha_{ij}^{t+1})$ is optimized based on the solution of $G(\boldsymbol{r}^{t},\alpha_{ij}^{t+1})$ by using α_{ij}^{t+1} as a constant, and in turn $G(\boldsymbol{r}^{t+2},\alpha_{ij}^{t+3})$ is optimized by using $\boldsymbol{r}^{t+2}$ as a constant in $G(\boldsymbol{r}^{t+2},\alpha_{ij}^{t+1})$, we have $G(\boldsymbol{r}^{t+2},\alpha_{ij}^{t+1}) \le G(\boldsymbol{r}^{t},\alpha_{ij}^{t+1})$ and $G(\boldsymbol{r}^{t+2},\alpha_{ij}^{t+3}) \le G(\boldsymbol{r}^{t+2},\alpha_{ij}^{t+1})$ due to the convexity of each programming. Slightly adjusting the superscripts in the latter inequality, the proposition is proved. ■

Remark 3

In other words, **Proposition 3** says that whether we start the iteration from the landfill location or garbage classification, the algorithm makes the objective non-increasing.

Looking into the specific constraints, we have the following proposition:

Proposition

The non-increasing monotonicity of the lower bound of constraint (2) is sufficient, but not necessary, to the improvement of the objective.

Proof of Proposition 4

It can be found that for each index j, the lower found of constraint (2) denotes the total transportation cost for each town. If this cost is non-increasing through the algorithm, the summation of the total cost for all the towns is non-increasing. This causal relationship, however, is irreversible. Thus the proposition can be proved. ■

Remark 4

The reason behind **Proposition 4** can be described as follows: the objective function focuses on the total ton-kilometer cost of the whole county, whereas constraint (2) provides a limit to the solution by considering the ton-kilometer cost from each village to the landfill in the county. Therefore, if the component-wise cost is smaller, the total cost will undoubtedly be smaller. But a smaller total cost does not necessarily mean a small component-wise cost.

With further discussion on the constraints, we have the following property:

Property 1

If $f(\alpha_{ij}, h_{ij})$ is non-increasing with α_{ij}, the optimal solution α_{ij}^{*} is always equal to its lower bound α_0, and the optimal solution $\boldsymbol{r}^{*}$ can be found by at most two iteration times.

Proof of Property 1

If the iteration begins with an arbitrarily initiated location site, α_{ij}^{*} can be solved as equal to its lower bound, due to the minimization scenario and non-increasing monotonicity of constraint (3). Then $\boldsymbol{r}^{*}$ can be found, given a fixed α_{ij}^{*}, during the first iteration, which is essentially a location optimization problem. If the iteration, on the contrary, begins with an initiated α_{ij}, α_{ij}^{*} can be found for the first iteration and $\boldsymbol{r}^{*}$ can be found for the second. Thus, the property can be proved.

Considering the practical application, α_{ij} can be set as a general standard for the whole county, e.g., α. For this, we have the following discussion:

Remark 5

Although a scalar variable, which can be denoted as α rather than a matrix (vector) that has been denoted by α_{ij} in the modeling, does not violate any of the above propositions and properties; it may cause an intractability problem as we use an equality constraint as (2). Subject to such an equality constraint, intractability may also be caused by not only the inappropriate settings of the total budget A but also the landfill capacity C and the initial landfill location. For instance, an increase of the lower bound of constraint (2) may violate this constraint, although (4) is active. Furthermore, we find that satisfying constraint (2) and (3) are not only necessary but also sufficient to a solvable problem. The above observations indicate

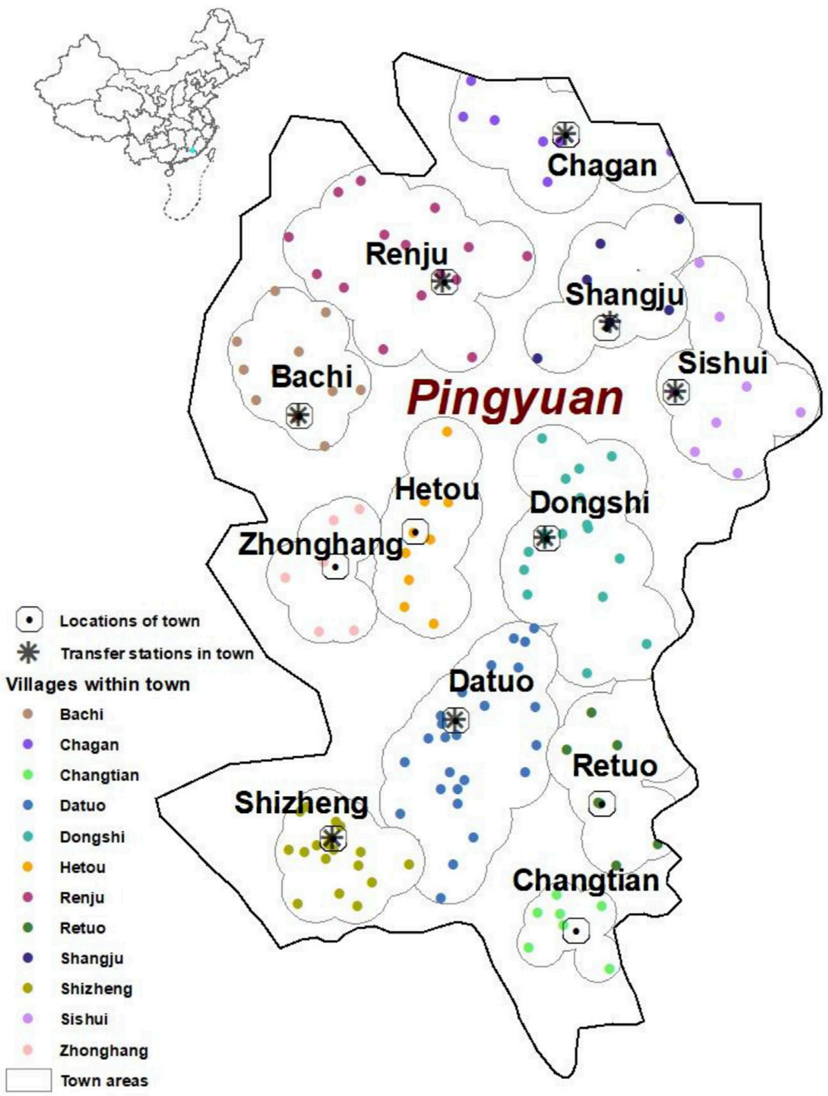

FIGURE 2 | Study area.

that, in practice, the appropriation size and local operational work have a mutual impact on each other. For instance, a too-small appropriation amount may cause an undesirable location decision for the landfill, in terms of environmental quality. A lack of financial support may also bring about a household's negative motivation regarding garbage classification, or worse, a negative motivation regarding the implementation of the whole system.

NUMERICAL EXPERIMENT

Data

The numerical experiment was conducted on a real case from Pingyuan county, China (**Figure 2**).

There are a total of 12 towns and 143 villages in the county. The specific corresponding relationship between the village names and indices i in practice is reported in **Table B-1a** in **Supplementary Appendix B**. Their coordinates are reported in **Table B-1b**. The entire garbage production from all the villages reached 30,529.25 tons in 2018, which cost 5.44 million RMB[3] to pay the cleaning staff. The transfer expenditure undertaken by the town government was 3.16 million RMB. More detailed information derived from the surveyed information, such as the village coordinates, population garbage production for each village and the location of the transfer station in each town, etc., are reported in **Tables B-1b, B-1c and B-1c**. This information can be used later as a benchmark for comparison with the optimized solution.

To facilitate the analysis, we simplify$f(\alpha_{ij}, h_{ij})$ into a linear form, e.g., $f(\alpha_{ij}, h_{ij}) = \gamma\alpha_{ij}h_{ij}$, in which γ denotes the marginal

[3]US$1 = 6.99 RMB (as of 7/20/2020).

governance cost of the classified garbage volume. Here, we denote $\gamma = 58.5$ RMB per ton according to the following calculation.

Governance Cost in Villages

Average garbage production per village equals 213.5 tons per year and that the annual salary for the village officer is about 36,000 RMB, according to the provincial standard. Based on our survey of the county, we find about one-quarter of the working time is spent on inspection and the officer usually goes for inspection for twice a time (using 0.5 in the denominator).[4] So marginal governance cost is calculated as:

$$marginal\ governance\ cost = \frac{36000 \times 0.25 \times (250/360)}{213.50 \times 0.5} \approx 58.5\,(RMB/ton)$$

That is to say, to manage the garbage classification work, the village committee needs to pay 58.5 RMB of compensation per ton of garbage to the village officials.

In reality, however, there is no such expenditure paid to village officials. Thus this paper will also contribute to the optimization of a village officer's salary in terms of fiscal decentralization efficiency.[5]

Marginal Transportation Cost From Town to County

For the transportation cost, we use 6.18 and 16.10 RMB per ton as the lower and upper bounds. The average distance from the transfer station of a town in Pingyuan county to the landfill site is equal to 7.3 km. Considering that the allocated funds for garbage transportation in that town equal to 340.9 thousand RMB and that the local garbage production equals 4,717 tons, the marginal cost is 9.9 RMB per ton-kilometer, if we only consider using the funds on transporting the garbage. Given the contract value is of 212.7 thousand RMB between that town and the commercial company, the cost equals 6.18 RMB per ton-kilometer. Taking the higher price 16.10 quoted by other companies as reference, we use the smaller value, i.e., 6.18 RMB, as the lower bound, and the sum, i.e., 16.10 RMB, as the upper bound in setting the related parameter. For the numerical experiment, we start from the lower bound to check the result and vary this value from 6.18 to 16.10 RMB in the extension case to see the impact of such a variation on the optimized cost.

Landfill Location

We use the real location of the landfill in Pingyuan County as the initial point to start the algorithm and the benchmark case to compare our results.

Optimized Result

In the numerical experiment, first, we report the result by using **Eq. 3** as an inequality constraint with 35,000 tons as the capacity. The actual production of garbage in the study area is 30,529.25 tons per year. Later we vary constraint parametrically up to a constraint of 8,000 tons. We use MATLAB (2010b) to solve the optimization problem.

Result With Inequality Constraint

The specific result with the inequality constraint is listed in **Table 1**, in which the total classified (outbound) volume is equal to 6,052.33 tons. There is always a gap between the optimized retained amount and the calculated number at either the town government or the village committee. The optimized total appropriation size is also found to be smaller than the predetermined budget C. The classification ratio for all villages reaches the lower bound, i.e., 0.2.

Result With Equality Constraint and Reduced Capacity

We reduce the capacity to 8,000 tons and replaced constraint (2) to equality in the optimization model. The results listed in **Table 2** show that the total transportation cost increases from 640,390.66 to 648,446.40 RMB.

Also, the funds from the county to towns, the optimized amount retained in villages, as well as the gap of the retained amount in villages, are larger than those in the previous case, where the inequality constraint is used, and a capacity of 35,000 tons is assumed. The main reason can be attributed to the increased garbage volume delivered. Due to the increment of the garbage processing task, however, we suggest that the retained funds be increased as well. As shown in **Figures 3A,B**, most of the towns have higher retained funds in the result with an equality constraint and a considerably more amount of delivered garbage than in the result with an equality constraint and a smaller amount of delivered garbage. This is mainly because that more delivered garbage requires larger amount of funds to support, which will, according to our modeling logic, lead to larger amount of retained funds.

For the location result, it reaches the same position as Datuo town, i.e., (115.9072, 24.5829), despite the variation of the targeted processed garbage, as well as of the appropriation size. This is because no matter how much garbage is transported to the landfill, such a location point will lead to the minimum transportation cost.

For the classification strategy, we find that larger ratios always come from the villages in Datuo town, because it has the most substantial amount of garbage production. We also find that the larger the production the village has, the smaller the classification ratio it has suggested be implemented. Such a finding is graphically depicted in **Figures 4A,B**. To more clearly display the ratios among different villages, we multiplied the data by 10,000 in **Figure 4B**. We find it exists in $\alpha_{ij}h_{ij}$ of constraint (2)—a small (large) classification ratio is always expected to be accompanied by large (small) garbage volume to reduce the product size.

This result can also be found in the actual situation of our surveyed area, where the classification work is more efficient in villages where garbage production volume is small. For a fiscal decentralization strategy, the numerical result confirms the qualitative analysis.

Sensitivity Analysis

Although some result can be qualitatively derived and numerically testified, e.g., larger garbage production in one

[4]Assume the effective working days in China equal 250, due to weekends and legal holidays.

[5]As we use 58.5 as a constant in (QP), the optimized salary for each village officer would not be 36,000 RMB per year;

TABLE 1 | Optimization results given **inequality (3)** and **capacity** ≤ **35,000** tons for constraint (1).

Initial location	**(115.9483; 24.5557)**	**Optimized location**	**(115.9098; 24.6200)**
Capacity (ton)	35,000	Delivery (tons)	6,052.33
Salary (RMB)	176.8	Funds from county to towns (in RMB)	4,590,507.55
Constraint (1)	*Inequality*	Gap of CART(in RMB)	823,764.00
Total cost (RMB)	640,390.66	Optimized amount retained in town (in RMB)	924,682.74

Optimized FTV(RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	793,657.80	339,301.98	512,991.65	534,459.50	272,212.32	174,684.67
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	184,921.10	183,232.70	175,396.01	229,808.93	150,475.93	215,600.94

Optimized expenditure in villages (in RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	488,079.69	145,390.73	332,321.68	329,963.86	107,594.59	75,165.74
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	41303.24	61267.66	76208.39	109004.54	59893.26	91184.67

Optimized ARV(in RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	152,789.05	96,955.62	90,334.99	102,247.82	82,308.87	49,759.46
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	71,808.93	60,982.52	49,593.81	60,402.19	45,291.34	62,208.14

CARV (in RMB)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	305,578.10	193,911.25	180,669.98	204,495.64	164,617.73	99,518.93
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	143,617.86	121,965.04	99,187.62	120,804.39	90,582.67	124,416.27

Distance (km)

Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	4.13	21.58	8.58	13.75	17.18	30.99
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	21.51	20.58	22.09	12.88	9.41	7.53

Notes: *FCT, funds from the county to towns; ART, amount retained in town; CART, amount retained in town that is calculated by subtracting the optimized cost in town from the optimized allocated amounts from county to town; FTV, funds from towns to villages. ARV, amount retained in village; CARV, the amount of ARV that is derived by the similar formulation used for CART; "Distance" refers to the landfill site to each town.*

town along with shorter distance from the landfill to that town will suggest the result locate landfill near the town etc., we still had some trails, including varying the garbage stock for different towns in order to check the variation of the positioning result, vary the classification techniques (i.e., the bounds of the classification constraints) to check the impact on the solution, and change the marginal transportation cost in order to check the sensitivity of the total cost to the variation etc.

Varied Parameters to Location Result

As we vary some parameters like the appropriation funds amount, transportation marginal cost, as well as collection cost from the village etc., location result is affected little. As we, however, arbitrarily increase the garbage amount of one town in the sensitivity analysis, the result to our expectation shows the variation from Datuo to that town, for instance Dongshi where the position is (115.9600, 24.6786). This makes sense, since no matter how we changed the parameters other than the logistics cost, i.e., the town-kilometer, the location result would not be changed due to the minimization objective of the system. On the contrary, as long as we change that key factor, e.g., the distance from the garbage source to the destination, or the weight of the garbage production, the result would be changed accordingly. In terms of the sensitivity of the model, we claim that the location result is robust to the environment variation of the system.

Impact of Classification Techniques on the Solution

To identify the impact of classification techniques (i.e., the lower and upper bounds of a classification decision) on the solution, we solve the model at different values of α_{ij}, with the other predetermined parameters fixed. The result is reported given C = 12500 tons and $A = 400$ million RMB. In the garbage processing practice, the classification ratio is restricted by the

TABLE 2 | Optimization result given **equality (3)** and **capacity** = **8,000** tons for constraint (1).

Initial location		**(115.9072; 24.5829)**		**Optimized location**		**(115.9098; 24.6200)**
Capacity(ton)		8,000.00		Delivery (ton)		8,000.00
Salary(RMB)		176.8		FCTs (in RMB)		5,693,646.37
Constraint (1)		*Equality*		Gap of CART (in RMB)		970,832.15
Total cost(RMB)		648,446.40		Optimized ART (in RMB)		1,155,279.96
Optimized FTV (RMB)						
Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	1,491,023.58	397,246.21	621,426.13	603,192.44	312,078.83	194,061.21
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	160,190.43	203,493.21	194,930.49	258,952.32	164,788.22	243,576.84
Optimized expenditure in villages (in RMB)						
Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	1,105,101.61	145,390.73	332,321.68	329,963.86	107,594.59	75,165.74
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	41,303.24	61,267.66	76,208.39	109,004.54	59,893.26	91,184.67
Optimized ARV(in RMB)						
Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	192,960.98	125,927.74	144,552.23	136,614.29	102,242.12	59,447.73
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	59,443.59	71,112.77	59,361.05	74,973.89	52,447.48	76,196.08
CARV(in RMB)						
Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	385,921.96	251,855.48	289,104.45	273,228.58	204,484.23	118,895.47
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	118,887.19	142,225.54	118,722.09	149,947.78	104,894.97	152,392.17
Distance (km)						
Town	Datuo	Renju	Dongshi	Shizheng	Bachi	Chagan
Fund	0.00	25.69	12.16	10.49	20.48	35.08
Town	Shangju	Sishui	Changtian	Retuo	Zhonghang	Hetou
Fund	25.37	23.94	26.18	10.67	11.89	1.38

Notes: *FCT, funds from the county to towns; ART, amount retained in town; CART, amount retained in town that is calculated by subtracting the optimized cost in town from the optimized allocated amounts from county to town; FTV, funds from towns to villages; ARV, amount retained in village; CARV, the amount of ARV that is derived by the similar formulation used for CART; "Distance" refers to the landfill site to each town.*

real situation, or techniques, at town and county levels. Thus, we address the following analysis to simulate the reality.

We change the lower bound of the classification from 0.0 to 0.1, given the upper bound equals 0.8. Results show that the total transportation cost under such a scenario is lower than that under the scenario in which the lower bound is 0.2. Tapping into the specific allocation solution, we find the garbage following $\alpha_{ij} = 0$ is mainly transported from the four closer towns (Datuo, Shizheng, Retuo, and Hetou).

As we use 0.1 as the lower bound, garbage still mainly comes from three out of the four towns; the exception is Hetou, whose ratio decreases to 0.1. That is because the volume that should have been undertaken by Hetou is distributed to the other towns.

As we change the upper bound of the classification from 0.8 to 0.7, given the lower bound equals 0.2, the result shows that the total cost increases from 815,906.23 RMB (in the benchmark case) to 886,563.37 RMB and the allocated funds from the county to town increases from 80,603,456.25 to 130,656,102.66 RMB. That is because more garbage should be collected from the farther towns, as the classification technique in the closer towns is limited. Thus the ton-kilometer cost increases. For the allocation strategy, only Datuo and Shizheng are advised to send out more garbage, but the other towns are advised to keep the ratio equal to the lower bound. As we then decrease the lower bound from 0.7 to 0.6, the transportation cost increases to 963,000.77 tons, and the allocated funds increase to 256,774,139.17 RMB. Three more towns, Retuo, Hetou and Zhonghang, in addition to the above two, are advised to deliver more garbage than the others. Zhonghang town has the fifth nearest distance to the landfill. When the upper bound ratio decreases from 0.6 to 0.5, there are six major supplying towns, including Datuo, Dongshi, Shinzheng, Retuo, Zhonghang and Hetou. Although the transportation cost increases again, to 1,055,076 16 RMB, the allocated funds decrease sharply from 256,774,139.17 to 5,892,470.16 RMB.

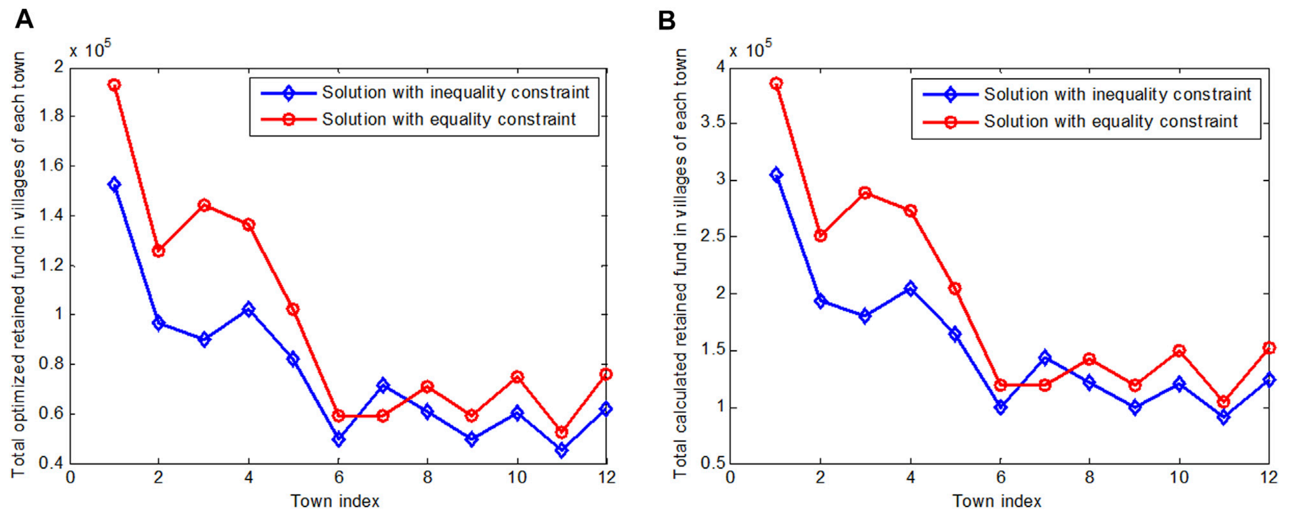

FIGURE 3 | Comparison of the retained amount at the villages of each town in the result with a larger amount of delivered garbage and an equality constraint, with that in the result with a smaller amount of delivered garbage and an inequality constraint. **(A)** optimized result; **(B)** calculated result by subtracting village cost from the optimized allocated funds from towm to village.

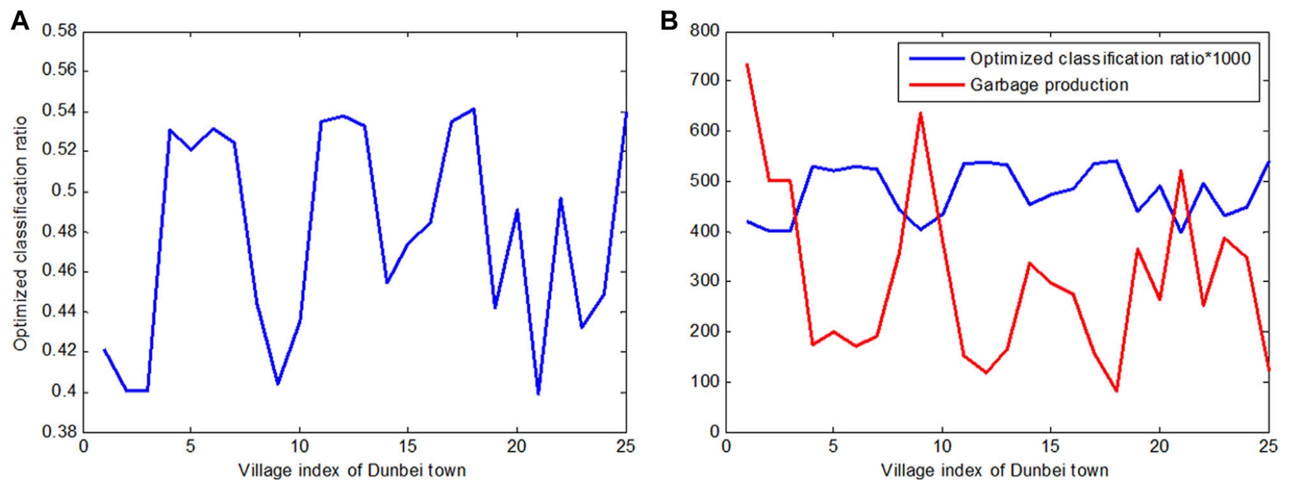

FIGURE 4 | Comparison of classification ratio and garbage production from the same villages in Datuo town. **(A)** classification ratio; **(B)** classification ratio (multiplied by 1000) and garbage production

Form a practical perspective, the above solutions indicate that stricter classification requirements (lower bound ratio) result in higher transportation costs but do not necessarily lead to a larger appropriation size. A lower classification technique (upper bound ratio) also results in higher transportation costs but does not lead to lower total appropriations. In summary, the impact of varied classification ratios' constraints on the fiscal decentralization strategy has less clear direction than the capacity constraints and budget restrictions. Also, it is not very practical to impose strict garbage classification standards from the very beginning, or set up different waste classification ratios for different towns and villages in the same county. Since it will bring us with higher management and government cost. For more efficiently using the government funds, the result implies to further refine government's waste management categories. so that more specific number regarding the funds retain and allocation can be determined in advance. Based on the variation of funds decentralization against garbage

Trans cost	6.38	6.58	6.78	6.98	7.18	7.38	7.58	7.98
Total cost	669,431.72	690,417.04	711,402.36	Non-convex	753,373.00	774,358.32	795,343.64	816,328.96

classification rate, a more effective and efficient rate can be found, in order to unify the requirement on each farm household.

About the Convexity

As we find the optimal result, the convexity is found sensitive to some factors, for instance the marginal cost for collecting the garbage in the village, and the transportation cost. For instance, as we increase or decrease the collecting cost around the original data, by a large magnitude as 35 and 85 etc., the objective function will be not convex, and will affect the iteration process of the algorithm; also as we increase the marginal transportation cost, non-convexity can be still found during the iteration. The following table shoes the sensitivity of the objective value, i.e., the total cost of the system, to the variation of the marginal transportation cost. We can tell from the table that the total cost varies a lot due to the small change of the transportation cost.

CONCLUSION

Governments around the world have been promoting garbage classification due to the public's increased awareness of environmental problems. China started sorting garbage in rural areas, but it suffers from low efficiency in the multilevel governance structure and the fiscal decentralization strategy.

We addressed the fiscal decentralization problem from a quantitative optimization perspective, and we modeled the local garbage processing system into a logistics network. The classification ratio for each village, as well as the location of the landfill for the county, were treated as decision variables in the model. Fund requirements from different government levels are formulated as constraints to characterize the programming and the mechanism by which the governance cost of garbage classification affects the overall system cost was analyzed. The analytical results helped to identify the sufficiency of the constraints to the optimality of the objective. It also helped to derive the classification solution from a qualitative point of view and depict the iteration process in terms of the algorithm's accessibility to the globally optimal solution. Additionally, we also qualitatively proved that there is always a gap between the optimized funds and calculated expenditures at each government level. If the model is extended, it can also be used in other applied researches, for example, when considering how to build three-level rural logistics network nodes such as the county and rural areas, and how the government supports the development of strategic emerging industries affected by location factors.

The numerical experiment on real cases from the county in rural China shows that larger classification ratios are always placed on smaller, productive villages when the capacity does not exceed some threshold. This result follows the reality that classification is usually easier to implement in the villages with lower garbage production. The extended experiment on varied parameters also shows that strict constraints on garbage classification in a village may result in a prohibitively large appropriation size if such a constraint is required to follow the landfill capacity in the county. However, direct modification of the classification requirement, regardless of the capacity variation, may neither raise the potential of retaining the funds at each government level nor necessarily lead to reductions in total transportation costs in the garbage processing system. The sensitivity analysis based on the numerical result shows that the convexity of the model is impacted a lot by some factors, such as the garbage collecting cost in the village and the marginal transportation cost from town to county etc. Also, we found the total cost is sensitive to the marginal transportation cost.

For future research, specific issues impeding efficiency at each government level throughout the garbage processing system should be identified. Identification of these issues should help to formulate all necessary constraints to build a better cost-minimizing model that captures the effects of fiscal decentralization on garbage sorting.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

QM mainly completed the construction of the model and most of the original manuscript. DH designed research, performed research and analyzed the data. HL completed the formula part. YH and KP primarily completed the task of data collection, while SZ and JZ completed the refinement of the manuscript and the correction of the patterns.

FUNDING

Granting agency: Philosophy and Social Science Planning Project of Guangdong Province. Grant number: GD19CYJ14. Funder's role: The department who funds the research that relates to a wide range of social researches. Granting agency: Natural Science Foundation of Guangdong Province. Grant number: 2018A030310687 and 2019A1515012149. Funder's role: The department who funds the research that relates to a wide range of natural science researches in Guangdong province.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.686561/full#supplementary-material

REFERENCES

Anwar, S., Elagroudy, S., Abdel Razik, M., Gaber, A., Bong, C. P. C., and Ho, W. S. (2018). Optimization of Solid Waste Management in Rural Villages of Developing Countries. *Clean. Techn Environ. Pol.* 20, 489–502. doi:10.1007/s10098-018-1485-7

Badran, M. F., and El-Haggar, S. M. (2006). Optimization of Municipal Solid Waste Management in Port Said - Egypt. *Waste Manage.* 26, 534–545. doi:10.1016/j.wasman.2005.05.005

Balaman, Ş. Y., and Selim, H. (2014). A Network Design Model for Biomass to Energy Supply Chains with Anaerobic Digestion Systems. *Appl. Energ.* 130, 289–304. doi:10.1016/j.apenergy.2014.05.043

Bartolacci, F., Paolini, A., Quaranta, A. G., and Soverchia, M. (2018). Assessing Factors that Influence Waste Management Financial Sustainability. *Waste Manage.* 79, 571–579. doi:10.1016/j.wasman.2018.07.050

Boonrod, K., Towprayoon, S., Bonnet, S., and Tripetchkul, S. (2015). Enhancing Organic Waste Separation at the Source Behavior: A Case Study of the Application of Motivation Mechanisms in Communities in Thailand. *Resour. Conservation Recycling* 95, 77–90. doi:10.1016/j.resconrec.2014.12.002

Cooper, L. (1963). Location-allocation Problems. *Operations Res.* 11, 331–343. doi:10.1287/opre.11.3.331

Dutt, N., and King, A. (2014). The Judgment of Garbage: End-Of-Pipe Treatment and Waste Reduction. *Manage. Sci.* 7 (60), 1812–1828. doi:10.1287/mnsc.2013.1827

Gregorio, D. G., Fatorellia, L., Paavolaa, J., Locatellib, B., Pramovab, E., Nurrochmatd, D. R., et al. (2019). Multilevel Governance and Power in Climate Change Policy Networks. *Glob. Environ. Change* 54, 64–77.

Gundupalli, S. P., Hait, S., and Thakur, A. (2017). A Review on Automated Sorting of Source-Separated Municipal Solid Waste for Recycling. *Waste Manage.* 60, 56–74. doi:10.1016/j.wasman.2016.09.015

Idowu, I. A., Atherton, W., Hashim, K., Kot, P., Alkhaddar, R., Alo, B. I., et al. (2019). An Analyses of the Status of Landfill Classification Systems in Developing Countries: Sub Saharan Africa Landfill Experiences. *Waste Manage.* 87, 761–771. doi:10.1016/j.wasman.2019.03.011

Levaggi, L., Levaggi, R., and Trecroci, C. (2018). Decentralisation and Waste Flows: A Welfare Approach. *J. Environ. Manage.* 217, 969–979. doi:10.1016/j.jenvman.2018.03.067

Li, X., Bi, F., Han, Z., Qin, Y., Wang, H., and Wu, W. (2019). Garbage Source Classification Performance, Impact Factor, and Management Strategy in Rural Areas of China: A Case Study in Hangzhou. *Waste Manage.* 89, 313–321. doi:10.1016/j.wasman.2019.04.020

Ma, Q., Paudel, K. P., and Cui, L. (2018). A Multi-Objective Optimization Problem for Using Poultry Litter in Electricity Production. *Appl. Energ.* 228, 1220–1242. doi:10.1016/j.apenergy.2018.06.109

Nguyen, T. T. P., Zhu, D., and Le, N. P. (2015). Factors Influencing Waste Separation Intention of Residential Households in a Developing Country: Evidence from Hanoi, Vietnam. *Habitat Int.* 48, 169–176. doi:10.1016/j.habitatint.2015.03.013

Nie, Y., Wu, Y., Zhao, J., Zhao, J., Chen, X., Maraseni, T., et al. (2018). Is the Finer the Better for Municipal Solid Waste (MSW) Classification in View of Recyclable Constituents? A Comprehensive Social, Economic and Environmental Analysis. *Waste Manage.* 79, 472–480. doi:10.1016/j.wasman.2018.08.016

Oates, W. E. (1999). An Essay of Fiscal. *Federalism J. Econ. Lit.* 37 (3), 20–1149.

Peri, G., Ferrante, P., La Gennusa, M., Pianello, C., and Rizzo, G. (2018). Greening MSW Management Systems by Saving Footprint: The Contribution of the Waste Transportation. *J. Environ. Manage.* 219, 74–83. doi:10.1016/j.jenvman.2018.04.098

Srivastava, A. K., and Nema, A. K. (2012). Fuzzy Parametric Programming Model for Multi-Objective Integrated Solid Waste Management under Uncertainty. *Expert Syst. Appl.* 39 (5), 4657–4678. doi:10.1016/j.eswa.2011.09.022

Stoeva, K., and Alriksson, S. (2017). Influence of Recycling Programmes on Waste Separation Behaviour. *Waste Manage.* 68, 732–741. doi:10.1016/j.wasman.2017.06.005

Tavares, G., Zsigraiová, Z., and Semiao, V. (2011). Multi-criteria GIS-Based Siting of an Incineration Plant for Municipal Solid Waste. *Waste Manage.* 31, 1960–1972. doi:10.1016/j.wasman.2011.04.013

Wu, B., Sarker, B. R., and Paudel, K. P. (2015). Sustainable Energy from Biomass: Biomethane Manufacturing Plant Location and Distribution Problem. *Appl. Energ.* 158, 597–608. doi:10.1016/j.apenergy.2015.08.080

Zegras, C., Nelson, J., Macário, R., and Grillo, C. (2013). Fiscal Federalism and Prospects for Metropolitan Transportation Authorities in Portugal. *Transport Policy* 29, 1–12. doi:10.1016/j.tranpol.2013.03.003

Zhang, K., Zhang, Z., and Liang, Q. (2017). An Empirical Analysis of the green Paradox in China: From the Perspective of Fiscal Decentralization. *Energy Policy* 103, 203–211. doi:10.1016/j.enpol.2017.01.023

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 20 July 2021
doi: 10.3389/fenrg.2021.701551

Research on the Relationship Between Green Energy Use, Carbon Emissions and Economic Growth in Henan Province

Ya-li Wang[1,2]*

[1]*Institute of Guangdong Economy and Social Development, Guangdong University of Finance and Economics, Guangzhou, China,* [2]*Guangdong Provincial Key Laboratory of Public Finance and Taxation with Big Data Application, Guangdong University of Finance and Economics, Guangzhou, China*

Edited by:
You-hua Chen, South China Agricultural University, China

Reviewed by:
Mingwei Song, Huazhong Agricultural University, China
Dongxiao Yang, Hunan University of Technology and Business, China

Correspondence:
Ya-li Wang
wangyali201031@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *28 April 2021*
Accepted: *06 July 2021*
Published: *20 July 2021*

Citation:
Wang Y-l (2021) Research on the Relationship Between Green Energy Use, Carbon Emissions and Economic Growth in Henan Province. Front. Energy Res. 9:701551. doi: 10.3389/fenrg.2021.701551

This article takes Henan Province as the research object and analyzes the relationship between the green energy use, carbon emissions and economic growth in Henan Province by constructing a VAR model. The results show that: *1*) There is a long-term equilibrium relationship between the green energy use, carbon emissions and economic growth in Henan Province. The green energy use can simultaneously promote the reduction of carbon dioxide emissions and sustainable growth of economy; *2*)The article examines the "creative" effect and "destructive" effect of green energy use on economic structure in Henan Province, and the "creative" effect is greater than the "destructive" effect, so, the green energy use can help Henan Province to achieve green and low-carbon economic growth; *3*) Carbon dioxide emission and economic growth are the important factors affecting the green use of energy in Henan Province. Recently, the call of national carbon emission reduction and the pressure of economic development transition have induced Henan Province to change to a clean and green use of energy to some extent; *4*) The contribution rate of green energy use to economic growth shows an inverted U-shaped trend, which increases first and then decreases. Carbon emission has influence on both green energy use and economic growth to a certain degree. Finally, targeted recommendations are presented to promote the green energy use and ensure the coordinated and sustainable development of economy and environment of Henan Province.

Keywords: green energy use, carbon dioxide emissions, economic growth, sustainable development, VAR model

INTRODUCTION

Since the reform and opening up, Henan has witnessed rapid economic development. The province's GDP has exceeded 5 trillion yuan, and the per capita GDP has exceeded 8,000 US dollars. However, its rapid economic development relies heavily on the input and use of fossil energy such as coal. In 2019, the total energy consumption of the province exceeded 22,000 tons of standard coal, with coal accounting for 67.4%. And before 2019, the energy coal accounted for more than 69%. The massive investment and use of energy, especially coal, has promoted the rapid economic development, but it has also led to serious environmental pollution and the emission of a large amount of greenhouse gases such as CO_2, which has brought enormous pressure to the environmental governance and carbon emission reduction of Henan Province.

Energy is the cornerstone and pillar of economic development. A large amount of energy investment has promoted the rapid growth of regional economy, but it has led to a large number of greenhouse gas emissions such as CO_2 and serious ecological environmental problems, which in turn will affect the economic development. The "Fourteenth Five-Year Plan for National Economic and Social Development of Henan Province and the Outline of the 2035 Long-Term Goals (Draft)" hereinafter referred to as the "Draft Outline," puts forward the goal of building an ecologically strong province. It points out that we shall form a green way of production and life. And at the same time the carbon emissions shall reach a peak after a steady decline. Meanwhile the man and nature basically realize the modernization of harmonious coexistence. Low-carbon and green have become the keynote of Henan's economic development. Under this background, the green energy use has become an important measure of carbon emission reduction in Henan Province.

The green energy use can reduce the emission of greenhouse gases such as CO_2, but the economic growth of Henan Province is heavily dependent on traditional energy sources such as coal. Therefore, how to rationally arrange the green energy use in the balance between carbon emission reduction and economic growth has become an important research issue. Schumpeter pointed out that "creative destruction" of economic structure is the fundamental driving force of economic growth and the essence of innovation. Green energy use in Henan Province will have a significant impact on the original economic structure of Henan Province: On the one hand, green energy use will have a negative impact on traditional energy production and processing industries with high energy consumption, high pollution and high emission, such as coal, oil and other traditional manufacturing industries, resulting in a "destructive" effect on economic development and growth. However, green energy use will also promote the rise and development of clean energy production and use industries such as new energy batteries, new energy automobiles and other industries, which will bring new sources of growth to economic growth, namely the "creative" effect. Therefore, it is necessary to comprehensively evaluate whether the green energy use in Henan promotes or hinders the economic growth and development of Henan Province. Only when the "creative" effect of the green energy use is greater than the "destructive" effect, the green energy use in Henan Province can be an important measure conducive to the high-quality development of Henan Province.

The outline of the "14th Five-Year Plan" focuses on accelerating the green transformation of development methods, and synergistically promoting high-quality economic development and high-level protection of the ecological environment. The coordinated development of green, low-carbon and high- quality has become the overall background of economic growth. Under the background of national advocacy, it is important for Henan Province to find the balance between the green energy use, carbon emission reduction and economic growth to ensure the coordinated and sustainable development of economy and environment.

Accordingly, in order to study the relationship between the green energy use, carbon emission reduction and economic growth in Henan Province, this article will construct a vector autoregressive (VAR) model to analyze how green energy use can achieve a balance between carbon emission reduction and economic growth. At the same time, the article will further examine whether the requirements of carbon emission reduction and economic growth can promote and induced the green energy use.

The contributions of this paper lie in five aspects: first, it fills the gap in the research on the relationship between the green energy use, carbon emissions and economic growth in Henan Province. Second, it finds out that how the green energy use can achieve a balance between carbon emission reduction and economic growth. Third, it examines the "creative" effect and "destructive" effect of green energy use on economic structure in Henan Province, and provides theoretical support for green energy use in Henan Province. Fourth, it analyzes the effect of green energy use on the economic growth of Henan Province, which provides a reference for the energy development and reform of other countries and regions like Henan Province. Finally, the paper provides relevant countermeasures and suggestions for the green energy use in Henan Province, which has a certain significance for the energy reform in Henan Province.

The rest of this article is structured as follows: Literature review is provided in "Literature review" section. The Research design is established in the "Research design" section, where data source, data processing and model design, are introduced. The results are discussed in the "Empirical analysis" section. In this section, we analyze the relationship between the green energy use, carbon emissions and economic growth in Henan Province. The "Discussion" section shows implications of research results for developing countries and regions. Conclusions and recommendations are drawn in the final section.

LITERATURE REVIEW

Whether green energy use can reduce carbon emissions, most scholars believe that the relationship between the two is positive: for example Fei et al. (2014) conducted research on energy use in Norway and New Zealand and found that clean energy input can help reduce carbon dioxide emissions. Shafiei and Salim (2014) believes that the increase in renewable energy consumption will help reduce carbon dioxide emissions. Dogan and Seker (2016) pointed out that the green use of energy can reduce carbon dioxide emissions. Zoundi (2017) believes that the increase in renewable energy consumption will negatively affect carbon dioxide emissions. Feng and Zou (2008) believe that low-carbon energy structure can positively drive carbon dioxide emissions reduction. Lu et al. (2013) pointed out that greener use of energy structure can restrict carbon dioxide emissions. Zou et al. (2021) pointed out that solar energy, wind energy, hydro energy, nuclear energy and hydrogen energy are the main force of new energy, which will help the power sector to achieve low carbon emissions. "Green hydrogen" is the backup of new energy, helping to further reduce carbon emissions in industrial and transportation sectors.

There is no unified conclusion on the relationship between green energy use and economic growth. Some scholars believe that green energy use will promote economic growth: for instance Apergis and Payne (2012) and Inglesi-Lotz (2016) believe that the increase in renewable energy consumption has promoted positive economic growth. Pao et al. (2014) and Kahia et al. (2017) point out that there is a mutually reinforcing relationship between the use of renewable energy and economic growth. Cang et al. (2020) concluded that the economic growth rate supported by new energy is higher than that supported by traditional energy. Li and Xu (2020) found that renewable energy consumption plays an important role in stimulating economic growth through co-integration test and establishment of VECM model analysis. Xu (2021) pointed out that new energy demonstration cities are an institutional attempt of energy policy. The implementation of such policies has significantly promoted the growth of regional GDP and per capita GDP, and with the deepening of the policy, the effect becomes more significant. However, some scholars believe that the greening of energy use will negatively affect economic growth:for example Ocal and Aslan (2013) and Maji (2015) both believe that the consumption and use of renewable energy hinders economic growth. Qi and Li (2018) point out that the use of renewable energy consumption will have a negative impact on economic growth.

There is not much literature on the combination of green energy use, carbon emissions and economic growth in a unified framework for research: Wang (2020) conducted an empirical study on the relationship between green energy use, carbon emissions and economic growth by establishing a vector autoregressive model (VAR).

The research showed that there is a long-term equilibrium relationship between green energy use, carbon emissions and economic growth in our country. The green energy use not only reduces carbon dioxide emissions but also promotes sustainable economic growth in our country.

In reviewing the relevant literature, it can be found that, in recent years, there is almost no relevant research on the combination of green energy use, carbon emission and economic growth in Henan Province, which relies heavily on traditional fossil energy for economic development. Therefore, this article takes the relationship among the green energy use, carbon emissions and economic growth in Henan Province as the research object, which can fill this gap in the literature. At the same time, it analyzes how the green energy use in Henan Province can achieve a balance between carbon emission reduction and economic growth, which is of great significance for the development of new energy, high-quality economic growth and high-level protection of the ecological environment in Henan Province.

RESEARCH DESIGN

Data Source and Processing

Since this article focuses on the interaction mechanism between the green energy use, carbon emissions and economic growth in Henan Province, this article will take carbon emissions and economic growth as the dependent variables for the analysis, and green energy use as the independent variables to construct a research model. Among them, green energy consumption is measured by the proportion of natural gas, primary power and other energy consumption to total energy consumption, recorded as CE, carbon emissions are measured by the carbon emissions of Henan Province's primary energy consumption, recorded as CO_2, and the economic growth is measured by per capita GDP, recorded as PGDP.

This article selects the relevant data of Henan Province from 1996 to 2019 for analysis. In order to eliminate the impact of inflation, the per capita GDP is converted into constant prices based on 1996. The data related to energy and economic growth are from the 1997–2020 "Henan Statistical Yearbook," and the carbon emissions data are from calculations. The specific calculation formula is as follows:

$$C = \alpha_1 C_1 + \alpha_2 C_2 + \alpha_3 C_3 \tag{1}$$

C is the total amount of carbon dioxide emitted by the combustion of coal, oil, and natural gas, and the unit is ten thousand tons. α_1, α_2, α_3 are the carbon emission coefficients of coal, oil and natural gas, and the unit is 10,000 tons/10,000 tons of standard coal. C_1, C_2, C_3, represents the actual consumption of coal, oil, and natural gas.

Since the energy consumption data in the current statistics has been converted into standard coal, it is necessary to convert these data into physical quantities again. For the physical amount of various primary energy consumption, we use the reciprocal of the coefficient of conversion of various types of energy into standard coal announced by the National Development and Reform Commission, that is, 1 ton of standard coal = 1.4 tons of coal = 0.7 tons of oil = 0.5883 tons of natural gas (Shang, 2011). The carbon emissions coefficients of coal, oil and natural gas (Energy Research Institute, National Development and Reform Commission, 2003) are shown in **Table 1**.

Therefore, the final carbon emission calculation formula is:

$$\begin{aligned} C &= C_1 * 0.7476 + C_2 * 0.5825 + C_3 * 0.4435 \\ &= E * \mathbf{a}_1 * 1.4 * 0.7476 + E * a_2 * 0.7 * 0.5825 + E * a_3 * 0.5883 * 0.4435 \\ &= E * (a_1 * 1.04664 + a_2 * 0.40775 + a_3 * 0.26091) \end{aligned} \tag{2}$$

Among them, E are the total energy consumption, the unit is ten thousand tons of standard coal. a_1, a_2, a_3 are respectively the proportion of coal, oil and natural gas in the total energy consumption (%).

In order to eliminate the heteroscedasticity problem that may exist in the data analysis process, the three time series data of CE, CO_2, and PGDP are processed by logarithm, and they are

TABLE 1 | Carbon emissions coefficients of three energy sources.

Coal	Petroleum	Natural gas
0.7476	0.5825	0.4435

recorded as LNCE, $LNCO_2$, and LNPGDP respectively, as shown in **Figure 1**.

Figure 1 shows the change trend of LNCE, $LNCO_2$ and LNPGDP, and it can be concluded that there are three stages in clean energy development in Henan Province: the gentle development stage is from 1996 to 2000, the slow development stage is from 2001 to 2009 and the rapid development stage is from 2010 to 2019. The proportion of clean energy in Henan Province increased from 3.1% in 1996 to 16.8% in 2019, indicating that Henan Province has made remarkable achievements in green energy consumption and energy structure optimization. It can also be seen from **Figure 1** that although Henan Province's carbon dioxide emissions have been increasing year by year, its growth rate has slowed down significantly after 2010, indicating that Henan's industrial structure upgrade and energy consumption structure optimization and other related measures have achieved certain results and contribute to the decline in the growth rate of carbon emissions. In addition, Henan's per capita GDP maintained a rapid growth trend from 1996 to 2019.

MODEL DESIGN

The vector autoregressive model (VAR) can effectively predict and judge whether multiple groups of correlated time series variables will affect their future development. Therefore, this paper chooses the VAR model to study the impact of green energy use on carbon emissions and economic growth in Henan Province. The expression of VAR model is as follows:

$$y_t = \alpha_1 y_{t-1} + \alpha_2 y_{t-2} + \cdots + \alpha_n y_{t-n} + \beta x_t + \mu_t, t = 1, 2, 3 \ldots T \quad (3)$$

Where, y_t is the k-dimensional endogenous variable, x_t is the exogenous variable, $\alpha_1, \alpha_2, \cdots \alpha_n$ and β are the parameter matrix to be estimated, μ_t is the random error term.

The VAR model is expressed in matrix form as follows:

$$\begin{bmatrix} y_{1t} \\ y_{2t} \\ \cdots \\ y_{kt} \end{bmatrix} = \alpha_1 \begin{bmatrix} y_{1t-1} \\ y_{2t-1} \\ \cdots \\ y_{kt-1} \end{bmatrix} + \alpha_2 \begin{bmatrix} y_{1t-2} \\ y_{2t-2} \\ \cdots \\ y_{kt-2} \end{bmatrix} + \cdots + \alpha_n \begin{bmatrix} y_{1t-n} \\ y_{2t-n} \\ \cdots \\ y_{kt-n} \end{bmatrix} + \beta \begin{bmatrix} x_{1t} \\ x_{2t} \\ \cdots \\ x_{kt} \end{bmatrix} + \begin{bmatrix} u_{1t} \\ u_{2t} \\ \cdots \\ u_{kt} \end{bmatrix}, t = 1, 2, 3 \ldots T \quad (4)$$

EMPIRICAL ANALYSIS

The Unit Root Test

Before analyzing the VAR model, it is necessary to perform a unit root test on the data to avoid "false regression" and ensure the stability of the VAR model data. Therefore, this article chooses the ADF unit root test method to test the original logarithmic data LNCE, LNCO2 and LNPGDP for the stationarity. The specific test results are shown in **Table 2**.

According to **Table 2**, LNCE, $LNCO_2$ and LNPGDP and their first-order difference are all non-stationary series at the significance level of 5%, but their second-order difference series are stationary series at the significance level of 5%, so it is a second-order single integral process.

Cointegration Test

Although the original sequence is not stationary, it is likely that there is a long-term equilibrium relationship between the original sequences. Therefore, this paper uses Johansen co-integration test to determine how many linearly independent co-integration vectors there are between the original sequences. The specific results are shown in **Table 3**.

The cointegration rank trace test (trace statistic) including the constant term and the time trend term shows that there is only

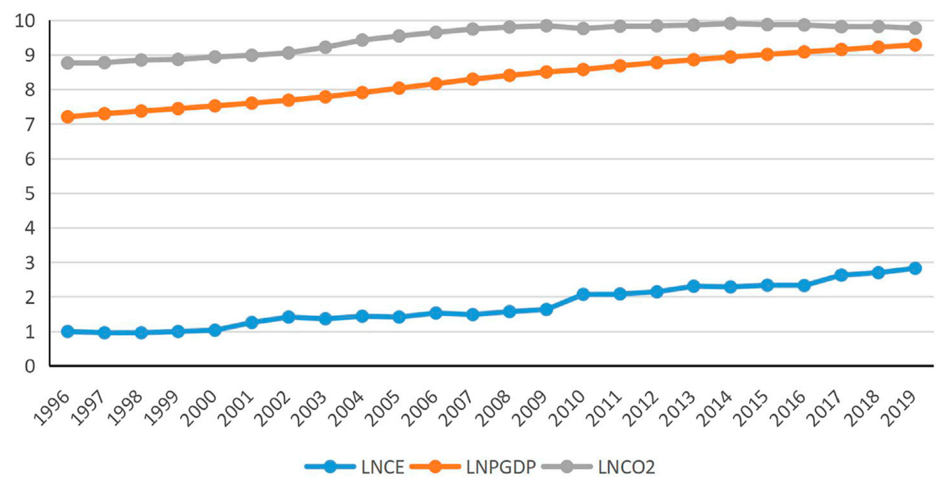

FIGURE 1 | Time series diagram of LNCE, $LNCO_2$ and LNPGDP.

TABLE 2 | ADF unit root test results.

Variable	ADF statistics	5% Threshold	*p* value	Conclusion
LNCE	0.532	–3.000	0.9858	Unstable
LNPGDP	–1.415	–3.000	0.5753	Unstable
$LNCO_2$	–2.265	–3.136	0.1836	Unstable
DLNCE	–2.518	–3.000	0.1754	Unstable
DLNPGDP	–1.395	–3.000	0.5847	Unstable
$DLNCO_2$	–2.307	–3.136	0.1696	Unstable
D2LNCE	–5.518[a]	–3.000	0.0000	Stable
D2LNPGDP	–5.478[a]	–3.000	0.0031	Stable
$D2LNCO_2$	–7.334[a]	–3.136	0.0016	Stable

D represents first-order difference, D2 represents second-order difference.
[a]Denotes the rejection of the null hypothesis of sequence instability at the significance level of 5%.

one linearly independent cointegration vector (starred in **Table 3**). However the maximum eigenvalue test (max statistic) shows that the null hypothesis of "cointegration rank is 0" can be rejected at the 5% level, but the null hypothesis of "cointegration rank is 1" can not be rejected. Thus, the corresponding cointegration equation can be drawn as follows:

$$-0.3615563 * LNCO_2 + 1.202035 * LNPGDP = LNCE \quad (5)$$

According to the co-integration **Eq. 5**, there is a long-term equilibrium relationship between the green energy use and carbon emissions and economic growth in Henan Province. From a long-term perspective, the green energy use in Henan Province can not only reduce carbon dioxide emissions in Henan Province, but also promote Economic growth in Henan Province. we can see that if the proportion of green energy use in Henan province is increased by 1%, the carbon dioxide emission can be reduced by 2.7658%, indicating that the implementation and efforts of Henan Province's energy clean-up policies and projects such as "coal to gas" have effectively reduced carbon dioxide emissions. In addition, an increase in the proportion of green energy use in Henan Province by 1% can increase per capita GDP by 0.8319%. This shows that the green energy use in Henan Province has indeed promoted the economic growth and development of Henan Province, and at the same time, it also indicates that the win-win economic growth goal of environmental effect and economic benefit is achieved to a certain extent. Therefore, from the perspective of the long-term economic development planning of a province, the "creative" effect of the green energy use in Henan Province is greater than the "destructive" effect, and the green and low-carbon economic growth in Henan Province has been realized. In other words, the sustainable and coordinated development of economy and environment can be realized to some extent. Hence, in the long term, the green energy use is an important measure of energy conservation, emission reduction and sustainable development for Henan Province.

Granger Causality Test

The co-integration test has confirmed that there is a long-term equilibrium relationship between LNCE, LNCO2 and LNPGDP. In order to further determine the causality between the variables, this paper will conduct a Granger causality test on them, and the test results are shown in **Table 4**.

It can be seen from **Table 4** that both carbon emissions and economic growth are Granger reasons for green energy use, and green energy use is not the Granger reason for carbon emissions and economic growth. It shows that the carbon emissions and economic growth of Henan Province have a great impact on the green energy use in Henan Province. Therefore, the increasing pressure of carbon emission reduction and the unsustainable extensive economic growth mode will force the change of energy use to clean, low-carbon and green in Henan Province.

Impulse Response Analysis

According to the stationary test and co-integration test, $LNCO_2$, LNCE and LNPGDP are all second-order single integration processes, so the VAR model can be constructed. In order to estimate the VAR model, it is necessary to first determine the optimal lag period of the VAR model according to the information criteria. The specific results are shown in **Table 5**.

It can be seen from **Table 5** that the optimal lag order of the VAR model is 2, so the VAR(2) model can be established. The coefficient matrix estimation results are as follows:

$$\begin{bmatrix} LNCE_t \\ LNCO_{2t} \\ LNPGDP_t \end{bmatrix} = \begin{bmatrix} -3.09 \\ 1.40 \\ 0.02 \end{bmatrix} + \begin{bmatrix} 0.27 & -0.37 & 0.10 \\ -0.19 & 1.35 & -0.17 \\ 0.70 & 0.26 & 1.14 \end{bmatrix} \begin{bmatrix} LNCE_{t-1} \\ LNCO_{2t-1} \\ LNPGDP_{t-1} \end{bmatrix} + \begin{bmatrix} 0.22 & 0.01 & -0.03 \\ -0.65 & -0.10 & 0.07 \\ 1.83 & 0.28 & -0.27 \end{bmatrix} \begin{bmatrix} LNCE_{t-2} \\ LNCO_{2t-2} \\ LNPGDP_{t-2} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \\ \varepsilon_{3t} \end{bmatrix} \quad (6)$$

TABLE 3 | Johansen tests for cointegration.

Rank	Parms	LL	Eigenvalue	Trace statistic	5% Critical value
0	15	131.32527	.	39.5595	34.55
1	20	143.01686	0.65454	16.1763*	18.17
2	23	149.98683	0.46934	2.2364	3.74
3	24	151.10502	0.09666		
Rank	**Parms**	**LL**	**Eigenvalue**	**Max statistic**	**5% Critical value**
0	15	131.32527	.	27.3832	23.78
1	20	143.01686	0.65454	13.9399	16.87
2	23	149.98683	0.46934	2.2364	3.74
3	24	151.10502	0.09666		

TABLE 4 | Granger causality test results.

The null hypothesis	F Statistic	*p* value	Conclusion
$LnCO_2$ is not the Granger cause of lnCE	3.97	0.0307	Refuse
LNCE is not the Granger cause of $LNCO_2$	2.23	0.1381	Not refuse
LNPGDP is not the Granger cause of LNCE	4.9	0.0209	Refuse
LNCE is not the Granger cause of LNPGDP	2.91	0.0816	Not refuse

TABLE 5 | Optimal lag period of VAR model.

Lag	LL	LR	FPE	AIC	HQIC	SBIC
0	12.235		0.00008	−0.923499	−0.894343	−0.77414
1	126.651	228.83	3.2e−09	−10.846	−10.6419	−9.80044
2	135.78	12.577	4.30e−09	−11.4651*	−11.3485*	-10.8677*
3	149.002	26.509	2.10e−09*	−11.002	−10.6212	−9.0587

If an effective impulse response analysis is to be carried out, the stability of the VAR model must be ensured. Therefore, the VAR model needs to be tested for stability before impulse response analysis. The test results are shown in **Figure 2**.

As can be seen from **Figure 2**, all eigenvalues of the model are within the unit circle, so the VAR model is stable and can be analyzed by impulse response analysis and variance decomposition analysis.

Figure 3 is a graph of the impulse response of $LNCO_2$ and LNPGDP to LNCE. In **Figure 3**, the vertical axis is the value of the relevant response, and the horizontal axis is the period setting. This article is set to 10 periods.

It can be seen from **Figure 3** that after a positive impact on green energy use, it will lead to a reduction in carbon dioxide emissions and an increase in per capita GDP. The green energy use will continue to negatively affect carbon dioxide emissions. At the same time, it maintains a positive impact on per capita GDP, which indicates that the green energy use in Henan Province can effectively reduce carbon dioxide emissions. Therefore, green energy use is an important measure for carbon emission reduction in Henan Province.

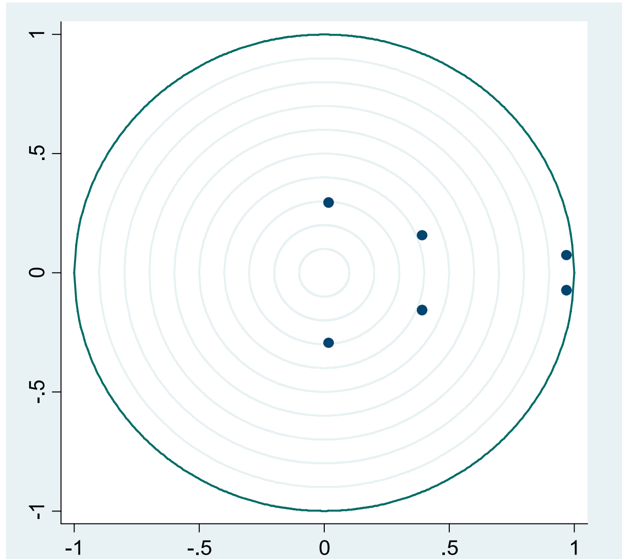

FIGURE 2 | Stability test of VAR model.

Variance Decomposition Analysis

After the impulse response analysis, the variance decomposition analysis can observe the contribution rate of the green energy use, carbon dioxide emissions and economic growth in Henan Province to the changes of the three variables. **Table 6** shows the variance decomposition results of carbon dioxide emissions, and **Table 7** shows The results of the variance decomposition of economic growth, **Table 8** shows the results of the variance decomposition of green energy use, and the time is set to 10 periods.

It can be seen from **Table 6** that carbon dioxide emissions are mainly affected by itself and the green energy use. Until the 10th period, the influence of the two remained above 94.7%. The contribution rate of economic growth to carbon dioxide emissions has also continued to increase and the influence reached 5.3376% in the 10th period. As can be seen from **Table 7**, economic growth is mainly influenced by itself, followed by carbon dioxide emissions. The contribution rate of green energy use to economic growth shows an inverted U-shaped trend that first rises and then falls, indicating that the impact of green energy use on economic growth increases first and then decreases. The data in **Table 8** shows that the green energy use is mainly affected by itself, and its own contribution rate has been maintained at more than 81%. The impact of carbon emissions and economic growth on the green energy use is increasing, indicating that the continuous increase of carbon emissions in Henan Province, the pressure of emission reduction and the continuous growth of economy have promoted the clean and green energy use in Henan Province to some extent.

DISCUSSION

Furthermore, our results suggest that there is a long-term equilibrium relationship between green energy use, carbon emissions, and economic growth for energy, especially coal-dependent developing regions. The article examines the "creative" effect and "destructive" effect of green energy use on economic structure in Henan Province, and the "creative" effect is greater than the "destructive" effect, that is to say the green and low-carbon economic growth in Henan Province has

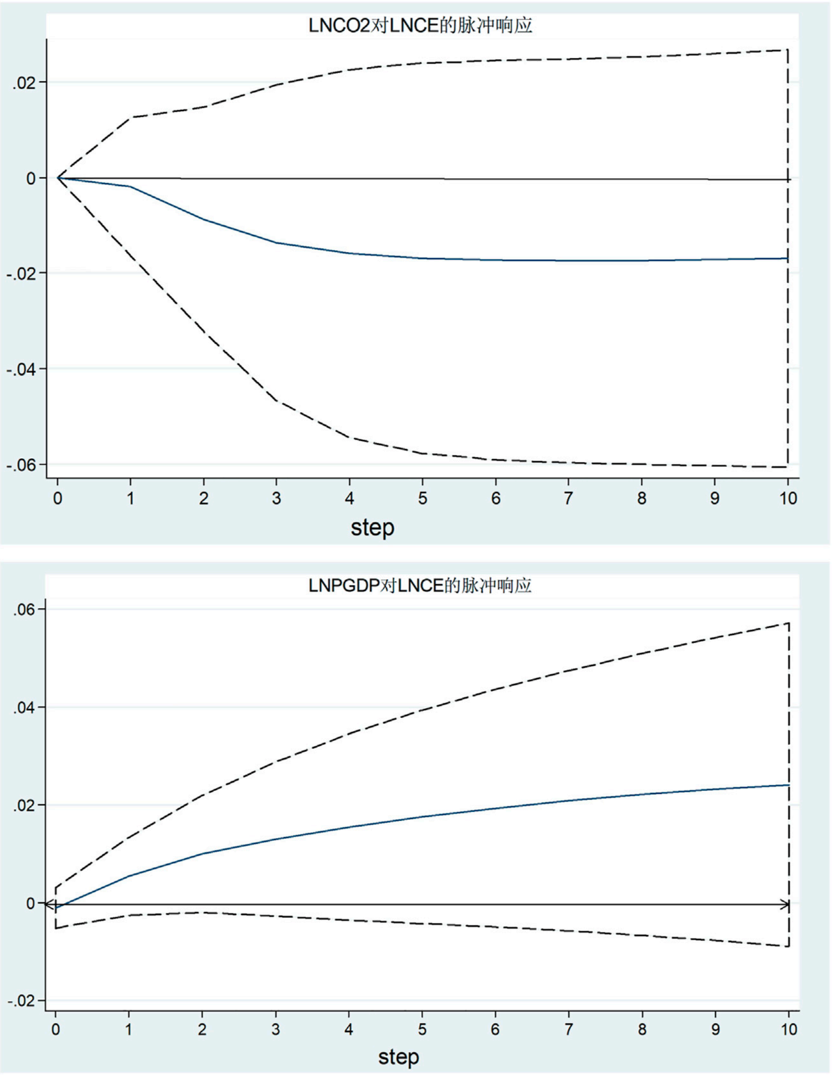

FIGURE 3 | Impulse response of $LNCO_2$ and LNPGDP to LNCE.

TABLE 6 | Variance decomposition of $LNCO_2$.

Period	LNCO2	LNPGDP	LNCE
1	93.3229	0.0000	6.6771
2	88.9412	0.0887	10.9701
3	80.1060	0.9422	18.9518
4	75.7441	1.9761	22.2798
5	73.2303	2.8351	23.9346
6	71.5475	3.5164	24.9362
7	70.3403	4.0732	25.5865
8	69.4256	4.5461	26.0283
9	68.6961	4.9619	26.3420
10	68.0901	5.3376	26.5723

TABLE 7 | Variance decomposition of LNPGDP.

Period	LNPGDP	LNCO2	LNCE
1	94.6318	0.0000	5.3682
2	82.2556	7.7194	10.0250
3	71.5822	13.9748	14.4430
4	66.5595	17.6386	15.8019
5	65.6575	20.0555	14.2870
6	64.3407	21.7544	13.9049
7	63.9154	22.9869	13.0977
8	63.0280	23.9098	13.0622
9	62.4820	24.6217	12.8963
10	62.1612	25.1842	12.6546

been realized, which provides a reference for the energy development and reform of other countries and regions like Henan Province.

For developing countries and regions like Henan Province with an average annual output value of about 5 trillion yuan, the green energy use will indeed promote carbon emission reduction

TABLE 8 | Variance decomposition of LNCE.

Period	LNCE	LNCO2	LNPGDP
1	100.0000	0.0000	0.0000
2	99.5956	0.0591	0.3453
3	97.3802	1.8546	0.7652
4	93.5021	3.7785	2.7194
5	90.6899	4.2186	5.0115
6	88.7380	4.2393	7.0227
7	87.1288	4.2603	8.6108
8	85.4785	4.7869	9.7347
9	83.5111	6.0960	10.3928
10	81.0741	8.3094	10.6165

and sustainable economic growth. Therefore, the green energy use is the progress of the economic development of developing countries and regions, and it is also the inevitable choice of developing countries and regions under the international call of "carbon neutral" and "carbon peak."

The clean and green energy use can reduce carbon dioxide emissions and promote economic growth for developing energy-dependent countries and regions.

Therefore, when developing countries and regions are faced with the choice between carbon emission reduction and economic growth, the clean and green energy use is a major measure and method. The clean and green energy use can promote the optimization of energy structure and industrial structure in developing countries and regions. And it also can assist developing countries and regions to achieve high-quality economic development and high-level protection of the ecological environment. Hence, the clean and green energy use is imperative for developing countries and regions.

However, this article uses a regional data from Henan Province to conduct the research, and the regional samples are limited. This study will expand on this and select more regional samples to conduct research to verify the long-term equilibrium relationship between green energy use, carbon emissions, and economic growth. At the same time, this article also will find a balance between green energy use, carbon emission reduction and economic growth to ensure the coordinated and sustainable development of the economy and the environment.

CONCLUSIONS AND POLICY RECOMMENDATIONS

This paper takes Henan Province as the research object and analyzes the relationship between the green energy use, carbon emissions and economic growth in Henan Province by constructing a VAR model. The main conclusions are as follows:

1) There is a long-term equilibrium relationship between the green energy use, carbon emissions and economic growth in Henan Province. The co-integration equation also shows that the green energy use in Henan Province can simultaneously promote the reduction of carbon dioxide emissions and the sustainable growth of the economy. The acceleration of green energy use for Henan Province can ensure the realization of its win-win goals for energy conservation, emission reduction and sustainable economic development. Through impulse response analysis, we can still see that the green energy use is an important measure to achieve the carbon emission reduction and economic growth. This is mainly because the "creative" effect of green energy use in Henan Province on economic growth exceeds the "destructive" effect, and finally Henan Province has realized the green and low-carbon economic growth.
2) The Granger causality test shows that carbon dioxide emissions and economic growth are important factors affecting the green energy use in Henan Province. Recently, the call of national carbon emission reduction and the pressure of economic development and transformation have forced Henan Province to change its energy use to a cleaner and greener way to some extent. This is also an important reason for Henan Province to accelerate the optimization and transformation of industrial structure, accelerate the construction of energy saving and emission reduction industrial system and the construction of "coal to gas" project in recent years.
3) According to variance decomposition analysis, the contribution rate of green energy use to carbon dioxide and economic growth is between 5 and 27%, especially its contribution rate to economic growth shows an inverted U-shaped trend that increases first and then decreases. Carbon emissions have a certain influence on both green energy use and economic growth. However, its influence on economic growth is greater than its influence on the greening of energy use. However, although economic growth has a certain influence on the greening of energy use and carbon emissions, the influence is relatively small.

Based on the conclusion, this article proposes the following policy recommendations:

1) The promotion of green energy use in Henan Province is an important measure for Henan Province to reduce the pressure on the ecological environment and promote sustainable and healthy economic development. Therefore, it is suggested that Henan Province should focus on the dual effects of green energy use in reducing carbon emissions and promoting economic growth, and actively promote clean and green energy use in the province. At present, Henan Province ranks fifth in the national economic aggregate rankings. It is a large agricultural province and a populous province in the country. Economic development and employment stability are still the key goals of Henan Province in the future. Therefore, Henan Province can take the following measures in terms of energy transition and greening: In traditional energy-using industries (such as industry), we should promote their transformation to intelligence, accelerate the elimination of backward production capacity, actively introduce energy-saving and emission reduction green equipment, increase the proportion of investment in clean energy and renewable energy, and realize the green use of energy from the

production side. For the clean energy production industry, the government should introduce corresponding policies and measures to ensure its construction and smooth production, and provide R&D tax credits and subsidies and other related measures to promote its rapid development to ensure the supply and use of clean energy in the province. For green industries such as new energy vehicles, the government should give strong policy and financial support, including subsidies and R&D tax incentives, to help enterprises go through the initial stage of smoothly promoting the development of green industries such as new energy. In addition, the whole province should pay attention to the construction and bidding of clean and green projects such as coal to gas to ensure the smooth implementation of green projects. Through the implementation of various measures related to energy greening, the process of energy greening and cleaning in Henan Province will continue to advance. After that a green and beautiful Henan will be realized as soon as possible, and the harmonious coexistence between man and nature will be truly realized.

2) The green energy use has forced Henan Province to optimize its energy use structure, which requires Henan Province to change its traditional energy consumption pattern. Its high dependence and high input on high-emission and high-polluting energy sources like coal should be gradually transformed. At the same time, the development and utilization of natural gas, hydropower, and nuclear energy should be accelerated. Henan Province also shall increase the proportion of clean energy in the province's production and living inputs, and improve the peak shaving capacity of clean energy reserves to expand its utilization range. At the same time, we must also *see* that the economic development of Henan Province is highly dependent on coal. In the short term, its economic development will still require a large amount of coal energy input. Therefore, Henan Province should speed up the research and application of coal clean and green technologies. For example, coal water slurry technology, carbon storage technology and circulating fluidized bed combustion and other high-efficiency and clean coal combustion and conversion technologies. This can promote the transformation of coal, a black energy source, into a cleaner and greener one.

3) Improve the low-carbon and green-related laws of the energy market, and innovate the incentive system for low-carbon and green energy. Developed countries such as the United States and the United Kingdom have formed relatively complete energy low-carbon and green energy laws and regulations. However, although energy low-carbon and green energy has received certain attention and development in our country, there is still a long way to go. Henan Province's laws and regulations on low-carbon and green energy have not formed a complete system. Therefore, Henan Province can consider expanding and detailing management measures for low-carbon and green energy use in industrial enterprises on the basis of the Ecological Environment Protection Law. For different types of industrial enterprises, different laws and regulations may be implemented. Henan Province needs to strengthen the regulatory mechanism for low-carbon and green development and operation of energy, and increase the employment rate of green industries. Henan Province can also innovate the incentive system for low-carbon and green use of energy, formulate incentive standards for green energy input and use, reward enterprises that meet the standards, set up good models, and drive the rapid transformation of energy use by enterprises in the province to green and clean energy.

4) Deepen the structural reform of the energy supply side, and give full play to the regulatory effect of the market mechanism in the energy market. With the vigorous development of green energy and green economy in Henan Province, the development of related industries will need a lot of financial support. Therefore, it is suggested that the government and financial institutions do a good job of green credit planning, make good use of green credit financial instruments, and give full play to their maximum effect, so as to meet the capital needs in the process of green energy use.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: Henan Statistical Yearbook.

AUTHOR CONTRIBUTIONS

Y-lW conceived the idea and designed the model. Y-lW performed the mathematical studies and wrote the manuscript. She also critically screened the manuscript.

FUNDING

This work is supported by Open Foundation of Guangdong Provincial Key Laboratory of Public Finance and Taxation with Big Data Application.

REFERENCES

Apergis, N., and Payne, J. E. (2012). Renewable and Non-renewable Energy Consumption-Growth Nexus: Evidence from a Panel Error Correction Model. *Energ. Econ.* 34 (3), 733–738. doi:10.1016/j.eneco.2011.04.007

Cang, D. b., Wei, X. p., Cao, M., and Tan, L. y. (2020). A Two-Stage Economic Growth Path Study Based on Energy Substitution and Environmental Pollution Control. *Chin. Manag. Sci.* 28 (9), 146–153. doi:10.16381/j.cnki.issn1003-207x.2020.09.015

Dogan, E., and Seker, F. (2016). Determinants of CO2 Emissions in the European Union: The Role of Renewable and Non-renewable Energy. *Renew. Energ.* 94, 429–439. doi:10.1016/j.renene.2016.03.078

Energy Research Institute "China Sustainable Development Energy and Carbon Emission Analysis" Research Group (2003). China Sustainable Development Energy and Carbon Emission Scenario Research. *China Energy* 6, 5–11.

Fei, Q., Rasiah, R., and Shen, L. J. (2014). The Clean Energy-Growth Nexus with CO2 Emissions and Technological Innovation in Norway and New Zealand. *Energ. Environ.* 25 (8), 1323–1344. doi:10.1260/0958-305x.25.8.1323

Feng, X., and Zou, J. (2008). Economic Analysis of CO2 Emission Trends in China. *China Popul. Resour. Environ.* 3, 43–47. doi:10.1016/S1872-583X(09)60005-X

Inglesi-Lotz, R. (2016). The Impact of Renewable Energy Consumption to Economic Growth: A Panel Data Application. *Energ. Econ.* 53, 58–63. doi:10.1016/j.eneco.2015.01.003

Kahia, M., Aïssa, M. S. B., and Lanouar, C. (2017). Renewable and Non-renewable Energy Use - Economic Growth Nexus: The Case of MENA Net Oil Importing Countries. *Renew. Sustain. Energ. Rev.* 71, 127–140. doi:10.1016/j.rser.2017.01.010

Li, P. y., and Xu, W. x. (2020). Empirical Analysis of China's Renewable Energy Consumption and Economic Growth. *Energ. Conservation Techn.* 38 (4), 365–370.

Lu, W. B., Qiu, T. T., and Du, L. (2013). Research on the Influencing Factors of Carbon Emissions at Different Stages of Economic Growth in China. *Econ. Res.* 48 (4), 106–118.

Maji, I. K. (2015). Does Clean Energy Contribute to Economic Growth? Evidence from Nigeria. *Energ. Rep.* 1, 145–150. doi:10.1016/j.egyr.2015.06.001

Ocal, O., and Aslan, A. (2013). Renewable Energy Consumption-Economic Growth Nexus in Turkey. *Renew. Sustain. Energ. Rev.* 28, 494–499. doi:10.1016/j.rser.2013.08.036

Pao, H.-T., Li, Y.-Y., and Hsin-Chia Fu, H. C. (2014). Clean Energy, Non-clean Energy, and Economic Growth in the MIST Countries. *Energy Policy* 67, 932–942. doi:10.1016/j.enpol.2013.12.039

Qi, S. Z., and Li, Y. (2018). Threshold Effect of Renewable Energy Consumption on Economic Growth Under the Energy Transition. *China Popul. Resour. Environ.* 28 (2), 19–27.

Shafiei, S., and Salim, R. A. (2014). Non-renewable and Renewable Energy Consumption and CO_2 Emissions in OECD Countries: a Comparative Analysis. *Energ. Policy* 66, 547–556. doi:10.1016/j.enpol.2013.10.064

Shang, W. Y. (2011). Research on the Evolution of Carbon Emissions from Energy Consumption in Henan Province and its Relationship with Economic Growth. *Econ. fabric* (3), 39–42. doi:10.15931/j.cnki.1006-1096.2011.03.005

Wang, S. (2020). Research on the Relationship Between Green Energy Use, Carbon Emissions and Economic Growth in China. *Soft Sci.* 34 (10), 7–11. doi:10.13956/j.ss.1001-8409.2020.10.02

Xu, H. G. (2021). New Energy Demonstration Cities and Regional Economic Growth. *East China Econ. Manag.* 35 (1), 71–85. doi:10.19629/j.cnki.34-1014/f.200404003

Zou, C., Xiong, B., Xue, H., Zheng, D., Ge, Z., Wang, Y., et al. (2021). The Position and Role of New Energy in Carbon Neutrality. *Pet. Exploration Develop.* 48 (2), 1–10. doi:10.1016/s1876-3804(21)60039-3

Zoundi, Z. (2017). CO2 Emissions, Renewable Energy and the Environmental Kuznets Curve, A Panel Cointegration Approach. *Renew. Sustain. Energ. Rev.* 72, 1067–1075. doi:10.1016/j.rser.2016.10.018

Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 20 July 2021
doi: 10.3389/fenrg.2021.693767

Can CO_2 Emission Reduction and Economic Growth Be Compatible? Evidence From China

Zhuang Zhang[1], *You-Hua Chen*[1]* and *Chien-Ming Wang*[2]*

[1]College of Economics and Management, South China Agricultural University, Guangzhou, China, [2]Department of International Business, Ming Chuan University, Taipei, Taiwan

The influence of low-carbon energy on economic development is a vital issue. Using the provincial panel data in China from 2000 to 2017, this work investigated the aggregate effects of low-emission electricity. The results showed that 1) when the ratio of low-emission electricity to total electricity increases by 1%, the GDP per capita will increase by 0.16% and CO_2 emissions will decrease by 0.848%. In other words, low-emission electricity can achieve the goal of low-carbon economic development; 2) the self-supply of low-emission electricity, rather than trade and efficiency, is the main reason for China's boosted economic growth; and 3) low-emission electricity increases the regional economic gap in China. The effects of pollution inhibition and economic promotion on low-emission electricity in developed areas are significantly greater than those in less developed areas. Thus, the low-emission electricity policy in China should benefit the economy and avoid the excessive economic gap among regions. Policymakers should vigorously promote the low-emission electricity revolution and pay attention to the inclination of energy policy to the central and western regions.

Keywords: low-emission energy, CO_2 emissions, economic growth, regional heterogeneity, balance of development

OPEN ACCESS

Edited by:
Ian Edmund William Schindler, Université Toulouse 1 Capitole, France

Reviewed by:
Minxing Jiang, Nanjing University of Information Science and Technology, China
He Nie, National University of Singapore, Singapore

***Correspondence:**
You-Hua Chen
Chenyhua214@163.com
Chien-Ming Wang
cmwang8@gmail.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *12 April 2021*
Accepted: *03 June 2021*
Published: *20 July 2021*

Citation:
Zhang Z, Chen Y-H and Wang C-M (2021) Can CO_2 Emission Reduction and Economic Growth Be Compatible? Evidence From China. Front. Energy Res. 9:693767. doi: 10.3389/fenrg.2021.693767

INTRODUCTION

The 2015 Paris Climate Conference claimed that, in this century, the global temperature rise should be brought to 2°C lower than that before industrialization and ideally should be below 1.5°C (UNFCCC, 2015; Azam et al., 2020; Duan et al., 2021). For its ambitious aim, China's CO_2 emissions and energy consumption should be reduced by more than 90 and 39%, respectively, and China's cumulative policy costs may reach 2.8–5.7% of its GDP in 2050 (Duan et al., 2021). Duan et al. (2021) implied that the goal of CO_2 emission reduction and economic growth may be hard to coordinate due to the enormous costs.

Is it tough for CO_2 emission reduction to be compatible with the goal of economic growth[1]? Furthermore, what are the possible reasons? In response to Duan et al. (2021), we try to offer some

[1]We also recognize that COVID-19 caused uncertainty in economic growth and the contribution of energy to economic growth may be uncertain. Some studies suggested that energy, especially new energy, contributes to economic growth (Magazzino et al., 2021; Azam et al., 2020). However, there are also studies showing that energy had a negative impact on economic growth. For example, Garcia1 et al. (2020) believed that peak oil production will lead to economic contraction. The article gives compelling evidence that between 2000 and 2017 increasing the proportion of LEE in the energy mix contributed to economic growth and reduced CO_2 emissions in some regions of China.

details on the effects of low-emission electricity (LEE) on CO_2 emission reduction and economic growth. In this article, by employing the clean electricity consumption data of China, we give evidence supporting an answer to the following questions: 1) Can LEE be beneficial to CO_2 emission reduction and economic growth? 2) What are the possible mechanisms of LEE on economic development and CO_2 emissions? 3) Does the development of LEE in an economically disadvantaged region lead to the difference in regional economic growth?

What we were facing is a paradox. On the one hand, we know the adverse effects of greenhouse gas emissions caused by burning fossil energy on ecosystem activities. On the other hand, energy is an essential engine of economic development, which affects our essential well-being (Mendonç et al., 2020). The novel coronavirus pandemic has had a great impact on the global economy, and the demand for almost all energy products has dropped sharply. However, these negative effects are expected to recover in the short term, and the global energy demand is expected to rise in 2025 (IEA, 2020). Simultaneously, CO_2 emissions have increased from 205.18 million tons in 1990 to 32.314 billion tons in 2016 due to fossil fuel consumption and agriculture (IEA, 2018[2]).

Electricity is an integral part of modern energy and plays an essential role in economic growth (Das et al., 2012; Hamida, 2012; Tang and Tan, 2012; Mahfoudh and Amar, 2014). Of course, the acquisition of electricity mostly depends on the transformation of traditional energy (such as fossil fuel). Similar to other fuel-oil energy, electricity consumption faces the contradiction between economic development and environmental protection. Fortunately, this does not constitute an irreconcilable contradiction. Recent studies demonstrated that the application of renewable energy had decreased CO_2 emissions (Toumi and Toumi, 2019; Cosmas et al., 2019; Azam et al., 2020). Hydropower- and nuclear-related technologies have similar effects as well (Noorpoor and Kudahi, 2015). Unfortunately, not all countries or regions have enough economic or technological strength to produce electricity.

The electricity production of the world's highest income countries accounts for almost 70% of the world's electricity production (BPstats, 2018). The United States and European electric power consumption increased until 2007. Since then, their consumption has been slightly down (BPstats, 2018). From the perspective of electric technology, developed countries such as the United States, Canada, and Japan rely on coal energy less than 35%, while developing countries such as China and India rely on coal energy more than 60%. There is not enough data for third-world countries such as the sub-Saharan countries. As a representative sub-Saharan country, however, South Africa relies on coal energy as high as 87.73% for total electricity production. He et al. (2019) also reported that CO_2 emissions in the sub-Saharan region based on fossil fuel were severe.

[2]According to the EPA (https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data) 24% of greenhouse gas emissions come from land use, while all transportation accounts for only 14%.

The development of electricity is unbalanced not only in the world but also within countries. In China, the capacity for developing LEE varies in different regions. For example, northwest China has a vast territory, short rainy seasons, and sufficient light. It has the natural advantage of developing solar energy, wind energy, and biogas. The limitations for these regions are that there are not enough capital and technical advantages. China's coastal cities have certain technological advantages and can also develop geothermal energy and nuclear energy. For that of China's central region, the comparative advantages are not outstanding. China's overall level of LEE is constantly improving. For example, the proportion of clean electricity increased from 11.8% in 2013 to 17.4% in 2017, but compared with 66% proposed by Duan et al. (2021), China still needs to make great efforts for clean electricity development.

To our knowledge, current studies care more about the effects of LEE among different countries (Ozturk, 2010; Polemis and Dagoumas, 2013; Alper and Oguz, 2016) or within a country (Lee and Chang, 2005; Ho and Siu, 2007; Ang, 2008; Karanfil, 2008; Zhang and Cheng, 2009). Nevertheless, few pay attention to the heterogeneous effects of LEE on CO_2 emission reduction and economic growth in a country with unbalanced development. So, this work investigates the comprehensive effects of clean electricity based on the provincial panel data in China from 2000 to 2017. We found that 1) LEE development contributes to economic growth and carbon emission reduction, and its driving mechanism is internal LEE supply; 2) there are great differences in the impacts of LEE development among the three different regions of China; and 3) from 2000 to 2017, China's LFE to economic growth and carbon emission reduction is increasingly significant.

The conclusions of this article is a response to the questions of Duan et al. (2021) on China's energy cost pressure, and this study further offers a valuable paradigm for analyzing the LEE policy of countries with unbalanced economic development. The remainder of this article is arranged as follows. The second part introduces the literature review; the third part is the research design; the fourth part is the empirical analysis, which introduces the relationships among LEE, economic growth, and CO_2 emissions; and the last part is the discussions and conclusions.

LITERATURE REVIEW

Discussion on the relationship between LEE, CO_2 emissions, and economic growth is rare, while the research studies that involved energy and CO_2 emissions have been relatively old. Although there are many inconsistencies in the current conclusions, they provide rich theoretical support for understanding the relationship between LEE, CO_2 emissions, and economic growth. The pairwise correlation variables between the primary studies will be discussed in this section.

Energy and Economic Growth

Energy can be the power support of production and can partly replace capital or labor input. So, it is considered one of the significant reasons for promoting economic growth (Ozturk, 2010). Previous studies focus on the causality between traditional electricity consumption and economic growth using various methods, but the results are always different. Some literature found that energy can promote economic growth unidirectionally (Lee and Chang, 2005; Ho & Siu, 2007; Karanfil, 2008). Some demonstrated that economic growth can promote energy use unidirectionally (Ang, 2008; Zhang and Cheng, 2009). At the same time, some others implied that the relationships between economic growth and energy use can be bidirectional (Polemis and Dagoumas, 2013; Ohler and Fetters, 2014). Some researchers showed no relationship between economic development and energy use (Payne, 2009; Menyah and Wolde-Rufael, 2010). In summary, the relationship between energy and economic growth is complex, and the situations vary significantly in different countries (Alper and Oguz, 2016; Ozturk, 2010).

Compared with fossil fuels, LEE is useful for its low carbon emission and renewability. Studies show relevant evidence for the effects of LEE on economic growth. Based on the data from South Korea, Yoo and Jung (2005) found the effects of nuclear energy on economic growth in the short and long terms. Heo et al. (2011) and Wolde-Rufael (2012) also found similar conclusions. Recently, the relationships between LEE and GDP have been exploited in numerous methods. For example, Azam et al. (2020) tried to figure out the impact of natural gas, nuclear energy, and renewable energy on CO_2 emissions and economics. They found that the tasks of CO_2 emission reduction and economic growth could be more compatible in nuclear and renewable energy. Magazzino et al. (2021) used machine learning to predict the future changes in CO_2 in China, India, and the United States. They believe that renewable energy is a vital factor for the decline of CO_2 in China and the United States. Abbas et al. (2020) found that renewable energy can help sustain environmental conditions without affecting economic growth among the "Belt and Road" countries.

However, dispute about the causal relationship between nuclear energy consumption and economic growth also exists. For example, national differences may affect the effect of nuclear energy on economic growth (Menyah and Wolde-Rufael, 2010; Chang et al., 2014). Their long-term and short-term single causal relationships may not be stable (Apergis and Payne, 2010).

Energy and CO_2 Emissions

Numerous previous studies focused on the long-term relationships between economic growth and energy consumption. Energy consumption relying on burning fossil fuels causes greenhouse gas emissions, leading to climate change and environmental degradation (Ahmad et al., 2018). For example, China's extensive economic development combined with the rapid growth of energy consumption has also led to many greenhouse gas emissions (Riti et al., 2017).

Fortunately, a large number of studies have found evidence that renewable energy reduces pollution shocks. Chen et al. (2019) found that the global level of carbon dioxide emissions has increased due to the increase in the energy demand in recent decades. The primary approach to reduce CO_2 emissions is to develop renewable energy. Their study showed that nonrenewable energy and GDP growth increased CO_2 emissions, while renewable energy and foreign trade harmed CO_2 emissions. A study on carbon emissions in Nigeria showed a significant negative impact of renewable energy on carbon consumption (Cosmas et al., 2019). Zhang and Zhao (2019) believed that the investment in R&D and renewable energy plays a vital role in reducing CO_2 emissions in China's geographically advantageous areas. Noorpoor and Kudahi (2015) found that population size, per capita GDP, power intensity, and electricity consumption positively impact CO_2 emissions, while hydropower, nuclear power, and other renewable energy have a negative impact. Xu et al. (2019) showed that China's per capita GDP and oil consumption are positively correlated with CO_2 emissions, while natural gas consumption hurts emissions. A considerable part of the research also exhibited that renewable energy consumption increases energy self-sufficiency, stimulates sustainable economic growth, and reduces CO_2 emissions (Noorpoor and Kudahi, 2015; Gill et al., 2018; Lin and Raza., 2019). Some studies suggested that there is not much relationship between nuclear energy and carbon emissions (Jaforullah and King, 2015; Cai et al., 2018).

Relevant studies made outstanding contributions on the relationships of energy use, CO_2 emissions, and economic growth. To our best knowledge, these studies paid more attention to the effects of LEE among different countries (Polemis and Dagoumas, 2013; Alper and Oguz, 2016; Ozturk, 2010) or within a country (Lee and Chang, 2005; Ho and Siu, 2007; Ang, 2008; Karanfil, 2008; Zhang and Cheng, 2009), which provided solid theoretical support for the research of this article. However, few of them concern the LEE policy, especially electricity in a disadvantaged region; few focused on the possible mechanism of clean electricity boosting economic growth and heterogeneous effects of clean electricity on different areas in a country. These issues all inspired this article.

RESEARCH DESIGN

Empirical Strategy

This article employs two-way fixed-effect model, SYS-GMM (System GMM method, Arellano and Bover, 1995), and panel quantile regression (Koenker, 2004; Harding and Lamarche, 2009) to survey the impacts of LEE on CO_2 emissions and economic growth.

1) Two-way fixed effect model

$$y_{it} = x_{it}'\beta + z_i'\delta + u_i + \varepsilon_{it}. \quad (1)$$

In **Eq. 1**, y_{it} denotes economic growth or CO_2 emissions, x_{it} denotes the key variables and time-variant variables, β denotes the corresponding coefficient, z_i denotes time-invariant variables, and δ denotes the corresponding coefficient. The error term had been divided into two parts: u_i a denotes the time-invariant part, while ε_{it} represents the time-variant part.

For panel data, we should choose the random effect model (RE) or the fixed effect model (FE) according to the rule of **Eq. 2**. According to Hausman's method, if the difference between $\widehat{\beta}_{RE}$ and $\widehat{\beta}_{FE}$ is too large, we should choose $\widehat{\beta}_{FE}$ as it will be relatively correct; otherwise, we should choose $\widehat{\beta}_{RE}$ as it will be fully efficient. If the statistics is larger than the critical value, we should choose the FE model (Wooldridge, 2016),

$$\widehat{\beta} = \begin{cases} \widehat{\beta}_{RE} & Corr(u_i, z_i) = 0\&Corr(u_i, x_{it}) = 0, \\ \widehat{\beta}_{FE} & Others. \end{cases} \quad (2)$$

The corresponding hypothesis test and the corresponding statistics are shown in **Eq. 3**,

$$H_0: Corr(u_i, z_i) = 0\&Corr(u_i, x_{it}) = 0$$
$$Hausman = \left(\widehat{\beta}_{RE} - \widehat{\beta}_{FE}\right)' \left[Var\left(\widehat{\beta}_{RE}\right) - Var\left(\widehat{\beta}_{FE}\right)\right]\left(\widehat{\beta}_{RE} - \widehat{\beta}_{FE}\right) \xrightarrow{p} \chi^2(K) \quad (3)$$

2) SYS-GMM

To avoid estimate bias by potential endogeneity, we can add the lag term of y_{it} and x_{it}, which are the instrumental variables for endogenous variables (LEE), in **Eq. 1**. Then, **Eq. 1** will be transformed into **Eq. 4**.

$$y_{it} = \alpha + \rho_1 y_{i,t-1} + \rho_2 y_{i,t-2} \cdots + \rho_p y_{i,t-p} + x_{it}'\beta + z_i'\delta + u_i + \varepsilon_{it}. \quad (4)$$

Then, based on **Eq. 4**, we can get the efficient estimator $\widehat{\beta}_{SYS-GMM}$ by employing the GMM (generalized method of moments) method.

3) Panel quantile regression

To capture the provincial effect of LEE, we use the panel quantile regression model extended by Koenker (2004) and Harding and Lamarche (2009),

$$Q_{y_{it}}(\tau|x_{it}) = \alpha_i + x_{it}^T\beta(\tau) + e_{it}. \quad (5)$$

In **Eq. 5**, α_i is the individual fixed effect item that does not change with time, τ is the quantile, x_{it} is the independent variable, e_{it} is the individual random disturbance term, and $Q_{y_{it}}$ is the subsample dependent variable vector of the corresponding quantile τ.

Data

This article analyzed the effects of LEE on economic growth and CO_2 emissions in China. Some variables can be found in CBS (China Bureau of Statistics, http://www.stats.gov.cn/tjsj/ndsj/), which is the official organization responsible for the collection and publication of China's demographic, political, and economic data. CBS's official organization can offer variables such as fixed asset investment, employment, and per capita GDP. Other variables can be found in *China's environmental statistical yearbook* and *China energy statistical yearbook*, which could be easily found via the following link: https://www.epsnet.com.cn/index.html#/Home. From the two yearbooks, other variables, including CO_2 emissions, the production and consumption of clean electricity, the amount of energy available for consumption in the region, the amount of electricity loss, and the total production and consumption of electricity, can be easily found out. Eventually, we obtain relatively complete data of 30 provinces in China from 2000 to 2017.

Variables

The proportion of LEE in total electricity consumption is used to capture the effects of clean electricity, which can overcome the trend of time and reflect the development and change of clean power more truly. To obtain a more efficient estimator of LEE on economic growth and CO_2 emission, we controlled the relevant variables, such as total fixed assets investment, the number of people in work, and total electricity consumption.

To avoid time trends on the regression results, we perform panel unit root tests (see **table 2**) and panel co-integration tests (see **table 3**) for all key variables. Both LLC and IPS methods show no panel unit root, which indicates that the main variables are stable and there is no strong time trend (see **table 2**). The Kao, Pedroni, and Westerlund test show that LEE, CO_2 emissions, and economic growth have a long-term relationship (see **table 3**). Next, we will use the panel data and the corresponding estimation methods to capture LEE's impact on economic growth and CO_2 emissions in detail. The description of variables is given in **Table 1**, the results of the panel unit-root test are shown in **Table 2**, and the panel cointegration test results are outlined in **Table 3**.

EMPIRICAL RESULTS AND ANALYSIS

Effects of LEE on Economic Growth

In **Table 4**, from model 1 to model 4, we can get the positive effect of LEE on economic growth consistently. Hausman statistics in **Table 4** is 54.76, which is much larger than the critical value at the 5% significance level. Moreover, the corresponding p value is equal to 0.000, which shows strong support for FE. So, the results of FE are relatively correct. That is to say, keeping other variables fixed, when LEE increases by 1%, the GDP per capita will increase by 0.16%, and the parameter is significant.

However, a contrary effect of economic growth on LEE may exist. We cannot control the key variables, such as innovation, risk, and political reform, which may be the source of endogeneity. So, we restart to estimate the effects of LEE on economic growth by employing SYS-GMM. The results also support our conjecture.To better understand why LEE promotes economic growth, we choose some relevant variables, which are close to the economic function of LEE, from 2000 to 2015 to investigate the potential impact path. The related variables are listed in detail in **Table 5**. It should be emphasized that the data we found are hard to make a balanced panel. Nevertheless, the estimated results can also give us basic information on how LEE influences economic growth. After controlling the control variables, time effect, province effect, and their interaction, we get basic estimated results of LEE on relevant variables in **Table 6**. According to model 1 and model 2, LEE development could reduce transfer in the volume of electricity for some provinces in China. So, for some provinces whose economic source is power transmission, the inter provincial export of power

TABLE 1 | Description and definition of variables[3].

Variables	Definition	Mean	Std. Dev
LEE	Proportion of clean electricity in total electricity consumption	0.228	0.229
Economic growth	ln (GDP per capita: Yuan)	10.022	0.842
CO_2 emissions	ln (total carbon dioxide emissions: 0.1 billion tons)	15.443	0.774
Invest	ln (total fixed assets investment: 0.1 billion yuan)	8.381	1.275
Use	ln (total electricity consumption: 0.1 billion kwh)	7.839	0.674
Worker	ln (employment: Ten thousand people)	7.554	0.819
Observations	540		
Province	30		

TABLE 2 | Panel unit-root test.

Method	Levin-lin-chu (LLC)		Im-pesaran-shin (IPS)	
Variable	Statistic	*p*-value	Statistic	*p*-value
LEE	−8.399	0.000	3.351	0.000
CO_2 emissions	−8.128	0.001	−3.086	0.001
Economic growth	−2.862	0.002	1.885	0.970

TABLE 3 | Panel cointegration test.

Kao		Pedroni		Westerlund	
Statistic	*p*-value	Statistic	*p*-value	Statistic	*p*-value
−1.609	0.054	2.177	0.015	−3.131	0.001

will be obviously blocked. The results show that trade may be the short-term path for the effect of LEE on the economy, and it is hard to be the long-term one. To some extent, LEE can get rid of resource constraints for reducing local dependence on foreign electricity. In China, however, the diversity of geography and climate results in the congenital difference of clean resources. Although it is reasonable to develop local LEE, it is more important to give full play to the inherent advantages of resources, promote clean trade among regions, and achieve long-term stable growth (**Table 6**).

In terms of total LEE production, the quantity of electricity available for local consumption and the quantity of electric energy loss can also vividly demonstrate our ideas. The development of LEE promotes total LEE production and the quantity of electricity available for local consumption, which can partly support electricity's inner need. However, we should focus on the unobvious effects of LEE on the quantity of electric energy loss, which denotes the possible problems if a province only develops inner LEE without using the comparative advantages of other provinces rich in electric energy.

Effects of LEE on CO_2 Emissions

In **Table 7**, although different methods were used to estimate the effects of LEE on CO_2 emissions, we consistently obtained the same results. The Hausman test implied that we should choose model 4 as the most effective model. That is to say, ceteris paribus, if LEE increases by 1%, CO_2 emissions will approximately decrease by 0.848%. For lack of other control variables or ignorance effects of CO_2 emissions on LEE, the estimated coefficient of LEE on CO_2 emissions will be biased compared with true one (which means endogeneity probably exists in this study). Considering the potential endogeneity, we used SYS-GMM to capture the effect of LEE on CO_2 emissions. The corresponding coefficient is −0.782, which is highly consistent with model 1 to model 4. Thus, an adverse effect of LEE on CO_2 emissions may exist.

It is not hard to understand the negative effects of electric energy on CO_2 emissions. Its features, such as renewability, environmentally friendliness, circularity, and cost-effectiveness, reduce CO2 emissions.

1) Renewability: Wind power, hydropower, and solar power are renewable energies. As long as they are reasonably used, these energy sources can continuously generate electricity and do not impact the environment.
2) Environmental protection: Promoting LEE can greatly reduce CO_2 emissions. For example, construction of large- and medium-sized biogas projects in large- and medium-sized livestock farms produces a large amount of rural energy and solves the pollution of livestock manure.
3) Circularity: Developing LEE will open up new resources for China's economic growth. For example, an animal husbandry farm with an annual output of 100,000 pigs can produce 58,400 tons of feces. When properly processed, these feces—which are currently not only wasted but also disposed of in a manner causing pollution—can become a valuable resource. If these feces can be used for power, it could produce 5.5 million kilowatts per hour, and these energy sources can be applied to production again and again, with endless benefits.
4) Cost-effectiveness: The development of LEE can protect the environment and serve as the chain of the circular economy industry. It can solve the issues related to wastewater, waste residue, and waste gas in the production process of upstream products and use these wastes as the main raw materials of

[3]Clean electricity here mainly includes nuclear energy, wind energy, and solar energy.

TABLE 4 | Effects of LEE on economic growth.

Variables	(1)	(2)	(3)	(4)	(5)
	RE	FE	RE	FE	SYS-GMM
LEE	0.116	0.222**	0.103	0.160**	0.436*
	(0.102)	(0.106)	(0.0677)	(0.0685)	(0.248)
Control variables	NO	NO	YES	YES	YES
Time effect	NO	YES	NO	YES	YES
Province effect	NO	YES	NO	YES	YES
Time × province effect	NO	YES	NO	YES	YES
Constant	8.872***	8.848***	5.211***	5.280***	−0.045
	(0.0844)	(0.0335)	(0.186)	(0.175)	(15.97)
Hausman				54.76***	
AR (2)					0.772
Sargan					0.872
Observations	540	540	540	540	510
R-squared	0.971	0.971	0.988	0.988	---
Province	30	30	30	30	30

*Notes: ***p<0.01, **p<0.05, *p<0.1, the estimated coefficient is displayed in the table, the numbers in the parentheses are the corresponding standard errors. Control variables, time effect, province effect, and their interaction are also controlled in **Table 6**, **Table 8**, **Table 9**, **Table 10**, and **Table 11**.*

TABLE 5 | Description and definition of relevant variables.

Variable	Definition	N	Mean	Std. deviation
Loss	ln (quantity of electricity loss)	454	3.906	1.078
Out_ trans	ln (transfer out volume of the province)	451	−3.898	2.171
In_ trans	ln (transfer in volume of the province)	468	3.842	2.265
TCE	ln (total clean electricity production)	519	4.493	1.942
Consumption	ln (quantity electricity available for local consumption)	536	3.457	4.189

Notes: The rule of choosing relevant variables (RV): generate RV = ln (RV), if RV >0 and generate RV = -ln (-RV), otherwise. The unit of all the original variables is 0.1 billion kWh.

TABLE 6 | Effects of LEE on relevant variables.

Variables	(1)	(2)	(3)	(4)	(5)
	Trade		Supply		Efficiency
	Out_ trans	In_ trans	TCE	Consumption	Loss
LEE	−0.569	−2.192*	2.814***	6.016***	−0.0686
	(0.853)	(1.117)	(0.603)	(1.456)	(0.722)
Constant	−15.64	−340.4***	54.60	695.2***	50.13
	(90.76)	(113.8)	(60.93)	(147.0)	(74.44)
Observations	451	468	519	536	454
R-squared	0.666	0.537	0.795	0.554	0.462
Province	29	30	30	30	29

downstream products. It can save a lot of raw materials and has high economic value for production.

Based on the above analysis, the features of LEE and their influence on CO_2 emissions are outlined in **Figure 1**.

Discussions on Regional Heterogeneity

From **Table 4,7**, we find the positive effect of LEE on economic growth, and enough supply for the local province may be the potential path for its effects. Furthermore, we also show the contradiction of the province trade of the prosperous internal supply and the declining external supply of electricity, which will harm the balance of the economy. In this part, panel quantile regression and regression by areas are employed to test the ideas again.

The results of **Table 8** demonstrate that the positive influence of LEE on economic growth would increase with the increase in economic growth, especially in Q75 and Q90, which implies that LEE will vigorously promote the economic growth of high-development areas compared to the low-development ones. The corresponding reason is far more likely that the regions that are economically disadvantaged do not have the resources to invest in LEE, while the regions that are economically advantaged do have the resources.

As for the results of **Table 9**, all the models cannot get a significant effect of LEE on CO_2 emissions. However, the results

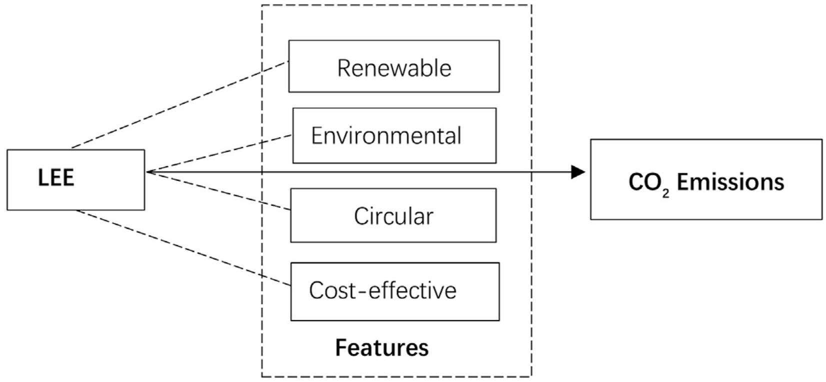

FIGURE 1 | Features of LEE and its influences on CO_2 emissions.

TABLE 7 | Effects of LEE on CO_2 emissions.

	(1)	(2)	(3)	(4)	(5)
	RE	**FE**	**RE**	**FE**	**SYS-GMM**
LEE	−0.974***	−0.678**	−0.738***	−0.848***	−0.782**
	(0.241)	(0.325)	(0.202)	(0.286)	(0.320)
Control variables	NO	NO	YES	YES	YES
Time effect	NO	YES	NO	YES	YES
Province effect	NO	YES	NO	YES	YES
Time × province effect	NO	YES	NO	YES	YES
Constant	14.83***	14.76***	7.881***	3.822***	10.33***
	(0.118)	(0.103)	(0.839)	(1.227)	(1.653)
Hausman					22.51***
AR (2)					0.331
Sargan					1.00
Observations	540	540	540	540	510
R-squared	0.596	0.596	0.686	0.693	---
Province	30	30	30	30	30

TABLE 8 | Panel quantile regression of LEE on economic growth.

Economic growth	(1)	(2)	(3)	(4)	(5)
	Q10	**Q25**	**Q50**	**Q75**	**Q90**
LEE	0.0357	0.0772	0.150	0.244**	0.300*
	(0.163)	(0.129)	(0.0921)	(0.124)	(0.170)
Observations	540	540	540	540	540

TABLE 9 | Panel quantile regression of LEE on CO_2 emissions.

	(1)	(2)	(3)	(4)	(5)
	Q10	**Q25**	**Q50**	**Q75**	**Q90**
LEE	−0.543	−0.702	−0.839	−0.946	−1.036
	(25.81)	(4.486)	(14.57)	(29.01)	(41.17)
Observations	540	540	540	540	540

show that the province could reduce its CO_2 emissions more if its previous CO_2 emission is too significant. Moreover, it is not fair in terms of development equity because the high-development areas based on significant CO_2 emissions can enjoy more benefits from CO_2 emission reduction and economic growth than the low-development ones.

TABLE 10 | Regression of LEE on CO_2 emissions and economic growth by areas.

	(1)	(2)	(3)	(4)	(5)	(6)
	Economic growth			**CO_2 emissions**		
	West	**Central**	**East**	**West**	**Central**	**East**
LEE	0.232***	−0.0855	0.227***	0.245	−0.223	−0.812***
	(0.0813)	(0.128)	(0.0707)	(0.562)	(0.416)	(0.299)
Constant	−1.317	20.37***	−7.286	−58.78*	16.73	54.43***
	(4.624)	(3.938)	(4.500)	(30.83)	(14.70)	(18.63)
Observations	198	108	234	198	108	234
R-squared	0.997	0.997	0.997	0.834	0.947	0.882
Province	11	6	13	11	6	13

The results of regression by areas also support our idea further (see **Table 10**). Model 1 and model 4 show that LEE can promote the economic growth of western areas but hamper the reduction in CO_2 emission. However, model 3 and model 6 indicate that

TABLE 11 | Annual effects of LEE on CO_2 emissions and economic growth.

Variables	(1)		(2)	
	Economic growth		CO_2 emissions	
	β1	*p*-value1	β2	*p*-value2
Control group: 2000×CE				
2001×LEE	−0.0251	(0.642)	−0.0360	(0.893)
2002×LEE	−0.0279	(0.627)	−0.271	(0.339)
2003×LEE	−0.0713	(0.263)	−0.710**	(0.024)
2004×LEE	−0.0692	(0.309)	−0.844**	(0.012)
2005×LEE	−0.0921	(0.217)	−0.817**	(0.026)
2006×LEE	−0.0727	(0.376)	−0.733*	(0.071)
2007×LEE	−0.0364	(0.689)	−0.717	(0.111)
2008×LEE	−0.0562	(0.559)	−0.766	(0.107)
2009×LEE	−0.0658	(0.535)	−0.804	(0.125)
2010×LEE	−0.0216	(0.852)	−0.925	(0.104)
2011×LEE	0.0069	(0.956)	−0.903	(0.143)
2012×LEE	0.0330	(0.799)	−0.793	(0.216)
2013×LEE	0.0690	(0.626)	−0.950	(0.174)
2014×LEE	0.0716	(0.624)	−0.947	(0.189)
2015×LEE	0.0974	(0.519)	−0.884	(0.236)
2016×LEE	0.121	(0.452)	−0.886	(0.264)
2017×LEE	0.0856	(0.613)	−0.999	(0.233)
Constant	−20.47***	(0.001)	6.147	(0.844)
Observations	540		540	
R-squared	0.996		0.859	
Province	30		30	

LEE can effectively make economic growth and reduce CO_2 emissions together in eastern areas. As for central regions, the impacts of LEE are not significant. The results demonstrate that an LEE policy may benefit the eastern and western regions but makes no difference to central regions. Western areas have rich natural resources for producing low-emission electricity, and eastern areas can take full technological advantage of LEE. Although LEE can promote the economic growth of western and eastern areas, CO_2 emissions of constructing LEE facilities could be detained in western areas. Due to the lack of comparative advantages of natural resources and technological innovations, the LEE has no significant impact on the central areas.

Discussions on Annual Heterogeneity

Based on **Eq. 1**, we add the interaction of LEE and time variable[4], where ϕ denotes the coefficient of the corresponding year,

$$y_{it} = \sum_{\text{year}=2001}^{2017} \phi_{\text{year}} \text{year} \times \text{CE} + x_{it}'\beta + z_i'\delta + u_i + \varepsilon_{it}. \quad (6)$$

By this way, we can capture the annual effects of LEE on economic growth and CO_2 emissions (results estimated are shown in **Table 11**). β_1 and β_2 denote the impact of LEE on economic growth and CO_2 emissions, while *p*-value1 and *p*-value2 are their significance separately (see **Table 11**).

Figure 2 captures the annual heterogeneity LEE's influence on economic growth and CO_2 emissions in **Table 11**. As shown in **Figure 2A**, β1 is smaller than zero before 2011 but larger than zero after 2011. Although LEE′s annual effects on economic growth are not significant, the corresponding coefficient implies the potential relationships between LEE and economic growth. The previous technology development and infrastructure construction of LEE need high costs. Only when these costs reach a particular scale can LEE promote the economy. After 2011, the positive effect of LEE on economic growth arises, and China maybe jumps into the range of growth benefits. As shown in **Figure 2B**, β2 becomes smaller and smaller with time and *p*-value2 is also small, which implies the increasing effects of LEE on CO_2 emissions.

[4]For avoiding dummy variable trap, 2,000 is not considered.

DISCUSSIONS AND CONCLUSIONS

Conclusions

Using the provincial panel data from 2000 to 2017 in China, we investigate the effects of LEE on economic growth and CO_2 emissions. The results show that LEE development can achieve the reduction in CO_2 emissions and economic growth simultaneously. However, we should not ignore the reasons for LEE to regional heterogeneity. For economic growth, LEE can add the supply of LEE and electricity available to local consumption without any help to trade and efficiency. Therefore, the adverse effects of LEE on economic growth may be short-term and regional unbalance.

Then, according to the regional and annual heterogeneity, this work shows further evidence for these ideas. The results of regional heterogeneity exhibited that the effects of LEE on economic growth and CO_2 emissions in eastern areas are better than those in western and central areas. Thus, LEE may widen the income gap between different areas. The results of annual heterogeneity imply that the effects of LEE on economic growth arise nowadays. However, the annual effects of LEE may be a little and not significant at the 5% significance level, which denotes the effects of LEE on economic growth, maybe short term.

Policy Implication

It is very unwise to have an economy dependent on finite resources for the trend in fossil fuels is more expensive extraction. The phenomenal growth of light tight oil produced from fracking has produced little profit (Craig, 2020). Second, in many regions, solar energy is now cheaper than coal energy (IEA, 2020). If the global epidemic is under control, the world's energy demand will recover by 2025 (IEA, 2020), but fossil fuel supply may struggle to keep up in the short term. Under-investment in oil exploration, for example, is a predictor of future oil price shocks (Hacquard et al., 2019). So, China should diversify its energy mix before it is obliged to because of decreasing availability of fossil fuels. Our research may provide valuable shreds of evidence for LEE policy. On the one hand, carrying out an LEE policy can reduce CO_2 emissions and promote economic growth. However, on the other hand, regional heterogeneity implies that the policymakers should focus on the details of the policy being carried out. The policy implications are outlined as follows.

FIGURE 2 | Annual effects of LEE on CO_2 emissions and economic growth.

First, this article demonstrates that LEE can make CO_2 emission reduction and economic growth compatible, but energy efficiency needs to be further enhanced. So, we should pay much attention to the LEE policy in the future. On the one hand, the government needs to strengthen financial investment in LEE and improve energy infrastructure construction; on the other hand, the government should pay attention to the improvement of LEE production technology, strive to improve energy production efficiency, and strive to achieve energy decarbonization as soon as possible.

Second, an LEE policy should be carried out in regions with comparative advantage of resources. Technological advantages of developed areas can be combined with the resource advantages of less developed areas. Even if the developed regions can achieve LEE self-sufficiency, they should also support the less developed regions as far as possible and help them transform their resource advantages into technological and economic advantages.

Third, early construction of LEE needs a lot of human, material, and financial resources and may have a certain degree of negative impact on the environment. Therefore, the development of LEE needs to pay attention to two crucial issues. On the one hand, policymakers should consider whether the current economic situation can support sustainable LEE construction. On the other hand, they should pay more attention to environmental protection in the construction process.

Finally, in developing LEE, those areas that have neither comparative technology advantage nor resource comparative advantage may not enjoy the blessing of LEE. For these areas, the government needs to tap their regional advantages, increase financial strength, and avoid an excessive regional development gap.

DATA AVAILABILITY STATEMENT

Data used in this study are available (https://www.epsnet.com.cn/index.html#/Home), all the code and data can be downloaded by private link (https://pan.baidu.com/s/17VSQtHQbXkDpc9NsSR2MTQ, Password of accessing is 6rid). Further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

ZZ wrote and revised this paper, Y-HC provided suggestions for the revision and framework of this paper, and C-MW gave some ideas of this paper.

FUNDING

This work was supported by the Key Program of the National Social Science Foundation of China (20&ZD117), Guangdong Social Science (GD2018CYJ01), the Foundation for Guangdong Province Universities and Colleges Pearl River Scholar Funded Scheme (GDUPS2019), the Natural Science Foundation of Guangdong (2021A1515011960).

ACKNOWLEDGMENTS

Thanks to the editors and reviewers for their suggestions for revisions to this article. Of course, the authors are fully responsible for the content.

REFERENCES

Abbas, Q., Nurunnabi, M., Alfakhri, Y., Khan, W., Hussain, A., and Iqbal, W. (2020). The Role of Fixed Capital Formation, Renewable and Non-renewable Energy in Economic Growth and Carbon Emission: a Case Study of Belt and Road Initiative Project. *Environ. Sci. Pollut. Res.* 27, 45476–45486. doi:10.1007/s11356-020-10413-y

Ahmad, M., Khan, Z., Ur Rahman, Z., and Khan, S. (2018). Does Financial Development Asymmetrically Affect CO_2 Emissions in China? an Application of the Nonlinear Autoregressive Distributed Lag (NARDL) Model. *Carbon Manag.* 9 (6), 631–644. doi:10.1080/17583004.2018.1529998

Alper, A., and Oguz, O. (2016). The Role of Renewable Energy Consumption in Economic Growth: Evidence from Asymmetric Causality. *Renew. Sustain. Energ. Rev.* 60, 953–959. doi:10.1016/j.rser.2016.01.123

Ang, J. B. (2008). Economic Development, Pollutant Emissions and Energy Consumption in Malaysia. *J. Pol. Model.* 30, 271–278. doi:10.1016/j.jpolmod.2007.04.010

Apergis, N., and Payne, J. E. (2010). A Panel Study of Nuclear Energy Consumption and Economic Growth. *Energ. Econ.* 32 (3), 545–549. doi:10.1016/j.eneco.2009.09.015

Arellano, M., and Bover, O. (1995). Another Look at the Instrumental Variable Estimation of Error-Components Models. *J. Econom.* 68 (1), 29–51. doi:10.1016/0304-4076(94)01642-d

Azam, A., Rafiq, M., Shafique, M., Zhang, H., and Yuan, J. (2020). Analyzing the Effect of Natural Gas, Nuclear Energy and Renewable Energy on GDP and Carbon Emissions: A Multi-Variate Panel Data Analysis. *Energy* 219, 119592. doi:10.1016/j.energy.2020.119592

BPstats (2018). *BP Statistical Review of World Energy in London*. Edinburgh, United Kingdom: Centre for Energy Economics Research and Policy, Heriot-Watt University. Available at: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

Cai, Y., Sam, C. Y., and Chang, T. (2018). Nexus between Clean Energy Consumption, Economic Growth and CO_2 Emissions. *J. Clean. Prod.* 182, 1001–1011. doi:10.1016/j.jclepro.2018.02.035

Chang, T., Gatwabuyege, F., Gupta, R., Inglesi-Lotz, R., Manjezi, N. C., and Simo-Kengne, B. D. (2014). Causal Relationship between Nuclear Energy Consumption and Economic Growth in G6 Countries: Evidence from Panel granger Causality Tests. *Prog. Nucl. Energ.* 77, 187–193. doi:10.1016/j.pnucene.2014.07.006

Chen, Y., Wang, Z., and Zhong, Z. (2019). CO_2 Emissions, Economic Growth, Renewable and Non-renewable Energy Production and Foreign Trade in China. *Renew. Energ.* 131, 208–216. doi:10.1016/j.renene.2018.07.047

Cosmas, N. C., Chitedze, I., and Mourad, K. A. (2019). An Econometric Analysis of the Macroeconomic Determinants of Carbon Dioxide Emissions in Nigeria. *Sci. Total Environ.* 675, 313–324. doi:10.1016/j.scitotenv.2019.04.188

Craig, F. (2020). *U.S. Operators Working Down DUC Backlog*. Worldoil. Available at: https://www.worldoil.com/magazine/2021/april-2021/features/us-operators-working-down-duc-backlog.

Das, A., Chowdhury, M., and Khan, S. (2012). The Dynamics of Electricity Consumption and Growth Nexus: Empirical Evidence from Three Developing Regions. *Margin: J. Appl. Econ. Res.* 6 (4), 445–466. doi:10.1177/0973801012462121

Duan, H., Zhou, S., Jiang, K., Bertram, C., Harmsen, M., Kriegler, E., et al. (2021). Assessing China's Efforts to Pursue the 1.5°C Warming Limit. *Science* 372 (6540), 378–385. doi:10.1126/science.aba8767

Garcia1, L. E., Illig, A., and Schindler, I. (2020). Understanding Oil Cycle Dynamics to Design the Future Economy. *Biophysical Econ. Sustainability* 5, 15. doi:10.1007/s41247-020-00081-4

Gill, A. R., Viswanathan, K. K., and Hassan, S. (2018). A Test of Environmental Kuznets Curve (EKC) for Carbon Emission and Potential of Renewable Energy to Reduce green House Gases (GHG) in Malaysia. *Environ. Dev. Sustain.* 20 (3), 1103–1114. doi:10.1007/s10668-017-9929-5

Hacquard, P., Simoën, M., and Hache, E. (2019). Is the Oil Industry Able to Support a World that Consumes 105 Million Barrels of Oil Per Day in 2025? *Oil Gas Sci. Technol. - Rev. IFP Energies Nouvelles* 74, 88. doi:10.2516/ogst/2019061

Hamida, R. B. (2012). Electricity Consumption and Industrial Gross Domestic Product Nexus in Sfax: An ARDL Bounds Testing Approach. *J. Energ. Develop.* 38 (1/2), 241–255.

Harding, M., and Lamarche, C. (2009). A Quantile Regression Approach for Estimating Panel Data Models Using Instrumental Variables. *Econ. Lett.* 104, 133–135. doi:10.1016/j.econlet.2009.04.025

He, J., Lu, L., and Wang, H. (2019). The Win-Win Pathway of Economic Growth and CO_2 Emission Reduction: a Case Study for China. *Chin. J. Popul. Resour. Environ.* 00, 1–12. doi:10.1080/10042857.2019.1574485

Heo, J.-Y., Yoo, S.-H., and Kwak, S.-J. (2011). The Causal Relationship between Nuclear Energy Consumption and Economic Growth in India. *Energ. Sourc. B: Econ. Plann. Pol.* 6 (2), 111–117. doi:10.1080/15567240802533971

Ho, C.-Y., and Siu, K. W. (2007). A Dynamic Equilibrium of Electricity Consumption and GDP in Hong Kong: an Empirical Investigation. *Energy Policy* 35 (4), 2507–2513. doi:10.1016/j.enpol.2006.09.018

IEA (2018). *Statistics CO2 Emissions from Fuel Combustion-Highlights*. Paris, France: International Energy Agency (IEA). Available at: https://webstore.iea.org/download/direct/2373?fileName=CO2_Emissions_from_Fuel_Combustion_2018_Highlights.pdf.

IEA (2020). *World Energy Outlook 2020*. Paris, France: International Energy Agency (IEA). Available at: https://www.iea.org/reports/world-energy-outlook-2020.

Jaforullah, M., and King, A. (2015). Does the Use of Renewable Energy Sources Mitigate CO_2 Emissions? A Reassessment of the US Evidence. *Energ. Econ.* 49, 711–717. doi:10.1016/j.eneco.2015.04.006

Karanfil, F. (2008). Energy Consumption and Economic Growth Revisited: Does the Size of Unrecorded Economy Matter? *Energy Policy* 36 (8), 3029–3035. doi:10.1016/j.enpol.2008.04.002

Koenker, R. (2004). Quantile Regression for Longitudinal Data. *J. Multivariate Anal.* 91 (1), 74–89. doi:10.1016/j.jmva.2004.05.006

Lee, C.-C., and Chang, C.-P. (2005). Structural Breaks, Energy Consumption, and Economic Growth Revisited: Evidence from Taiwan. *Energ. Econ.* 27, 857–872. doi:10.1016/j.eneco.2005.08.003

Lin, B., and Raza, M. Y. (2019). Analysis of Energy Related CO_2 Emissions in Pakistan. *J. Clean. Prod.* 219, 981–993. doi:10.1016/j.jclepro.2019.02.112

Magazzino, C., Mele, M., and Schneider, N. (2021). A Machine Learning Approach on the Relationship Among Solar and Wind Energy Production, Coal Consumption, GDP, and CO_2 Emissions. *Renew. Energ.* 167, 99–115. doi:10.1016/j.renene.2020.11.050

Mahfoudh, S., and Amar, M.B. (2014). The Importance of Electricity Consumption in Economic Growth: The Example of African Nations. *J. Energ. Develop.* 40 (1/2), 99–110.

Mendonç, A. K., Barni, G. A., Mor, M.F., and Bornia, A.C. (2020). Hierarchical Modeling of the 50 Largest Economies to Verify the Impact of GDP, Population and Renewable Energy Generation in CO Emissions. *Sustainable Prod. Consumption* 22, 58–67. doi:10.1016/j.spc.2020.02.001

Menyah, K., and Wolde-Rufael, Y. (2010). CO_2 Emissions, Nuclear Energy, Renewable Energy and Economic Growth in the US. *Energy Policy* 38 (6), 2911–2915. doi:10.1016/j.enpol.2010.01.024

Noorpoor, A. R., and Kudahi, S. N. (2015). CO_2 emissions from Iran's Power Sector and Analysis of the Influencing Factors Using the Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) Model. *Carbon Manag.* 6 (3–4), 101–116. doi:10.1080/17583004.2015.1090317

Ohler, A., and Fetters, I. (2014). The Causal Relationship between Renewable Electricity Generation and GDP Growth: a Study of Energy Sources. *Energ. Econ.* 43, 125–139. doi:10.1016/j.eneco.2014.02.009

Ozturk, I. (2010). A Literature Survey on Energy-Growth Nexus. *Energy Policy* 38, 340–349. doi:10.1016/j.enpol.2009.09.024

Payne, J. E. (2009). On the Dynamics of Energy Consumption and Output in the US. *Appl. Energ.* 86 (4), 575–577. doi:10.1016/j.apenergy.2008.07.003

Polemis, M. L., and Dagoumas, A. S. (2013). The Electricity Consumption and Economic Growth Nexus: Evidence from Greece. *Energy Policy* 62 (C), 798–808. doi:10.1016/j.enpol.2013.06.086

Riti, J. S., Song, D., Shu, Y., and Kamah, M. (2017). Decoupling CO_2 Emission and Economic Growth in China: Is There Consistency in Estimation

Results in Analyzing Environmental Kuznets Curve? *J. Clean. Prod.* 166, 1448–1461. doi:10.1016/j.jclepro.2017.08.117

Tang, C. F., and Tan, E. C. (2012). Electricity Consumption and Economic Growth in Portugal: Evidence from a Multivariate Framework Analysis. *Energ. J.* 33 (4), 23–48. doi:10.5547/01956574.33.4.2

Toumi, S., and Toumi, H. (2019). Asymmetric Causality Among Renewable Energy Consumption, CO_2 Emissions, and Economic Growth in KSA: Evidence from a Non-linear ARDL Model. *Environ. Sci. Pollut. Res.* 26 (16), 16145–16156. doi:10.1007/s11356-019-04955-z

UNFCCC (2015). Conference of the Parties (COP). Paris Climate Change Conference-November 2015, Paris, November 30–December 11, 2015. Available at: FCCC/CP/2015/L.9/Rev.1.

Wolde-Rufael, Y. (2012). Nuclear Energy Consumption and Economic Growth in Taiwan. *Energ. Sourc. Part B: Econ. Plann. Pol.* 7 (1), 21–27. doi:10.1080/15567240802564752

Wooldridge, J. M. (2016). *Introductory Econometrics: A Modern Approach*. 5th Edn. Boston: Cengage Learning Press.

Xu, B., Zhong, R., and Liu, Y. (2019). Comparison of CO_2 Emissions Reduction Efficiency of Household Fuel Consumption in China. *Sustainability* 11, 979. doi:10.3390/su11040979

Yoo, S.-H., and Jung, K.-O. (2005). Nuclear Energy Consumption and Economic Growth in Korea. *Prog. Nucl. Energ.* 46 (2), 101–109. doi:10.1016/j.pnucene.2005.01.001

Zhang, S., and Zhao, T. (2019). Identifying Major Influencing Factors of CO_2 Emissions in China: Regional Disparities Analysis Based on STIRPAT Model from 1996 to 2015. *Atmos. Environ.* 207, 136–147. doi:10.1016/j.atmosenv.2018.12.040

Zhang, X.-P., and Cheng, X.-M.(2009). Energy Consumption, Carbon Emissions, and Economic Growth in China. *Ecol. Econ.* 68 (10), 2706–2712. doi:10.1016/j.ecolecon.2009.05.011

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 29 July 2021
doi: 10.3389/fenrg.2021.704556

Market Power, Intertemporal Permits Trading, and Economic Efficiency

Minxing Jiang[1,2,3]*, *Xingliang Feng*[1] *and Liang Li*[1,2,3]

[1]School of Business, Nanjing University of Information Science and Technology, Nanjing, China, [2]Development Institute of Jiangbei New Area, Nanjing University of Information Science and Technology, Nanjing, China, [3]Research Center for Prospering Jiangsu Province with Talents, Nanjing University of Information Science and Technology, Nanjing, China

The banking and borrowing (BB) system has been developed gradually in the tradable permits market to perform a role as an environmental management tool. One question naturally arises as to how it will impact the behaviors of firms and the efficiency in presence of market power in the permits market. This paper considers market power in two cases: with and without the BB system. The equilibrium behaviors of the firms are identified in two cases. The findings show that the producing and discharging behaviors of firms depend on the permits price elasticity of output price without BB system, while they only depend on the growth rate of the output price in the BB system. Although both cases fail to obtain efficient solutions, the market with a BB system is capable of alleviating the inefficiency arising from market power compared with that without a BB system. The path of permits price satisfies the Hotelling rule in the case of the BB system, while it is closely related to the path of output price and output price elasticity of permits price in the case without the BB system.

Keywords: banking and borrowing, market power, tradable permits, intertemporal trading, efficiency

Edited by:
Yong-cong Yang, Guangdong University of Foreign Studies, China

Reviewed by:
Kangkang Zhang, China University of Geosciences Wuhan, China
Ruipeng Tan, Nanjing Normal University, China

***Correspondence:**
Minxing Jiang
18588847515@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *03 May 2021*
Accepted: *08 June 2021*
Published: *29 July 2021*

Citation:
Jiang M, Feng X and Li L (2021) Market Power, Intertemporal Permits Trading, and Economic Efficiency. Front. Energy Res. 9:704556. doi: 10.3389/fenrg.2021.704556

INTRODUCTION

The permits market is a cost-effective way to reduce pollution: the cost efficiency is attainable in a competitive tradable permits system. Generally, the efficiency availability needs two conditions in the case of an intertemporal tradable permits market: costs efficiency across firms and across time (Hagem and Westskog, 1998; Zhu et al., 2017; Jiang, et al., 2018). The banking and borrowing (BB) system enables the agents to move permits across time freely. Permits banking means saving some permits in one period to use or trade in later periods, and borrowing means using more in one period than the current standard amount and paying them back in the future (Kling and Rubin, 1997). The acid rain program in the United States firstly introduced banking. The EU ETS also allowed banking, but ruled out borrowing in phase I (2005–2007) and II (2008–2012). After that, it allowed both banking and borrowing in phase III (2013–2020). More studies consider the relationships between the BB system and costs efficiency. One question we are concerned with here is how the BB system impacts the firms' behaviors and total costs efficiency when considering market power in an intertemporal tradable permits system.

Cronshaw and Kruse (1996) and Rubin (1996) initially propose a formal analysis associated with the system-wide efficiency in a dynamic tradable permits market. More and more interesting issues were explored by a succession of exploitation work in several cases. Cronshaw and Kruse (1996) demonstrate that a full competitive tradable permits market with banking can lead to the lowest costs without profit regulation using a discrete-time model. Rubin (1996) proposes a model of tradable permits market with the BB system and shows that the decentralized solutions make the costs efficiency attainable under joint-cost minimization. However, the following studies show that a tradable permits market with the BB system does not necessarily mean welfare maximization when considering the negative externality of pollutions (Kling and Rubin, 1997; Leiby and Rubin, 2001) since agents in the market always sub-optimally discharge more in the early period than in future. Leiby and Rubin (2001) show that social welfare optimization can be obtainable if the emissions cap and trading ratio for banking and borrowing are correctly set. The analyses above are confined in the framework of the perfect information. In addition, some theoretical studies examine the influences of uncertainties in several cases (such as demand, abatement cost technologies, and forward trading) on permit prices and banking behavior (Schennach, 2000; Maeda, 2004; Newell et al., 2005). Yates and Cronshaw (2001) consider how to decide the optimal trading ratio in banking and borrowing under asymmetric information. Feng and Zhao (2006) examine the efficiency of permits markets with banking systems involved in both uncertainty and asymmetric information, and they show that welfare improvement by banking depends on the relative magnitude of the information effect and externality effect. A few papers propose empirical analysis of the BB system. Stevens and Rose (2002) show that the most gains are from permits trading across nations, but the gains from the trading market with the BB system are low. Cason and Gangadharan (2004) find that banking can reduce the price volatility arising from the imperfect emissions control but result in more emissions. On the contrary, Bosetti et al. (2009) show that the BB system can not only improve welfare but also reduce more emissions in short term. However, none of these studies have analyzed the market power in the tradable permits market.

The market power in the tradable permits market has been discussed in the seminal work of Hahn (1984). Egteren and Weber (1996), Westskog (1996), and Maeda (2003) also analyze the costs efficiency in various cases following Hahn's insight. After that, the costs efficiency and firms' behaviors are well examined by various thermotical models, which both consider the output market and tradable permits market (Sartzetakis, 1997a, Sartzetakis, 1997b; Eshel, 2005; Hatcher, 2012; Hintermann, 2017; Jiang et al., 2016). However, all these papers display an absence of dynamic modeling, namely, they do not consider banking and borrowing in the models. Hagem and Westskog (1998) initially examine market power in the dynamic case and show that both the BB system and durable system incur cost inefficiency since the former distorts the allocation of pollution abatements across firms and the latter distorts that across time. But it is not clear which system is better as it depends upon the conditions. The following study (Hagem and Westskog, 2008) further shows that market power brings about misallocation of permits across time market when allowing banking but rules out borrowing. Liski and Montero (2005) consider the stock and flow allocation between a large firm and a small firm. If the large one receives no stock allocation, it will bank by following the competitive permits price. But they do not supply the general equilibrium path of the firms. Liski and Montero (2006) analyze the impacts of spot trading, stock trading, and forward trading on the market power, and they show the large firm can manipulate the spot market, and the forward trading can alleviate the market power. However, they rule out borrowing in the model as well.

This paper mainly looks into how the firms behave in the tradable permits market with and without the BB system in the presence of market power. Specifically, we suppose that there are two types of firms regulated in a finite planning horizon. They are both price takers in output markets. The large firm is a monopoly seller or buyer in the permits market, and another is a fringe firm, which is considered as a price taker in the permits market. For simplicity, we only consider spot trading and one-to-one intertemporal trading in this paper. This study mainly contributes to characterizing the behaviors of firms' producing and discharging and price path in uncompetitive carbon market with banking and borrowing and without ones. Our results show that the carbon market with a BB system alleviates distortion arising from the market power compared to that without BB system. Furthermore, we identify the equilibrium behaviors of firms in two cases of without a BB system and with a BB system. The producing and discharging behaviors of firms depend on the permits price elasticity of output price in no BB (carbon permits banking and borrowing) system, while they only depend on the growth rate of output price in the BB system. The path of permits price still satisfies the Hotelling rule in the BB system, but it does not work anymore without the BB system in which the path of permits price is closely related to the path of output price and output price elasticity of permits price.

The rest of the paper is organized as follows. The following section proposes a basic model. In *Regulator's Problem*, we present a simple analysis of the behaviors of firms and efficient solutions, which makes the system-wide welfare maximization attainable. In *No Banking and Borrowing System*, we consider market power in the permits market and characterize the behaviors of firms without a BB system. In *Banking and Borrowing System*, we will characterize the behaviors of firms in the permits market with a BB system and show how a BB system alleviates the market power. The final section concludes.

BASIC MODEL

We suppose that there are two firms, $i = 1,\ 2$, in the output market and permits market. Both firms produce the same production without heterogeneity (such as electricity). They are both considered price takers in the output market[1]. We set a finite planning horizon of T without losing generality, and it can be flexible (being long or short time). $P(t)$ is the output price at time t.

It is inevitable to produce some unexpected productions by the firms, such as pollutions or CO_2. The regulator has to curb the emissions by setting an emission cap, $A = T \sum \overline{a}_i(t)$, for the entire

[1]For example, the electric power sector is the largest CO2 emitter in the region, and the price of electricity is almost regulated by the government such that all firms are price takers.

planning horizon. $\overline{a}_i(t)$ are the constant flow permits allocated to firm i. The cost function of firm i is $C^i(q_i(t), e_i(t))$, where $q_i(t)$ and $e_i(t)$ are the number of outputs and emissions at t, respectively. Some assumptions on the cost function are set as follows, $C^i_q > 0$and $C^i_e < 0$, which means costs increase with yields and decrease with emissions, respectively. $C^i(\cdot)$ is joint convex in $q_i$and e_i: $\Delta_i = C^i_{ee}C^i_{qq} - (C^i_{eq})^2 > 0$[2]. In addition, we assume that $C^i_{qq} > 0$, $C^i_{ee} > 0$, $C^i_{qe} < 0$, which means the marginal production costs increase with yields and marginal abatement costs decrease with emissions but increase with yields. The cost functions are common knowledge, and each firm has perfect foresee on the decisions made by any other. For simplicity, the third and higher-order partial derivatives of the cost functions are neglected, but this will not influence the results.

Suppose firm one might exercise its market power to manipulate permits prices to its own advantage. It may be a monopoly seller (or monopoly buyer) at each time, which means that it can credibly manipulate permits price by controlling the number of permits for sale at any time. Firm 2 may be a buyer (or seller) and price taker. In the following, we will only analyze the situation in which firm one is a monopoly seller and firm two is a buyer, while the other situation is easily understood as the analysis is processed in the same way. $\beta(t)$ is permits price at t. $x(t)$ is trading volume at t and is nonnegative. Then the profits of firms will be[3]:

$$\pi_i = Pq_i - C_i(q_i, e_i) - (-1)^i \beta x,\ i = 1, 2.$$

Any firm can transfer the permits across time by banking and borrowing as long as its cumulative emissions on the horizon are less than the total permits it holds. $B_i(t)$ denotes the banked or borrowed permits at t. Specifically, $B_i(t) \geq 0$ implies firm i banks some permits at t, which can be used or traded in the future. $B_i(t) < 0$ implies it borrows some permits at t from the later periods. Hence $B_i(t)$ should be a state variable in such banking and borrowing system. $\dot{B}_i$ is the change rate of the B_i:

$$\frac{dB_i}{dt} = \dot{B}_i = \overline{a}_i - e_i + (-1)^i x,\quad i = 1, 2.$$

The total change rate should be $\dot{B} = \sum \dot{B}_i = \sum(\overline{a}_i - e_i)$. Each firm has no bankable permits at the beginning of the horizon, and no one is willing to reserve any permit at the terminal time because *MAC* (marginal abatement costs) is strictly positive, hence

$$B_i(0) = 0, B_i(T) = 0 \tag{1}$$

REGULATOR'S PROBLEM

This section explores the paths of firms that achieve the regulator's goal, which needs to maximize the total welfare subjects to the emissions cap A on the horizon. We assume that the regulator owns perfect information about the cost functions of each firm and can completely control the output price. The maximization problem is specified as the paths of the emissions and outputs of firms that should be able to maximize the total welfare subjects to the emissions cap A. The problem will be

$$\max_{q_i, e_i} J = \int_0^T \left[P \sum q_i - \sum C^i(q_i, e_i) \right] e^{-rt} dt \tag{2}$$
$$s.t. \int_0^T (e_1 + e_2) dt \leq A.$$

Obviously, the integral term $P\sum q_i - \sum C^i(q_i, e_i)$ is concave associated with q_i and e_i. The constraint condition is the total emissions at the horizon that cannot exceed the emissions cap. However, according to the optimal theory, the optimal solutions of **Eq. 2** should be at the constraint boundary, which means the constraint condition is binding. The present value Lagrange equation is

$$L = \int_0^T \left(P \sum q_i - \sum C^i(q_i, e_i) \right) e^{-rt} dt + \lambda \int_0^T (A - e_1 - e_2) dt. \tag{3}$$

Lagrange multiplier λ indicates the discounted shadow price of the emission cap. Specifically, it denotes the discounted welfare improvements when the regulator increases the one-unit emission cap. Note that the integrand does not contain λ, so the optimal solution λ^* is independent on t. Furthermore, **Eq. 3** can be reformed as

$$L = \int_0^T \left\{ \left(P \sum q_i - \sum C^i(q_i, e_i) \right) e^{-rt} + \lambda \left(\frac{A}{T} - e_1 - e_2 \right) \right\} dt. \tag{4}$$

As T is fixed, the problem needs to optimize the integrand in each time. The necessary conditions for the optimal solutions are

$$P = C^i_q, -e^{-rt} C^i_e = \lambda, \forall i. \tag{5}$$

Eq. 5 implies that the welfare maximization calls for the necessary conditions: Firstly, the *MPC* (marginal production costs) of firms should equal the output price. Secondly, two firms should have the same *MAC* at each time, and the discounted *MAC* at each time should equal the discounted shadow price. Totally differentiating **Eq. 5** with respect to t yields

$$\dot{e}_i = \frac{-\dot{P} C^i_{qe} + r C^i_{qq} C^i_e}{\Delta_i}, \dot{q}_i = \frac{\dot{P} C^i_{ee} - r C^i_{eq} C^i_e}{\Delta_i}, i = 1, 2. \tag{6}$$

This specifies the behaviors of emissions and outputs along time of each firm. As Δ_i is positive, the signs of $\dot{e}_i$ and $\dot{q}_i$ are both determined by the numerators. ρ denotes growth rate of output price: $\rho = \frac{\dot{P}}{P}$. Define $k_i = \frac{C^i_{eq} C^i_e}{C^i_{ee} C^i_q}$, $l_i = \frac{C^i_{qq} C^i_e}{C^i_{eq} C^i_q}$, and $0 < k_i < l_i$,[4] The behaviors in various situations are shown in **Table 1**.

It can be found that the behaviors of each firm only depend on the growth rate ρ. Both the optimal emissions and outputs of firm i decrease with time if the growth rate is below $k_i r$. When the

[2] C^i_q denotes $\partial C^i(\cdot)/\partial q_i$, C^i_{qq} denotes $\partial^2 C^i(\cdot)/\partial q_i^2$, the same with hereafter.

[3] For simplicity, we omit the time variable t in the variables; here, for example, q_i denotes $q_i(t)$.

[4] Obviously, $0 < k, l$. $k - l = -\frac{\Delta C^i_e}{C^i_q C^i_{ee} C^i_{eq}} < 0$ since the numerator and denominator are both negative.

TABLE 1 | The behaviors of firms for welfare optimization.

ρ	Change of e_i	Change of q_i
$l_i r < \rho$	$\dot{e}_i > 0$	$\dot{q}_i > 0$
$k_i r < \rho < l_i r$	$\dot{e}_i < 0$	$\dot{q}_i > 0$
$\rho < k_i r$	$\dot{e}_i < 0$	$\dot{q}_i < 0$

growth rate is in the interval $k_i r < \rho < l_i r$, the emissions still decrease while the outputs change to increase. If the growth rate is large and exceeds $l_i r$, they will both increase with time. This implies that the price regulation policy has an impact on the firms' behaviors of producing and discharging, and the change of the optimal outputs path will precede that of the optimal emissions path when ρ keeps rising gradually. What's more, a positive growth rate of output price can alleviate the negative effect arising from discharging excessively in early periods (Kling and Rubin 1997). Given the growth rate is large enough ($l_i r < \rho$), total emissions will increase with time, which means that the system-wide banking will happen[5].

Eq. 5 shows precisely the necessary conditions for efficient solutions. Next, we will use these conditions to compare the inefficiency arising from market power between having no BB system and having a BB system and identify the behaviors of firms in two cases.

NO BANKING AND BORROWING SYSTEM

We reexamine Hahn's case (1984) in the dynamic view without a BB system. Either banking or borrowing is illegal in this situation. Therefore, no firms will store any permit, and they will use up all permits they hold each time. Therefore $\dot{B}_i = \dot{B} = 0$, which means $e_i = \overline{a}_i + (-1)^i x$, $i = 1, 2$. It is simple to analyze the behavior of firms in the output market because both firms are price takers. As stated in *Basic Model*, firm one is a monopoly seller that can control the number of permits for sale to manipulate permits price, while firm two is a buyer and price taker in the permits market. The cost functions are common knowledge. Firm two completely knows the actions of firm one at any time and then decides to buy or borrow any permits at each time. Firm one also completely knows firm 2's reflections before its own actions. Therefore, this is a classical Stackelberg game problem each time. We first analyze the actions of firm two and then move back to firm 1. The firms need to pick a path of outputs and trading volume to maximize the integral of the present value of profits $\pi_i e^{-rt}$ on the horizon:

$$\max_{q_i, x} J_i = \int_0^T \pi_i e^{-rt} dt, i = 1, 2.$$

The maximization problem requires that the profit each time, π_i, should be optimized as T is fixed. The first-order conditions for firm two are

$$P = C_q^2, \beta = -C_e^2, \forall t \in [0, T]. \tag{7}$$

The second-order conditions are shown in **Supplementary Appendix A1**. **Eq. 7** means that the fringe firm has to choose a level of output and the permits needed to buy in each time so as to make *MPC* equal the output price and make *MAC* equal the permits price. The following can be derived from **Eq. 7**:

$$\beta = \beta(x, P). \tag{8}$$

Because the trading market prohibits the firms from banking and borrowing, firm two does not get any extra permits each time except for buying from the market, and firm one does not gain any revenue from the excessive permits each time except for selling them to firm 2. The permits price thus strictly depends on x when P is prescribed exogenously. Move back to firm 1's problem, and the first-order conditions are

$$P = C_q^1, \beta + x\frac{\partial \beta}{\partial x} = -C_e^1, \forall t \in [0, T]. \tag{9}$$

The second-order conditions are also shown in **Supplementary Appendix A1**. **Eq. 9** shows firm one needs to select a level of outputs and permits for sale to make *MPC* equal the output price each time and make *MAC* equal the marginal revenue of the permits market. However, **Eq. 9** further shows the permits price equals *MAC* only when the trading volume is zero. Firm one will push up the permits price, which exceeds its *MAC* if $x > 0$ (we show that $\frac{\partial \beta}{\partial x} < 0$in **Supplementary Appendix A1**). This is essentially consistent with Hahn's results. Then, we will explore the optimal paths of firms following the basic results. $x^* = x^*(P)$, $q_1^* = q_1^*(P)$ can be derived from **Eqs 8**, **9**. Subsisting $x^* = x^*(P)$ to **Eq. 8** then we get the permits price in equilibrium, $\beta^* = \beta^*(P)$. Differentiating $\beta^*(P)$ with respect to t yields the paths of the permits price:

$$\frac{\dot{\beta}}{\beta} = \frac{\dot{P}}{P}\varepsilon \tag{10}$$

where $\varepsilon = \frac{d\beta}{dP}\frac{P}{\beta}$ is the permits price elasticity of the output price. We prove that $\varepsilon > 0$ (see the **Supplementary Appendix A2**), which implies the permits price will be pushed up once the output price rises. **Eq. 10** implies that the growth rate of the permits price is ε times the growth rate of the output price. This does not satisfy the Hotelling rule. Totally differentiating **Eq. 7** with respect to t yields the paths of emissions and outputs of firm 2:

$$\dot{e}_2 = \rho\frac{\left(\varepsilon C_e^2 C_{qq}^2 - C_q^2 C_{qe}^2\right)}{\Delta_2}, \dot{q}_2 = \rho\frac{\left(-\varepsilon C_{eq}^2 C_e^2 + C_q^2 C_{ee}^2\right)}{\Delta_2}, \tag{11}$$

If $\rho > 0$, the signs of $\dot{e}_2$ and $\dot{q}_2$ only depend on the expressions in the bracket. Then the relationships between ε and $\dot{e}_2$ (or $\dot{q}_2$) are obtained, as shown in **Table 2**.

The path of the emission of firm one is completely opposite to that of firm 2, $\dot{e}_1 = -\dot{e}_2$, which can be easily derived from the equations $\dot{x} = \dot{e}_2$ and $e_1 = \overline{a}_1 - x$. Totally differentiating $P = C_q^1$ with respect to t yields the path of outputs of firm 1:

[5]The flow allocation for the firms is constant in each time: $\sum \overline{a}_i$, thus some permits must be transferred to the later periods given that $\sum \dot{e}_i > 0$.

TABLE 2 | The behaviors of firms without a BB system (when $\rho > 0$).

ε	Change of e_i	Change of q_i
$\varepsilon < 1/l_2$	$\dot{e}_2 > 0,\ \dot{e}_1 < 0$	$\dot{q}_2 > 0,\ \dot{q}_1 > 0$
$1/l_2 < \varepsilon < 1/k_2$	$\dot{e}_2 < 0,\ \dot{e}_1 > 0$	$\dot{q}_2 > 0,\ \dot{q}_1 > 0$
$1/k_2 < \varepsilon$	$\dot{e}_2 < 0,\ \dot{e}_1 > 0$	$\dot{q}_2 < 0,\ \dot{q}_1 > 0$

$$\dot{q}_1 = \frac{\dot{P} - C^1_{qe}\dot{e}_1}{C^1_{qq}}.$$

The definitions of l_2 and k_2 are defined as that in *Regulator's Problem*. Given $\rho > 0$, the behaviors are closely related to the magnitude of the elasticity. This is quite different from the system-wide optimization situation in which the optimal paths only depend on the growth rate of output price. The fringe firm will discharge more in the early period than the later period if the permits price is sensitive enough to the output price ($1/k_2 < \varepsilon$). The permits price is increasing with output price, so the firm can expect that a slight rising in output price will incur a larger rising in permits price. This means it will suffer a higher *MAC* in the future (firm two is the price taker). It is therefore reasonable to buy more and discharge more in the early period. Conversely, it will discharge more in the later period if the elasticity is small enough ($\varepsilon < 1/l_2$). The paths of the outputs are the same as those of the emissions except in the case of $1/l_2 < \varepsilon < 1/k_2$. The outputs of firm one keep increasing given $\dot{P} > 0$ (the proof see **Supplementary Appendix A2**). Moreover, all the paths of the emissions and outputs of each firm will be inverse when $\dot{P} < 0$. It is a static case that is the same as Hahn's when $\dot{P} = 0$.

BANKING AND BORROWING SYSTEM

The firms can transfer the permits freely across time in such banking and borrowing systems. The equilibrium permits price in the intertemporal market with full competition satisfies the Hotelling rule: $\frac{\dot{\beta}}{\beta} = r$, which is from the basic insight from Rubin (1996). The Hotelling rule makes the discounted permits price constant in the entire horizon, $\beta(t)e^{-rt} = \overline{\beta}$, since any permits price differences between two periods are not optimal for firm 1 (Hagem and Westskog, 1998). We have shown that $\overline{\beta}$ depends on the total permits trading volume at the horizon, X, instead of the trading volume for each time (see the **Supplementary Appendix A3**). Therefore, the firms need to select X at the horizon instead of x. The constraint conditions thereby become: $\int_0^T e_i(t)dt = \overline{a}_i T - (-1)^i X$. What's more, the level of outputs and emissions during each time need to be decided by the firms. Then the firms' problem will be

$$\max_{q_i, e_i, X} J_i = \int_0^T \pi_i e^{-rt} dt \tag{12}$$

$$s.t. \int_0^T e_i(t)dt = \overline{a}_i T - (-1)^i X, \forall i.$$

The present value Lagrange equation of firm i is

$$L_i = \int_0^T (Pq_i - C_i(q_i, e_i) - (-1)^i \beta x) e^{-rt} dt + \Lambda_i \left(\overline{a}_i T - (-1)^i X - \int_0^T e_i(t)dt \right),$$

where Λ_i is a Lagrange multiplier. The first-order conditions of firm two are

$$P = C^2_q, -C^2_e e^{-rt} = \overline{\beta} = \Lambda_2 \tag{13}$$

As firm two is a price taker in both markets, its *MPC* still equals output price, and the discounted *MAC* still equals the discounted permits price. **Supplementary Appendix A3** has shown that the discounted permits price is the function of X and P:

$$\overline{\beta} = \overline{\beta}(X, P). \tag{14}$$

The first-order conditions of firm 1 are

$$P = C^1_q, \tag{15}$$

$$\overline{\beta} + X\frac{\partial \overline{\beta}}{\partial X} = -C^1_e e^{-rt} = \Lambda_1. \tag{16}$$

The left of **Eq. 16** is fixed, which means that the discounted *MAC* of firm one remains the same over time. However, the discounted price will be below the discounted *MAC* of firm 1 as long as the total sales of permits are not zero. Although a BB system results in inefficiency across firms, it can make the efficient allocation of permits across time. Because a BB system disables and segments the permits markets in two periods, the firm with market power fails to make an independent discrimination price during each time in the BB system. Consequentially, the monopoly firm can only make a uniform discrimination price, which leads to inefficiency across firms but efficiency across time. Therefore, the distortion from the market power cannot be eliminated completely but can be effectively alleviated by a BB system compared with having no BB system. In sum, differentiating **Eq. 13** with respect to t yields

$$\dot{e}_2 = \frac{-\dot{P}C^2_{qe} + rC^2_{qq}C^2_e}{\Delta_2}, \dot{q}_2 = \frac{\dot{P}C^2_{ee} - rC^2_{eq}C^2_e}{\Delta_2}. \tag{17}$$

The behaviors of firm two can be obtained from **Eq. 17**, which has the same form as **Eq. 6**. As $\int_0^T e_1(t) + e_2(t)dt = \overline{A}$, then $\dot{e}_2 = -\dot{e}_1$. Totally differentiating **Eq. 15** with respect to t yields the path of outputs of firm 1:

$$\dot{q}_1 = \frac{\dot{P} + C^1_{qe}\dot{e}_2}{C^1_{qq}} \tag{18}$$

As a result, the behaviors of a decentralized equilibrium with a BB system are shown in **Table 3**. The behaviors of emissions and outputs are just closely related to the growth rate of output price. The behaviors of firm two are the same as the ones of systemwide optimization, but the behaviors of firm one change. If the growth rate of output price is large enough, the emissions and outputs of firm two will both increase over time, and they will both decay if the growth rate is small enough. The optimal path of emissions of firm one is opposite to that of firm 2. However, we do not show

TABLE 3 | The behaviors of decentralized equilibrium with BB system.

ρ	Change of e_i	Change of q_i
$l_2r < \rho$	$\dot{e}_2 > 0,\ \dot{e}_1 < 0$	$\dot{q}_2 > 0$
$k_2r < \rho < l_2r$	$\dot{e}_2 < 0,\ \dot{e}_1 > 0$	$\dot{q}_2 > 0$
$\rho < k_2r$	$\dot{e}_2 < 0,\ \dot{e}_1 > 0$	$\dot{q}_2 < 0$

the optimal path output of firm 1 as a sign of $\dot{q}_1$ being uncertain when ρ changes.

CONCLUSION

We explored the behaviors of the firms in a finite horizon in two cases in which the firms are allowed to bank and borrow and not to do these in the tradable permits market with a monopoly seller. The behaviors of firms in the market without a BB system depend on the growth rate of output price and the permits price elasticity of the output price. If the permits price elasticity of the output price is large enough and the output price keeps rising, the emissions and outputs of the fringe firm both decrease with time, while the firm with market power discharges more in the later periods and the level of the output increases with the time. The behaviors of firms in the market without a BB system only depend on the growth rate of the output price. The emissions and outputs of firm two will both increase with time if the growth rate of output price is large enough, and they will both decay if the growth rate is small enough. The optimal path of emissions of firm one is opposite to that of firm 2. The growth rate of permits price with a BB system satisfies the Hotelling rule, but it is related to the growth rate of output price and permits price elasticity of output price in the situation without a BB system.

The tradable permits market in both cases leads to heterogeneously inefficient solutions. The fringe firm's strategy on settling the permits without a BB system is not as flexible as that with a BB system. It cannot get any more permits except for purchasing some from the market. Thereby, the monopoly seller is able to credibly manipulate the permits price each time, and this results in both inefficient allocations across the firms and time. The BB system provides more choices on distributing the permits, and the firms can transfer the permits across time freely. The monopoly firm can only make a uniform discrimination price at the horizon due to failing to segment the market across time. As a result, the market with BB system can alleviate the inefficiency compared with that without BB system.

The basic results proposed provide some policy implications. Firstly, banking and borrowing is a useful instrument to alleviate the distortion of permits price arising from the strategy firms with market power since the free transferability of permits in such a system will make the efficiency attainable across time. Secondly, the regulator can easily control the price of the output market to effectively adjust the behaviors of discharging instead of adjusting the emission cap, which is more complicated to implement in practice. For example, the strategy firm usually discharges more in the current period and less in the latter periods compared to the socially desirable path of discharging in a high growth rate of output price. In this case, the regulator can lower the growth rate to adjust the discharging path of the firm with market power close to the socially desirable path.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

MJ: Methodology, Original draft Writing; XF: Calculation, Draft writing; LL: Software, Writing-Reviewing and Editing.

ACKNOWLEDGMENTS

Our heartfelt thanks should be given to the National Natural Science Foundation of China (71903099), the General Foundation of Philosophy and Social Science Research in Colleges and Universities in Jiangsu Province (2019SJA0165), and the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (19KJB610019) for funding supports.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.704556/full#supplementary-material

REFERENCES

Bosetti, V., Carraro, C., and Massetti, E. (2009). Banking permits: economic efficiency and distributional effects. *J. Pol. Model.* 31, 382–403. doi:10.1016/j.jpolmod.2008.12.005

Cason, T. N., and Gangadharan, L. (2004). Emissions variability in tradable permit markets with imperfect enforcement and banking. *J. Econ. Behav. Organ.* 61, 199–216. doi:10.1016/j.jebo.2005.02.007

Cronshaw, M., and Kruse, J. (1996). Regulated firms in pollution permit markets with banking. *J. Regul. Econ.* 9, 179–189. doi:10.1007/BF00240369

Egteren, H., and Weber, M. (1996). Marketable permits, market power, and cheating. *J. Environ. Econ. Manag.* 30, 161–173. doi:10.1006/jeem.1996.0011

Eshel, D. M. D. (2005). Optimal allocation of tradable pollution rights and market structures. *J. Regul. Econ.* 28, 205–223. doi:10.1007/s11149-005-3109-5

Feng, H., and Zhao, J. (2006). Alternative intertemporal permit trading regimes with stochastic abatement costs. *Resource Energ. Econ.* 28, 24–40. doi:10.1016/j.reseneeco.2005.04.002

Hagem, C., and Westskog, H. (2008). Intertemporal emission trading with a dominant agent: How does a restriction on borrowing affect efficiency?. *Environ. Resource Econ.* 40, 217–232. doi:10.1007/s10640-007-9149-9

Hagem, C., and Westskog, H. (1998). The design of a dynamic tradeable quota system under market imperfections. *J. Environ. Econ. Manag.* 36, 89–107. doi:10.1006/jeem.1998.1039

Hahn, R. W. (1984). Market power and transferable property rights. *Q. J. Econ.* 99, 753–765. doi:10.2307/1883124

Hatcher, A. (2012). Market power and compliance with output quotas. *Resource Energ. Econ.* 34, 255–269. doi:10.1016/j.reseneeco.2011.12.002

Hintermann, B. (2017). Market Power in Emission Permit Markets: Theory and Evidence from the EU ETS. *Environ. Resource Econ.* 66, 89–112. doi:10.1007/s10640-015-9939-4

Jiang, M. X., Yang, D. X., Chen, Z. Y., and Nie, P. Y. (2016). Market power in auction and efficiency in emission permits allocation. *J. Environ. Manage.* 183, 576–584. doi:10.1016/j.jenvman.2016.08.083

Jiang, M., Zhu, B., Wei, Y.-M., Chevallier, J., and He, K. (2018). An intertemporal carbon emissions trading system with cap adjustment and path control. *Energy policy* 122, 152–161. doi:10.1016/j.enpol.2018.07.025

Kling, C., and Rubin, J. (1997). Bankable permits for the control of environmental pollution. *J. Public Econ.* 64, 101–115. doi:10.1016/S0047-2727(96)01600-3

Leiby, P., and Rubin, J. (2001). Intertemporal permit trading for the control of greenhouse gas emissions. *Environ. Resource Econ.* 19, 229–256. doi:10.1023/a:1011124215404

Liski, M., and Montero, J.-P. (2005). A note on market power in an emission permits market with banking. *Environ. Resource Econ.* 31, 159–173. doi:10.1007/s10640-005-1769-3

Liski, M., and Montero, J.-P. (2006). On pollution permit banking and market power. *J. Regul. Econ.* 29, 283–302. doi:10.1007/s11149-006-7400-x

Maeda, A. (2004). Impact of banking and forward contracts on tradable permit markets. *Environ. Econ. Pol. Stud* 6, 81–102. doi:10.1007/BF03353932

Maeda, A. (2003). The emergence of market power in emission rights markets: the role of initial permit distribution. *J. Regul. Econ.* 24, 293–314. doi:10.1023/a:1025602922918

Newell, R., Pizer, W., and Zhang, J. (2005). Managing Permit Markets to Stabilize Prices. *Environ. Resource Econ.* 31, 133–157. doi:10.1007/s10640-005-1761-y

Rubin, J. D. (1996). A model of intertemporal emission trading, banking, and borrowing. *J. Environ. Econ. Manag.* 31, 269–286. doi:10.1006/jeem.1996.0044

Sartzetakis, E. S. (1997a). Raising rivals' costs strategies via emission permits markets. *Rev. Ind. Organ.* 12, 751–765. doi:10.1023/a:1007763019487

Sartzetakis, E. S. (1997b). Tradeable emission permits regulations in the presence of imperfectly competitive product markets: welfare implications. *Environ. Resource Econ.* 9, 65–81. doi:10.1007/bf02441370

Schennach, S. M. (2000). The economics of pollution permit banking in the context of Title IV of the 1990 Clean Air Act Amendments. *J. Environ. Econ. Manag.* 40, 189–210. doi:10.1006/jeem.1999.1122

Stevens, B., and Rose, A. (2002). A dynamic analysis of the marketable permits approach to global warming policy: a comparison of spatial and temporal flexibility. *J. Environ. Econ. Manag.* 44, 45–69. doi:10.1006/jeem.2001.1198

Westskog, H. (1996). Market Power in a System of Tradeable CO2 Quotas. *Ej* 17, 85–103. doi:10.5547/ISSN0195-6574-EJ-Vol17-No3-6

Yates, A. J., and Cronshaw, M. B. (2001). Pollution Permit Markets with Intertemporal Trading and Asymmetric Information. *J. Environ. Econ. Manag.* 42, 104–118. doi:10.1006/jeem.2000.1153

Zhu, B., Jiang, M., Yuan, S., and Xie, R. (2017). Exploring the impacts of initial permits allocation on the efficiency of intertemporal carbon market. *Syst. Eng. - Theor. Pract.* 37, 2802–2811. doi:10.12011/1000-6788(2017)11-2802-10

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 16 August 2021
doi: 10.3389/fenrg.2021.715504

The Stimulation and Coordination Mechanisms of the Carbon Emission Trading Market of Public Buildings in China

Lingyan Li[1], Mimi Duan[1], Xiaotong Guo[1,2] and Yao Wang[1]*

[1]School of Management, Xi'an University of Architecture and Technology, Xi'an, China, [2]Laboratory of Neuromanagement in Engineering, Xi'an University of Architecture and Technology, Xi'an, China

The most important issue related to the establishment of carbon emission trading in China is how to motivate the owners of public buildings to participate. However, Existing research few considered the characteristics of public building owners and the influence of various uncertain factors in carbon emission trading investments. To fill this gap, this study constructs a carbon emission trading investment decision model of public building owners to study the mechanism that encourages them to participate, incorporating these characteristics and uncertain factors. The findings are as follows. First, carbon price is important in adjusting the emission reductions of different owners to minimize the total social cost of emission-reduction measures. Second, the price of carbon-emission permits has a significant impact on the investment threshold and decision-making behavior of public building owners. Finally, reducing the cost of energy-conservation and emission-reduction technologies in public buildings and appropriately subsidizing owners for their emission-reduction investment were effective methods to motivate them to participate in carbon emission trading. The results were used to quantitatively analyze the impact of a carbon emission trading mechanism on the decision-making behavior of public building owners and to construct the carbon emission trading mechanism used in China's public building industry.

Keywords: carbon emission trading market, public building owner, behavioral selection, carbon price, external coordination mechanism of trading

Edited by:
Yong-cong Yang, Guangdong University of Foreign Studies, China

Reviewed by:
Fanlin Meng, University of Essex, United Kingdom
Hadi Farabi-Asl, Research Institute for Humanity and Nature, Japan

***Correspondence:**
Mimi Duan
duanmimi@xauat.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *27 May 2021*
Accepted: *05 August 2021*
Published: *16 August 2021*

Citation:
Li L, Duan M, Guo X and Wang Y (2021) The Stimulation and Coordination Mechanisms of the Carbon Emission Trading Market of Public Buildings in China. Front. Energy Res. 9:715504. doi: 10.3389/fenrg.2021.715504

INTRODUCTION

At present, one of the biggest environmental problems that humans face on a global scale is climate change caused by the high concentration of greenhouse gases (GHG) in the atmosphere from fossil fuels and industrial processes (Burciaga, 2020). Controlling GHG emissions is an important goal for human societies. As early as 1997, the Kyoto Protocol indicated that there are six GHGs of anthropogenic origin that must be reduced: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbon (HFC), perfluorocarbons (PFC), and sulfur hexafluoride (SF_6). In this sense, CO_2 is the main anthropogenic GHG, composing approximately 76% of the total GHGs considered by the Kyoto Protocol (IPCC, 2014). Meanwhile, the Kyoto Protocol established a series of innovative cooperation mechanisms with the aim of decreasing the costs of GHG mitigation, namely, International Emission Trade, Joint Implementation, and Clean Development Mechanisms.

These three mechanisms involve carbon emission trading between countries (Liu and Dai, 2004). Since then, the carbon emission trading mechanism has become an important means to effectively decrease energy consumption. Internationally, there are large-scale trading platforms, such as the European Union Emissions Trading System (EU-ETS) and the Regional Greenhouse Gas Initiative. Following the official launch of carbon emission trading in China at the end of 2007, the carbon trading market completed 4,340.09 million tons of CO_2 trading volume in 2020.

At present, the three fields with the highest energy consumption in China are industry, transportation, and construction. In the construction industry, public buildings consume a relatively large amount of energy. Carbon emissions for the whole process of construction in China amounted to 4.93 billion tCO_2, or 51.3% of the national carbon emissions as of 2018. In addition, China's energy consumption in the building sector increased from 460 million tons to 2.23 billion tons, with an annual growth rate of 9.2% from 2000 to 2018. The rigid growth trend of carbon emissions in the construction sector is obviously higher than the growth rate of energy carbon emissions in industry and transportation (Li et al., 2021; Luo et al., 2021; Luo and Liu, 2021). The energy-consumption permit trading scheme (ECPTS) was proposed by the National Development and Reform Commission and the National Education Association in 2016 to achieve the dual energy control targets, selecting Zhejiang, Fujian, Henan, and Sichuan provinces as the pilot areas. By the end of 2020, nearly 1,000 enterprises in the four pilot provinces had participated in the ECPTS, with a volume of approximately five million tons of standard coal equivalent (Mtce), the value of which exceeded 110 million CNY (Zhang et al., 2021). With continuing urbanization, people's demand for public services will increase and the area occupied by public buildings will continue to grow. Predictably, the high energy consumption of public buildings will become increasingly severe. Therefore, introducing an appropriate carbon emission trading mechanism into the public building market can effectively decrease energy consumption in this sector. This issue involves the system builder (government), the GHG emission controller (public building owners), and transaction service providers (transaction agency, verification agency, and intermediary). The government is the representative of social interests, and its support for the establishment of the mechanism is self-evident. Service providers will emerge as needed when the mechanism has been established. Since the owners of public buildings are used to the current profit model and their concept of sustainable development is weak, the key issue, particularly at the outset, is to motivate them to participate in the mechanism.

Based on this, we studied the incentive and coordination mechanism of China's public carbon emission trading market. The rest of this paper is organized as follows. First, the literature review shows the theoretical influence mechanism of the carbon emission trading market. *Literature Review* presents an economic analysis of the behavioral decisions of public building owners. In this section, we investigate how carbon price affects the decision-making of owners after they enter the carbon emission trading market. Then, considering several uncertain factors, an emission-reduction-investment decision model was established under the constraint of a total amount, which was based on the real-option characteristics and several adjustable uncertain factors of public building owners' investments in carbon emission trading. This model was applied to further explore the impact of carbon prices on the decision-making behavior of individual public building owners. *Economic Analysis of the Behavior Decision-Making of Public Building Owners* discusses external coordination mechanisms for carbon emission trading in the public building sector. While also considering effective measures of public building owners who participate in carbon emission trading, this paper establishes a series of external coordination mechanisms. These include a risk-diversification mechanism, a technical-guarantee mechanism for trading media, an incentive-and-restraint mechanism for trading behaviors, and a policy-support mechanism for trading activities. These tools ensure smooth progress in the decision-making of owners to the final transactions. Finally, *Conclusion and Outlook* concludes the paper and offers future research prospects. The research framework of this study is shown in **Figure 1**.

LITERATURE REVIEW

Since 1968, when Dales (2002) first proposed the "emission market" to address global climate change, many scholars have suggested that the use of market trading can better lead to a reduction of pollution emissions. For example, using economics theory, Montgomery (1972) proved that the carbon emission trading market can optimize the allocation of environmental resources and thus minimize total emission costs for society. Chen and Tseng (2008), Chèze et al. (2009), and Anger (2010) analyzed carbon emission market mechanisms in the fields of power, industry, and aviation, respectively. Since 2010, an increasing number of scholars has focused on the carbon emission trading framework and its concrete operation. Based on issues in the US market, Kumarappan et al. (2011) constructed the carbon market trading framework.

Perino and Willner (2017) examined the impact of the market stability reserve (MSR) on the price and emission path of the EU emission trading system. They showed that the MSR will adjust the quota of the auction according to the surplus size, shifting the quota issue date to the future for large surpluses. Cansino et al. (2016) used the structural decomposition model to study the influencing factors of Spanish carbon emissions, and obtained six factors, including technology, energy intensity, and consumption mode. Jin et al. (2021) studied the impact of carbon trading prices on emissions and emission efficiency, and addressed the problem with a classic six-unit system. At the same time, with the expansion of building energy consumption, an increasing number of scholars are paying more attention to carbon emission trading in the field of building construction. For example, Chen et al. (2015) showed that carbon emission trading can promote building energy conservation and emission reduction, and further proposed steps to establish the carbon emission trading market in construction. Song et al. (2018) found the probability of local prosecution, the punishment of

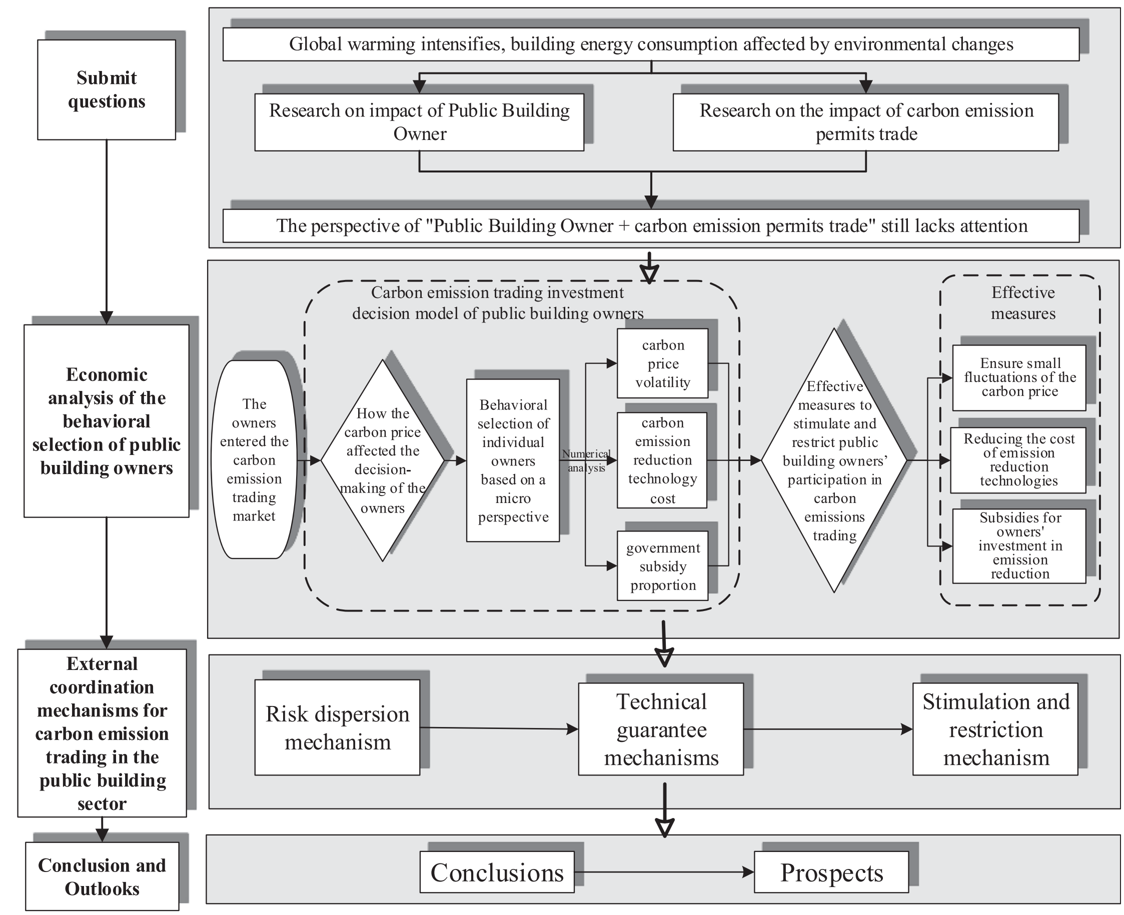

FIGURE 1 | Research framework.

violations, and the loss of the owner's reputation to be the key factors affecting the owner's behavior. Their multi-objective model provides a quantitative theoretical basis for promoting the construction of the ETS market in the construction industry.

Despite these contributions, few studies have addressed the investment decision-making behavior of carbon emission trading entities in China and internationally. However, research on the investment decision-making behaviors of energy conservation entities is similar to studies of the investment decision-making behaviors of carbon emission trading entities, such as the incentive policies for new buildings and analyses of stakeholders in energy-conservation renovations of existing buildings. This involves energy-saving building-renovation entities, energy-saving building developers, and energy-saving building consumers. Their willingness to participate is based on the investment income ratio (e.g., cost distribution and profit sharing). Therefore, research on the investment behaviors of public building owners participating in the carbon emission trading mechanism is of great significance. Qi et al. (2021), using the differentiation model and a series of robustness tests, examined whether the carbon trading market would produce the Porter effect. Astiaso Garcia et al. (2016) focused on the cost–benefit idea and explored the effects of different interventions (e.g., active or passive energy-conservation technologies) on different types of public buildings. Furthermore, they investigated the feasibility of an integrated power grid, new energy, and renewable energy for public buildings. Based on life-cycle costs, energy savings, carbon emissions, and indoor comfort, the energy-conservation renovation scheme was optimized to ensure the active application of energy-conservation technologies by different stakeholders, such as governments, developers, and consumers (Liu et al., 2020; Luo et al., 2021).

Compared with general carbon emissions trading, relatively little research has addressed the carbon emissions trading mechanism in the public building sector. The available research mainly focuses on theoretical explanations of the proposals and the feasibility of the trading framework in the construction sector. Essentially, scholars in this field have studied how to incorporate buildings into carbon emission trading from the perspective of the trading mechanism; however, they lack a quantitative analysis of the influence of this mechanism on public building owners' decision-making. The researchers also do not offer specific solutions for current problems in the field of public building energy conservation. In addition, domestic research on the investment decisions of public building owners tends to focus on a cost–benefit analysis. Most use traditional technical economic indicators, such as the net present value, the

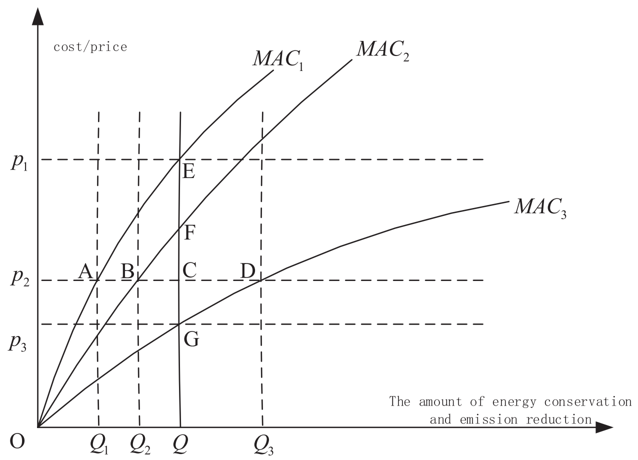

FIGURE 2 | Behavioral strategies of owner groups in carbon emissions permit trading in the public building sector.

internal rate of return, and the dynamic investment payback period. However, few have considered the option characteristics of energy-conservation and emission-reduction investment based on total control. Furthermore, few have clarified public building owners' investment decision-making behavior under the influence of various uncertain factors.

Therefore, this paper analyzes the influence of social and economic factors on carbon emission trading to illustrate the importance of this practice in Chinese cities from the macro perspective. Furthermore, we use economics to analyze how the carbon price affects the carbon emission trading market from the macro perspective. Then, from the micro perspective, a carbon-emission-reduction investment model is built, and a numerical analysis of public building owners is applied under the constraint of a total amount. This is done to further explore the impact of carbon price on individual public building owners' emission-reduction-investment decision-making, and it provides a theoretical basis for the construction of carbon emission trading mechanisms for public buildings. Combined with the analysis of effective incentives to promote the participation of public building owners in carbon emission trading, an external coordination mechanism of carbon emission trading for public buildings is constructed. The findings contribute to the quantitative analysis of the influence of the carbon emission trading mechanism on public building owners' decision-making behaviors. Furthermore, the carbon emissions trading mechanism in the public building sector in China is constructed.

ECONOMIC ANALYSIS OF THE BEHAVIOR DECISION-MAKING OF PUBLIC BUILDING OWNERS

Behavioral Decision-Making of Owner Groups Based on a Macro Perspective

Normally, the energy consumption of public buildings varies, and the cost of energy conservation per unit also differs. If carbon-emission permits can be transferred for a fee, public building owners, who are subject to relatively low costs of energy conservation and emission reduction, may be willing to engage in substantial transfers, thus benefiting from selling surplus carbon-emission permits. Consequently, they are economically motivated. Public building owners with relatively high costs of energy conservation and emission reduction must purchase carbon-emission permits because the cost of taking steps to improve energy conservation is higher than that of purchasing the permits. Therefore, they are economically constrained. Carbon price can be used as an important means for the government to regulate motivation and constrain energy-consumption management during the operation of public buildings. The specific behavioral strategies of public building owners based on carbon emission trading are illustrated in **Figure 2**.

In **Figure 2**, the horizontal axis represents the energy-conservation and emission-reduction amount of each public building owner, while the vertical axis represents the marginal cost of energy conservation and emission reduction. The figure assumes that AC + BC = CD (i.e., QQ1 + QQ2 = Q3Q), and that the carbon-emission market consists of three public building owners (1, 2, and 3), with carbon-emission permits traded between them. Based on the research on the marginal cost of emission reduction in China (Li et al., 2021), their marginal cost curves can be assumed as MAC1, MAC2, and MAC3, respectively. According to the atmospheric environment quality requirements, the volume of energy conservation and emission reduction should be 3Q. Initially, the government equally allocates carbon-emission permits to the three owners. Therefore, the three owners hold 3Q fewer carbon-emission permits than their current carbon emissions.

According to **Figure 2**, the behavioral strategies of the public building owner group are categorized as three cases based on different carbon prices:

- Case 1: Carbon price of P_1. P_1 is higher than the marginal cost of public building Owners 2 and 3 when the amount of energy conservation and emission reduction is Q. Owners 2 and 3 are willing to decrease their carbon emissions and sell their carbon-emission permits. For Owner 1, P_1 is equal to the marginal cost when the amount of energy conservation and emission reduction is Q; therefore, the owner does not need to purchase carbon-emission permits.
- Case 2: Carbon price of P_3. P_3 is lower than the marginal cost of public building Owners 1 and 2 when the amount of energy conservation and emission reduction is Q. Owners 1 and 2 are willing to purchase carbon-emission permits. For Owner 3, P_3 is equal to the marginal cost when the amount of energy conservation and emission reduction is Q, and Owner 3 will not decrease more to sell the carbon-emission permit.
- Case 3: Carbon price of P_2. P_2 is lower than the marginal cost of public building Owners 1 and 2 when the amount of energy conservation and emission reduction is Q. Owners 1 and 2 will decrease emissions Q_1 and Q_2, respectively. The carbon-emission permits they purchase from the trading

TABLE 1 | Comparison of carbon-emission reduction between owner participating in trade and not participating in trade.

Owner	Owner 1	Owner 2	Owner 3	Owner group
Cost when carbon price is P_1 or P_3	$\int_0^Q f_1(Q)$	$\int_0^Q f_2(Q)$	$\int_0^Q f_3(Q)$	$\int_0^Q f_1(Q) + \int_0^Q f_2(Q) + \int_0^Q f_3(Q)$
Cost when carbon price is P_2	$\int_0^{Q_1} f_1(Q)$	$\int_0^{Q_2} f_2(Q)$	$\int_0^{Q_3} f_3(Q)$	$\int_0^{Q_1} f_1(Q) + \int_0^{Q_2} f_2(Q) + \int_0^{Q_3} f_3(Q)$
Cost reduction	$\int_{Q_1}^{Q} f_1(Q)$	$\int_{Q_2}^{Q} f_2(Q)$	$-\int_{Q}^{Q_3} f_3(Q)$	$\int_{Q_1}^{Q} f_1(Q) + \int_{Q_2}^{Q} f_2(Q) - \int_{Q}^{Q_3} f_3(Q)$

market are QQ_1 and QQ_2, respectively. For Owner 3, P_2 is higher than the marginal cost when the amount of energy conservation and emission reduction is Q_3; therefore, the owner is willing to decrease emissions Q_3 and sell carbon-emission permits Q_3–Q. Consequently, $QQ_1 + QQ_2 = Q_3Q$. At this point, the carbon emission trading market of the public building sector reaches a balance between supply and demand.

Further analysis of the abatement costs and social costs undertaken by the public building owners in the above three cases is presented in **Table 1**, which compares the abatement costs in the case of carbon emission trading and non-carbon emission trading.

Consequently,

$$\int_{Q_1}^{Q} f_1(Q) + \int_{Q_2}^{Q} f_2(Q) - \int_{Q}^{Q_3} f_3(Q) > 0 \tag{1}$$

If the price of carbon-emission permits fluctuates around P_2 between P_1 and P_3, the emission reduction of different owners can be adjusted by the carbon price. Thus, the total social cost of emission reduction is minimized. From the macro perspective of the public building owner group, price fluctuation indicates the process of regulating the supply and demand of carbon-emission permits among public building owners in the trading market. During this process, the allocation of permits in the field of public building energy conservation is continuously optimized.

Behavioral Decision-Making of Individual Owners Based on a Micro Perspective

The carbon-emission-reduction investment of public building owners, under the constraint of a total amount, has clear real-option characteristics. Individual owners have two main ways to reduce emissions: one is to purchase carbon-emission permits from the market, and the other is to voluntarily reduce emissions. If owners adopt energy-conservation technology to decrease carbon emissions, they need to invest in technology, which is an investment choice. Its realization is affected by the income of future carbon emission trading (return), which, in turn, is affected by further uncertainties. Therefore, this section considers uncertain factors by using the real option theory. An emission-reduction-investment decision model of public building owners is established under the constraint of a total amount. This further explores the impact of carbon price on the investment behavior of individual owners.

The following presents the variable settings and basic assumptions:

1) The investment cost of public building owners' emission reduction measures is $C = \sum_{i=1}^{n} C_i + \sum_{i=1}^{m} C_j$, where C_i (i = 1, 2, 3, … , n) represents the costs of public buildings that participate in carbon emission trading. This includes the information cost to obtain information on potential trading partners, market supply and demand, prices, negotiation cost for bargaining, GHG emissions monitoring, and verification cost. C_j (j = 1, 2, 3, … , m) represents the costs incurred throughout the life cycle of public building energy-conservation technology. This includes the cost of pre-planning, design and feasibility studies for energy-conservation and emission-reduction technology, building energy-conservation technology, equipment construction and installation cost, and equipment maintenance and management cost.
2) The proportion of government subsidies for emission reduction is θ, and the probability is λ. The government switches between implementing subsidies and not implementing subsidies. This process fits a Poisson distribution with the parameter λ (i.e., during the period of $dt \to 0$, the probability of governmental implementation of subsidies is λdt).
3) The carbon-emission reduction is $Q_c = Q_{c0} - Q_{c1}$, where Q_{c0} represents the carbon emissions before the emission-reduction measures are implemented, and Q_{c1} represents the carbon emissions after the measures are implemented.
4) The price of a carbon emissions permit is P_c. We assume that it obeys a Brownian motion (i.e., $dP_c = \mu_c P_c dc + \sigma_c P_c dW_c$, where μ_c represents the carbon price growth rate, and σ_c represents the carbon price volatility).
5) r represents the risk-free interest rate of public building owners' carbon-emission reduction investment: $r > 0$.

According to the above variable settings and assumptions, the value function V of the carbon-emission reduction investment of public building owners is:

$$V = {}_t max \left[\int_{s=t}^{\infty} e^{-rs} \left(Q_c^0 - Q_c^1 \right) P_c d_s - (1-\theta) \left(\sum_{i=1}^{n} C_i + \sum_{j=1}^{m} C_j \right) \right] \tag{2}$$

The impact of the amount of emission reduction on the owners' investment income is clear, and a positive correlation exists between them. To simplify calculations, the carbon price is used to characterize the income of carbon-emission reduction investment. Let $Q_c = Qc_0 - Qc_1 = 1$ and $C = \sum_{i=1}^{n} C_i + \sum_{i=1}^{m} C_j$; the above equation can be simplified as:

$$V = {}_t max\left[\int_{s=t}^{\infty} e^{-rs} P_c d_s - (1-\theta)C\right] \tag{3}$$

In this equation, C does not change with time, and the emission-reduction investment is equal at any time. P_c obeys the Brownian motion:

$$\int_{s=t}^{\infty} e^{-rs} P_c d_s = \frac{P_c}{r-\mu_c} \tag{4}$$

Therefore, the investment value can be expressed as:

$$V = \frac{P_c}{r-\mu_c} - (1-\theta)C \tag{5}$$

The Bellman equation of **Eq. 5** is:

$$rVd_t = E(dV) \tag{6}$$

where $E(dV)$ represents expectations. From the above, the probability that the government subsidizes the emission-reduction behavior of public building owners is λdt. Using Ito to develop $E(dV)$ yields:

$$E(dV) = \frac{\partial V}{\partial t}dt + \mu_c P_c \frac{\partial V}{\partial P_c}dt + 0.5\sigma_c^2 P_c^2 \frac{\partial^2 V}{\partial P_c^2}dt + \lambda[V_1(P) - V_0(P)]dt \tag{7}$$

The Bellman equation of $V = \frac{P_c}{r-\mu_c} - (1-\theta)C$ can be expressed as:

$$\frac{\partial V}{\partial t}dt + \mu_c P_c \frac{\partial V}{\partial P_c}dt + 0.5\sigma_c^2 P_c^2 \frac{\partial^2 V}{\partial P_c^2}dt - (\lambda + r)V_0(P) + \lambda V_1(P) = 0 \tag{8}$$

The corresponding characteristic equation of **Eq. 8** is:

$$T = 0.5\sigma_c^2 \beta(\beta - 1) + \mu_c \beta - (\lambda + r) \tag{9}$$

Let $T = 0$, and the positive solution of the characteristic equation is:

$$\beta = \frac{1}{2} - \frac{\mu_c}{\sigma_c^2} + \sqrt{\left(\frac{1}{2} - \frac{\mu_c}{\sigma_c^2}\right)^2 + \frac{2(r+\lambda)}{\sigma_c^2}} \tag{10}$$

Then, the general form of the solution of **Eq. 8** can be expressed as:

$$V(P_c) = AP_c^{\beta}/(1-\theta)C^{\beta-1} \tag{11}$$

Assuming value matching and smooth conditions:

$$\begin{cases} V(P_c) = \dfrac{P_c}{r-\mu_c} - (1-\theta)C \\ \dfrac{\partial(P_c)}{\partial P_c} = \dfrac{1}{r-\mu_c} \end{cases} \tag{12}$$

Equations 11, **12** yield:

$$P_c^* = \frac{\beta}{\beta - 1}(r-\mu_c)(1-\theta)C \tag{13}$$

Equation 13 shows that, only when the permit price $P > P_c^*$ will public building owners choose to invest in emission reduction. Thus, P_c^* indicates the investment decision point of public building owners. A larger P_c^* indicates a higher threshold of owners' emission-reduction investment, and their decision-making behavior tends to delay investment. In contrast, a smaller P_c^* indicates a lower threshold for the owners' emission-reduction investment, and their decision-making behavior tends to accelerate investment. According to **Eqs. 10**, **13**, the value of the investment decision point is related to the risk-free interest rate r, the expected rate of return μ_c, the proportion of governmental subsidy θ, the technical investment costs of unit energy savings C, the government subsidy probability λ, and the carbon price volatility σ_c.

Numerical Analysis of the Influencing Factors of Owners' Behavioral Decision-Making

Based on the investment decision model established above, this section uses data from real cases to illustrate the influence of various uncertain factors, such as carbon price volatility, technology emission-reduction cost C, government subsidy proportion, and government subsidy probability, on the investment decision point of emission reduction.

The investment for the renovation of solar water heating technology for a public building in Xi'an is used as example. The initial investment cost, corresponding to unit power savings, is about 1.459 yuan/kwh (calculated *via* the total initial emission-reduction investment divided by the annual electricity savings). The annual electricity savings are 870,254 kwh, and the annual carbon-emission reduction is 823 t of CO_2. The adopted electricity price is the first level of public building electricity price in Xi'an in 2016. With regard to the setting of parameter values of μ_c and σ_{c0}, please refer to the relevant literature (Gülay Zorer Gedik et al., 2017; Xu and Wang, 2018; Luo Xi, et al., 2019). The initial values of each parameter are listed in **Table 2**.

Matlab (R2012a) was used to simulate the carbon-emission reduction investment model of public building owners and to assess the impact of various uncertain factors on the investment decision point. The model-building process is shown in **Figure 3**, and the results are shown in **Figures 4–7**.

The Impact of Carbon Price Volatility on Investment Decisions

Let $C_0 = 1{,}543$, $r = 0.059$, $\mu_c = 0.01$, $\theta_0 = 0$, and $\lambda_0 = 0$ to explore the impact of carbon price volatility (σ_c) on public building owners' carbon-emission reduction investment decision point. The variation of the decision point P_c^* (carbon price) with σ_c is shown in **Figure 4**. When $\sigma_c = 0.03$, the carbon price is 95 yuan/t of CO_2; when σ_c increases to 0.07, the carbon price increases to approximately 105 yuan/t of CO_2. With the increasing volatility of the carbon price, the decision point P_c^* increases continuously, which indicates that large fluctuations of carbon price will increase the threshold for investment by public building owners. This hinders owners from investing in carbon emission reduction.

TABLE 2 | Values of parameters in the carbon-emission reduction investment model of public building owners.

Parameters	Initial values	Notes
Q_{C0}	823 tCO_2	Actual project value
Q_{e0}	870,254 kwh	Actual project value
C_0	1,543 yuan	Calculated from actual project values (1.459 yuan/kwh/0.9457 kg CO_2 × 1,000 kg)
r	0.059	Obtained from literature
μ_{C0}	0.01	Obtained from literature
σ_{C0}	0.01	Obtained from literature
θ_0	0	Initial value of governmental subsidy proportion being zero
λ_0	0	Initial value of governmental subsidy probability being zero

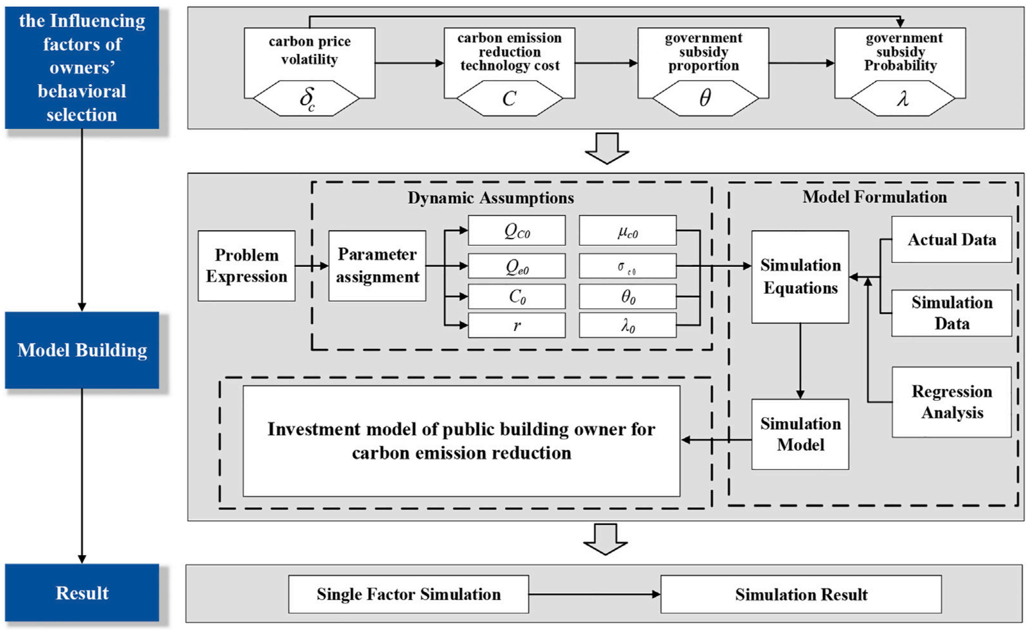

FIGURE 3 | Model-building process.

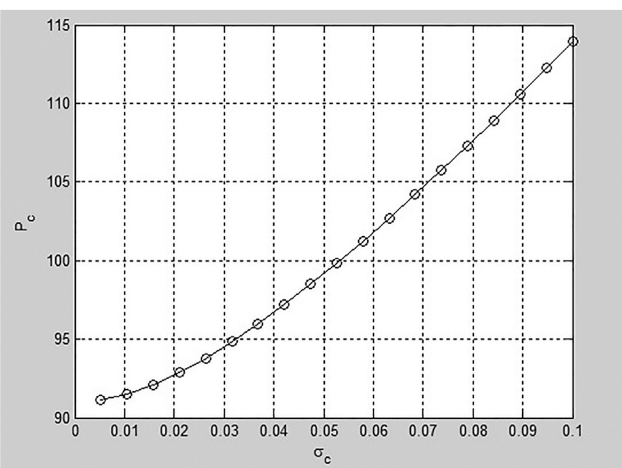

FIGURE 4 | Curve of $[P_c^* - \sigma_c]$

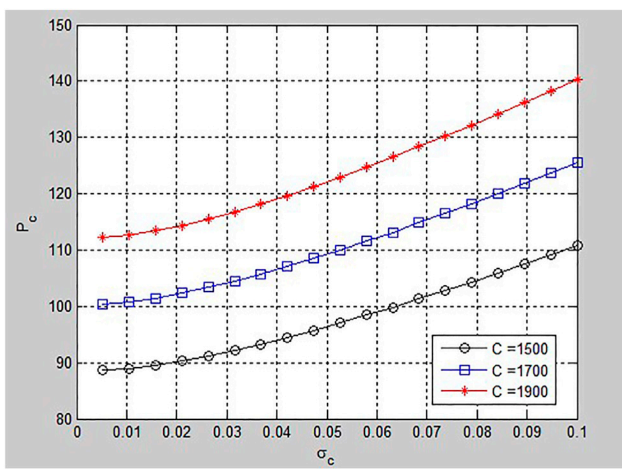

FIGURE 5 | Curve of $[P_c^* - C]$

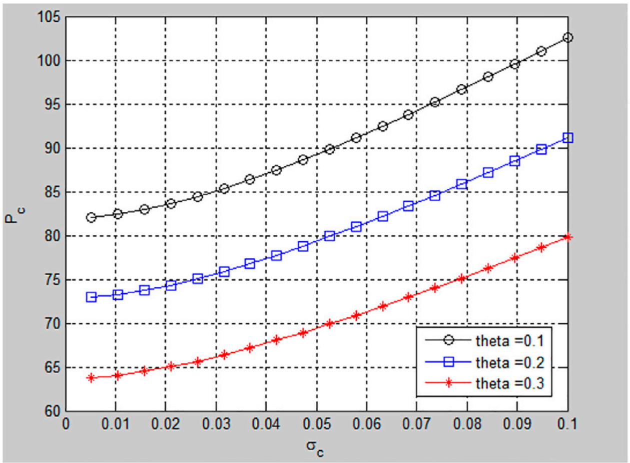

FIGURE 6 | Curve of $[P_c^* - \theta]$

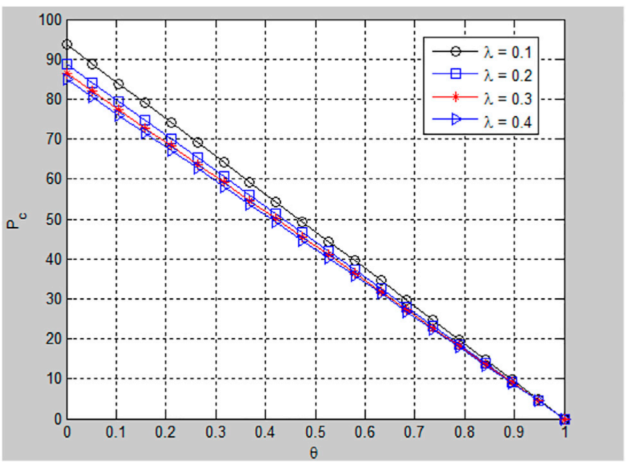

FIGURE 7 | Curve of $[P_c^* - \lambda]$

The Impact of Carbon-Emission Reduction Technology Cost on Investment Decisions

Let $r = 0.059$, $\mu_c = 0.01$, $\theta = 0$, and $\lambda = 0$; the impact of different technology costs on the decision point for owners' carbon emission-reduction investment is explored in the case of carbon price fluctuations. The variation of the decision point P_c^* (carbon price) with C is shown in **Figure 5**. When $\sigma_c = 0.01$, technology costs are 1,500 yuan, 1,700 yuan, and 1,900 yuan. The corresponding carbon prices are 89 yuan/t of CO_2, 101 yuan/t of CO_2, and 113 yuan/t of CO_2, respectively. With increasing carbon emission-reduction technology costs, the decision point P_c^* continues to increase, indicating that higher technology costs will increase the threshold for the investment of public building owners. This hinders owners from investing in carbon emission reduction.

The Impact of Government Subsidy Proportion on Investment Decisions

Let $C = 1{,}543$, $r = 0.059$, $\mu_c = 0.01$, and $\lambda = 0.1$; the impact of different government subsidy proportions on the decision point for owners' carbon emission-reduction investment is explored in the case of carbon price fluctuations. The variation of the decision point P_c^* (carbon price) with θ is shown in **Figure 6**. When $\sigma_c = 0.01$, the government subsidy proportions (θ) are 0.1, 0.2, and 0.3, and the corresponding carbon prices are 83 yuan/t of CO_2, 74 yuan/t of CO_2, and 64 yuan/t of CO_2, respectively. With increasing government subsidy proportions, the decision point P_c^* decreases. This indicates that the increase in government subsidies of carbon emission reduction will decrease the threshold for owners' investment. This encourages public building owners to invest in carbon-emission reduction.

The Impact of Government Subsidy Probability on Investment Decisions

Let $r = 0.059$, $\mu_c = 0.01$, and $\sigma_c = 0.1$; the impact of government subsidy probability (λ) on the decision point for owners' emission-reduction investment is explored in the case of simultaneous changes in government subsidy probability and subsidy proportion. The variation of the decision point P_c^* (carbon price) with λ is shown in **Figure 7**. With an increasing probability of government subsidies, the decision point P_c^* decreases, indicating that increasing the probability of government subsidies will decrease the risk expectations of owners for investment in emission reduction. This lowers the threshold for public building owners' investment and encourages them to invest in carbon-emission reduction.

Effective Measures to Stimulate and Restrict Public Building Owners' Participation in Carbon Emissions Trading

The above analysis of the impact of carbon price on public building owners' trading behaviors and emission-reduction investment decisions from macro and micro perspectives indicates that the uncertainties affecting owners' decision-making in emission-reduction investment can be identified. The following presents a summary of the effective measures to stimulate and restrict owners' participation in carbon emissions trading.

Ensure Small Fluctuations of the Carbon Price Within a Reasonable Range

Large carbon price fluctuations will cause public building owners to expect higher risks in the emission trading market, thus raising the threshold for emission-reduction investment and hindering both energy conservation and emission reduction of public buildings. Therefore, corresponding management measures should be taken to regulate the carbon price, which will ensure that fluctuations remain within a reasonable range. The aim is to reduce the risk expectations of public building owners in carbon-emission reduction investment to promote investment and applications of energy-conservation and emission-reduction technologies.

Reduce the Cost of Energy-Conservation and Emission-Reduction Technologies

Reducing the cost of energy-conservation and emission-reduction technologies can lower the decision point of owners with regard to emission-reduction investment. Consequently,

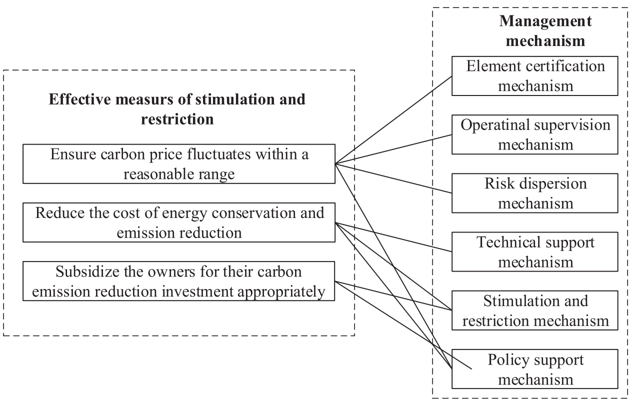

FIGURE 8 | Management mechanism to stimulate public building owners to participate in carbon emissions permit trading.

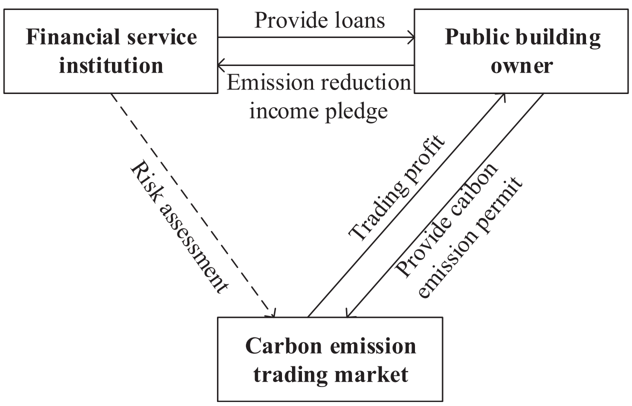

FIGURE 9 | Pattern of dispersing carbon-emission reduction investment and transaction risk of financial institutions.

they are still willing to invest in emission reduction at a lower carbon price. Furthermore, to utilize the energy-conservation potential of public buildings, conserve energy, and improve energy efficiency, the model relies heavily on energy-conservation technologies. These can significantly improve energy efficiency, decrease energy consumption, reduce costs, and increase the possibility that public building owners will participate in the emission trading market. Moreover, imitative innovation plays an important role in emission reduction, while the introduction of technology does not work very well, and original innovation even increases carbon emissions.

Appropriately Subsidize Owners for Their Carbon-Emission Reduction Investment

Providing government subsidies to public building owners who invest in energy conservation and emission reduction can decrease their investment decision point. Consequently, they can invest at a lower carbon price. The greater the probability of the government's subsidies, the more likely owners will be to have good expectations for emission-reduction investment, leading them to make investment decisions accordingly. However, excessive governmental subsidies create fiscal pressures for the government; therefore, subsidies should remain within a reasonable range to encourage owners to implement market-oriented energy conservation and emission reduction.

For the above measures to effectively stimulate and restrict public building owners, a corresponding management mechanism is required, as shown in **Figure 8**. Based on the decision-making pattern of owners, all management mechanisms should stimulate their participation in emissions trading.

EXTERNAL COORDINATION MECHANISMS FOR CARBON EMISSION TRADING IN THE PUBLIC BUILDING SECTOR

Risk Dispersion Mechanism of Public Building Owners' Trading Decisions

Investment Risk Dispersion

Uncertainties affect both the application of energy-conservation and emission-reduction technologies and the participation of public building owners in carbon emission trading. The discount period for the incremental cost of carbon emission reduction and carbon emission trading (the incremental benefits, in particular) can be extended to about 50 years or more. This puts many public building owners at significant investment risk. To disperse these risks, owners should count on the capital advantages of financial institutions, such as banks, investment companies, insurance companies, and fund securities companies, to jointly disperse the investment risks.

The first method is to provide a wealth of financial services. First, financial institutions jointly provide loans for large-scale energy-conservation and emission-reduction projects with promising potential. After the carbon emission trading has been completed, the benefits can be used to pay for the costs of carbon emission-reduction measures and for carbon emission trading activities. Then, financial institutions can allow owners to pledge the carbon-emission-reduction benefits to be earned. They can also be provided with early funds to help smaller public building projects overcome problems associated with front-end investment. The specific model is shown in **Figure 9**.

The second method is to encourage energy service companies to participate in carbon emission trading, which is a new type of financing mode. These companies provide energy-conservation renovation services for public building owners, gain benefits by selling the remaining carbon-emission permits, and then invest the money in the renovation project to overcome the funding problem. To promote this trading model and attract participants, the investment risk dispersion model, after adding the energy service company, is shown in **Figure 10**.

The third method is to cultivate carbon finance professionals in the public building sector. To propose a reasonable and effective carbon finance policy, it is necessary to have a good grasp of public building energy conservation, carbon emission

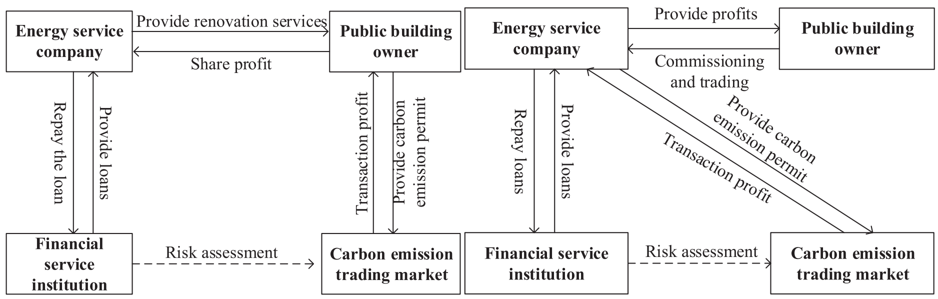

FIGURE 10 | Pattern of dispersing carbon-emission reduction investment and transaction risk of financial institutions and energy service companies.

trading, and financial knowledge. However, the introduction of carbon emission trading mechanisms to the public building sector is still new, and professional talents are rare. Therefore, both the energy-conservation-management department and the carbon-emission-trading-management department should jointly organize training programs and offer opportunities to study at mature international carbon financial institutions. Consequently, professional talents could be cultivated to provide personnel support for making financial policies, enriching financial services, and innovating financial instruments and products.

Emission Reduction Risk Dispersion

Unlike industrial buildings, it is more complicated for public buildings to measure energy consumption and determine energy savings. Thus, owners need to take great risks. Therefore, to reduce this uncertainty, first, methodology should be developed with regard to carbon emission trading in the field of public building energy conservation. The existing Kyoto Protocol framework treats energy conservation in the public building sector and other industrial fields as equal. However, this approach is questionable because the basic methods of energy use and emission reduction differ; they cannot simply be treated as equal. It should be noted that public building energy conservation is the combined result of various technical factors. Using the government's energy-conservation and energy-consumption standards as a reference, appropriate methods should be adopted to develop methodologies to determine the baseline of energy consumption for public buildings and calculate emission reductions. Second, professional energy-conservation-monitoring agencies should be established to provide accurate energy-consumption data and energy-savings data for owners.

Technical-Guarantee Mechanisms for the Trading Medium of Public Building Owners

The medium with which public building owners can conduct carbon emission trading is the carbon emissions permit (i.e., a quota). The determination of such a carbon emissions permit is closely related to the energy-consumption levels of public buildings. Therefore, to protect the carbon emission permit to which public building owners are entitled, it is necessary to monitor energy-consumption levels of public buildings accurately and scientifically using the appropriate energy-consumption monitoring technology.

This requires the full utilization of the energy-consumption monitoring platform of public buildings; it is also important to establish energy consumption data monitoring platforms in various provinces and cities, and achieve real-time monitoring of equipment with high energy consumption in public buildings. *Via* remote transmission, the energy consumption data can be collected, classified (e.g., electricity, gas, and water), and itemized (air conditioning electricity, lighting socket electricity, power electricity, and electricity for special uses), as shown in **Figure 11**. Regular surveys of public buildings need to be conducted, and online monitoring and dynamic analysis of energy consumption need to be realized to achieve accurate control of energy consumption and to optimize energy management. Work needs to be coordinated with public building owners, property sectors, and energy departments to improve data reporting efficiency, strengthen energy-consumption data management, and provide both accurate and reliable data for trading through manual and digital collections.

Stimulation-And-Restriction Mechanism for the Trading Behaviors of Public Building Owners

As a post-evaluation system for the entire trading activity, the stimulation-and-restriction mechanisms evaluate public building owners' trading behavior after a certain performance period. The government rewards owners who follow the transaction rules, and it punishes those who do not. It also allocates quotas for the next performance period based on their performance according to the contract. In this way, the carbon emission trading market will play a significant role in the stimulation and restriction of public building owners' behavior in emissions reduction.

Diversified Stimulation Methods

When the benefits from the carbon emission trading market are inadequate to appropriately stimulate the participation of traders, the government can apply different stimulating measures for the public building energy-conservation stakeholders who are involved in carbon emission trading. With the applied measures and the "profit-driven" effect, the carbon emission

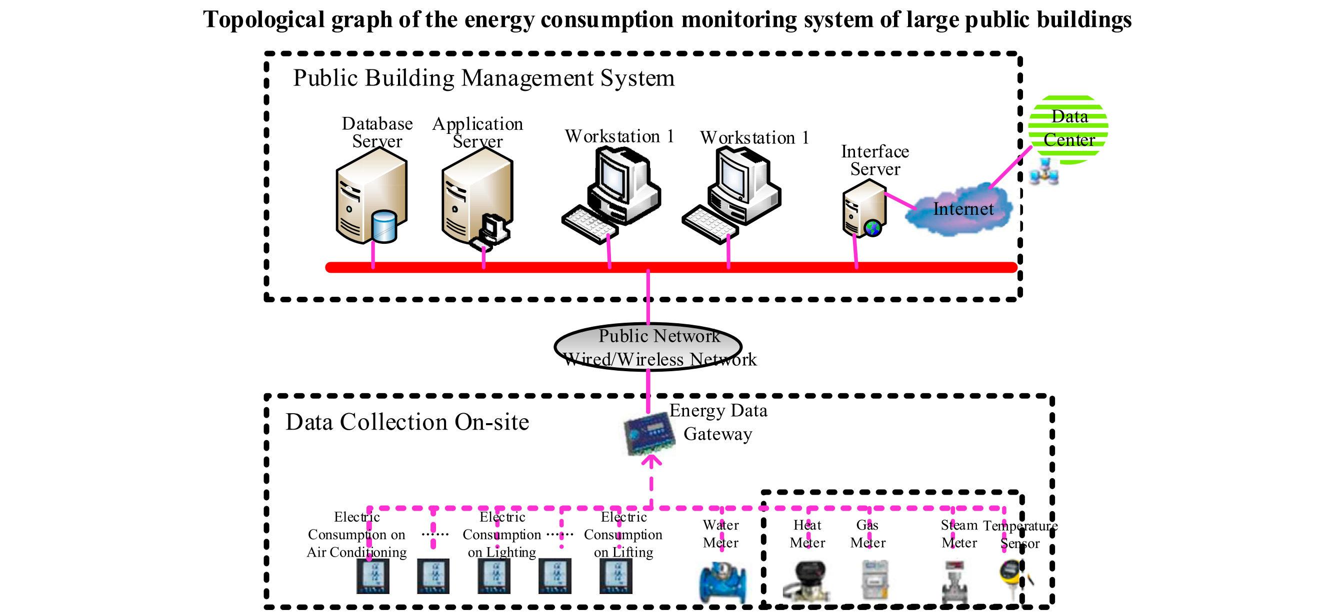

FIGURE 11 | Topological graph of the energy-consumption monitoring system. Source: Energy-consumption monitoring platform of Xi'an

trading market in the public building sector can function smoothly.

The first measure is to issue goal-oriented stimulation policies that aim to formulate targeted carbon emission trading incentive policies in the public building sector. Successful examples from other countries indicate that, instead of being generalized and mutually contradictory, all policies of emission reduction and energy conservation are independent and aimed to achieve corresponding goals. The British carbon fund, for example, was established to undertake the responsibilities as outlined in the Kyoto Protocol to reduce GHG emissions. Therefore, supportive documents about finance, regulation, stimulation, and inspection should be presented prior to introducing the carbon emission trading mechanism in the public building sector. This will clarify the obligations and responsibilities of carbon emission trading stakeholders, such as public building owners, property sectors, construction units, materials and equipment suppliers, design units, and government regulatory agencies.

The second measure establishes special funds for carbon emission trading in the public building sector. Here, trading participants who are actively engaged in energy conservation and emission reductions should receive priority when subsidizing. These can be identified through energy-conservation renovation, construction of green buildings, green low-carbon technologies, and use of renewable energy. Currently, the application of energy-conservation technologies introduced by local governments is subsidized by area. For example, the subsidy for solar energy projects is 200 yuan/m^2 by the collector area. For demonstration projects of renewable energy buildings that use ground source heat pump technology, the subsidy is 30 yuan/m^2 by the load area. This subsidy method is not based on energy savings; therefore, when subsidizing public buildings that are involved in carbon emission trading, the energy savings and costs of related energy-conservation technologies need to be considered.

For public building owners, the appropriate subsidy amount can be estimated by the energy-conservation and emission-reduction-investment decision model established as **Eq. 14**:

$$\begin{cases} P_c^* = \dfrac{\beta}{\beta - 1}\left(r - \mu_c\right)(1-\theta)C \\ \beta = \dfrac{1}{2} - \dfrac{\mu_c}{\sigma_c^2} + \sqrt{\left(\dfrac{1}{2} - \dfrac{\mu_c}{\sigma_c^2}\right)^2 + \dfrac{2(r+\lambda)}{\sigma_c^2}} \end{cases} \tag{14}$$

The solar water heating technology of a public building in Xi'an is used as an example. The proportion of subsidy that the government should provide for the owners when the carbon price is fixed is calculated. Let $P_c^* = 80$ yuan/t of CO_2, $r = 0.059$, $\mu_c = 0.01$, $\sigma_c = 0.1$, $\lambda = 1$, $C = 1{,}543$ yuan, and $\theta = 0.0175$; therefore, the subsidy amount (yuan/kwh) that the government should give to the public building owners who invest in energy-conservation technologies can be calculated. It can be expressed as a subsidy amount (yuan/kwh), which is equal to the cost of energy savings per unit (yuan/kwh) times the subsidy proportion.

According to **Eq. 14**, the subsidy amount is related to the carbon price and the technology-based emission-reduction cost. Let $C = 1{,}543$ yuan, and observe the change of θ with P_c. The results are shown in **Table 3**. When the carbon price decreases, higher government subsidies are required to encourage emission-reduction investment by public building owners. However, when the carbon price increases to a certain level, the owners will be willing to invest and participate in the carbon emission trading even without governmental subsidies.

TABLE 3 | The proportion of government giving subsidies to owner for investment of carbon-emission reduction under different carbon prices.

P_c	10	20	30	40	50	60	70	80	90	100	110
θ	0.877	0.754	0.632	0.509	0.386	0.263	0.140	0.018	−0.105	−0.228	−0.351

TABLE 4 | The proportion of government giving subsidies to owner for investment of carbon-emission reduction under different technical costs.

C	1,400	1,500	1,600	1700	1800	1900	2000	2,100	2,200	2,300	2,400
θ	−0.083	−0.011	0.053	0.108	0.158	0.202	0.242	0.278	0.311	0.341	0.368

TABLE 5 | Bonus penalty strategy.

Range of the difference	Fine (yuan)
A=$(Q\text{-}Q_0)/Q \times 100\% \in (0,\ a\%]$	$\overline{P}_C(Q - Q_0)$
B=$(Q\text{-}Q_0)/Q \times 100\% \in (a\%,\ b\%]$	$2\overline{P}_C(Q - Q_0)$
C=$(Q\text{-}Q_0)/Q \times 100\% \in (b\%,\ \infty)$	$3\overline{P}_C(Q - Q_0)$

Let P_c = 80 yuan/t of CO_2; the change of θ with C is shown in **Table 4**. After the costs of technology-based emission reduction have been lowered to a certain level, even without government subsidies, public building owners will still choose to invest in emission reduction and participate in carbon emission trading.

The construction-related management department shall, in combination with the carbon emission trading management department, conduct research on the costs corresponding to energy savings per unit of various energy-conservation technologies. Relevant standards should be introduced so that public building owners can better invest in emission reduction and make appropriate trading decisions.

The third method is to provide tax preference or convenient loan services. Proper tax preference or subsidies should be directed to owners who are actively engaged in carbon emission trading and who invest in emission reductions. Alternatively, subsidized funds can be used to help trading agents purchase quotas for their participation in carbon emission trading. This not only stimulates the demands of the trading market, but also realizes subsidization. Furthermore, financial institutions are encouraged to provide loans to public building owners or energy service companies that actively participate in carbon-emission reduction.

Multi-Level Punitive Measures

The carbon emission trading mechanism for public buildings is still in its pilot stage, which lacks the protection of laws and regulations. Therefore, to achieve the goals of energy conservation and emission reduction, the policies, regulations, laws, rules, and systems concerning public building energy conservation must be comprehensively considered, and corresponding punitive measures must be taken.

The first measure is to impose a fine. For those who do not participate in carbon emission trading and who are responsible for illegal emissions, a penalty is specified based on the amount of illegal discharge. A bonus penalty strategy should be adopted (e.g., grading pricing is implemented for the part of carbon emissions that exceeds the emission quota). The higher the amount of excessive emissions, the higher the price will be. Suppose the average carbon price of the trading market is $\overline{P}_C$ over a period of time; then, the total carbon-emission quota of a public building owner is Q_0, and the total carbon-emission amount of public buildings is Q. According to the bonus penalty strategy, different fines are imposed. As shown in **Table 5**, the ranges of A, B, and C directly reflect the degree of punishment of the public building owners. The larger the range of B and C, the greater the punishment imposed on owners who fail to perform as required.

Moreover, the typical carbon emission trading systems in foreign countries can be used as examples. For instance, in the EU market, if the carbon emissions of a trader exceed the assigned quota, the trader will be punished for excessive portions. The excess will be deducted from the quota of the next year. In New Zealand, if a trader who is forced to reduce carbon emissions intentionally fails to fulfill their obligations, they will be subject to legal accountability. Failing obligations due to negligence will be punished with a fine, which will be doubled if non-compliance occurs again. These negative incentives can effectively force public building owners to actively reduce energy consumption.

The second measure is to cause loss of reputation. Disclosure of public building owners who do not participate in carbon emission trading and who violate emission rules can cause loss of reputation and encourage financial institutions to cancel their loans.

A Policy-Support Mechanism for Trading Activities of Public Building Owners

Due to the large number of public building owners and various interest demands, their trading behaviors differ greatly. To guarantee the rights of traders, relevant policies and regulations are required to guide and protect them. The carbon emission trading market is strongly policy-oriented, highly risky, and professional, involving issues of environmental property rights. Only a sound legal and regulatory policy system can appropriately contribute to the formation of a carbon emission trading market; such a system would regulate and restrict the operation of the market to ensure fair and equitable trading. Therefore, prior to the formation of a national public building carbon emission trading market, relevant laws and regulations need to be issued. These include detailed rules for quota allocation, transaction procedures, verification methods, regulatory measures, incentive measures, and punitive measures. Legislation needs to come first and serve as a legal reference for trading behaviors, thus reducing poor trading behaviors.

CONCLUSION AND OUTLOOK

Based on the high energy consumption of the operation of public buildings, this paper uses the real option theory to construct a carbon-emission reduction investment decision model for public building owners from both macro and micro perspectives, and it assesses the impact of the characteristics of public buildings and various uncertainties on carbon trading investment. Furthermore, an external coordination mechanism for carbon emission trading in the public building sector is established to ensure efficiency for owners from decision-making to the close of transactions. Through this analysis, the following conclusions have been reached.

First, carbon price is important in adjusting the emission reduction of different owners to minimize the total social cost of emission-reduction measures. By applying economic theories from a macro perspective, this paper analyzed the impact of carbon price as an incentive for and constraint on the decision-making behavior of property owners after they enter the carbon emission trading market. Price fluctuations indicate the process of regulating the supply and demand of the carbon-emission permit among public building owners in the trading market. During this process, the allocation of carbon emission trading in the field of public building energy conservation is continuously optimized.

Second, the price of carbon-emission permits has a significant impact on the investment threshold and decision-making behavior of public building owners. Considering several uncertain factors, an emission-reduction investment-decision model was established under the constraint of a total amount, which was based on the micro perspective. Meanwhile, combined with a case study, this paper simulated and analyzed the factors of public building owners' behavior decisions and explored the influence of carbon price on the emission-reduction-investment decision-making behavior of public building owners.

Third, based on the macro and micro perspectives of the impact of carbon price on the main trading behavior and emission-reduction-investment decisions, we identified effective means to encourage and restrain public building owners to participate in carbon emission trading. That is, to ensure the small fluctuation of carbon prices within a reasonable range, reduce the technical cost of energy conservation and emission reduction of public buildings and appropriately subsidize the owners' emission-reduction investment.

Moreover, this paper constructs an external coordination mechanism for carbon emission trading for public buildings while fully considering the incentive and restraint behavior of the building owners. The includes the risk-analysis mechanism, the technical-guarantee mechanism, and the policy-support mechanism. Based on the current research results, the following issues can be further studied in the future. First, this study enables a comparative analysis of the behavioral strategies of public building owners who participate in carbon emission trading of different types, in different countries, and in different regions, according to prevailing socio-techno-economic conditions. Due to case limits, this paper only used one case to numerically analyze the behavioral strategies of these owners. However, conducting further comparative studies on owners' decisions will help to set different carbon emission trading policies (Fu et al., 2020; Li et al., 2021). Also needed is an in-depth study of the risks associated with the introduction of carbon emission trading market mechanisms in the public building sector. The relationship between macro economy and carbon trading market still needs to be studied in the future. During the early phase of the carbon emissions trading market, environmental investment is associated with higher risk, and its payback period can reach 100 years or more. In contrast to general investment projects, the risk greatly impacts the formation of the carbon emissions trading market in the public building sector. Therefore, it is necessary to classify the risks that are introduced with the implementation of a carbon emission trading mechanism in the public building sector. Furthermore, to analyze the possible impacts in detail, a risk aversion system needs to be formulated, a basis for the government to formulate relevant policies needs to be provided, and public building owners require help to make investment decisions scientifically.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization, LL; methodology, MD; software, XG; validation, LL; formal analysis, MD; data curation, YW; writing—original draft preparation, MD and LL; writing—review and editing, XG; visualization, LL and MD; supervision, LL; project administration, LL; and funding acquisition, LL. All authors have read and agreed to the published version of the manuscript.

FUNDING

This research was supported by the National Key R&D Program of China (grant no. 2018YFD1100202), the Ministry of Education Humanistic and Social Science Program of China (grant no. 19YJC630080), the General Project of Shaanxi Province Soft Science Research Program (grant no. 2019KRM197), the Philosophy and Social Science Research Program of Education Department of Shaanxi Province (grant no. 12JK0070), and the Shaanxi Social Science Fund General Project (grant no. 2015R006).

ACKNOWLEDGMENTS

The authors would like to thank the comments and suggestions of reviewers for their important help in improving the quality of this article.

REFERENCES

Anger, A. (2010). Including Aviation in the European Emissions Trading Scheme: Impacts on the Industry, CO2 Emissions and Macroeconomic Activity in the EU. *J. Air Transport Manag.* 16 (2), 100–105. doi:10.1016/j.jairtraman.2009.10.009

Astiaso Garcia, D., Cumo, F., Tiberi, M., Sforzini, V., and Piras, G. (2016). Cost-Benefit Analysis for Energy Management in Public Buildings: Four Italian Case Studies. *Energies* 9 (7), 522. doi:10.3390/en9070522

Burciaga, U. M. (2020). Sustainability Assessment in Housing Building Organizations for the Design of Strategies against Climate Change. *Hightech. Innov. J.* 1 (4), 136–147. doi:10.28991/hij-2020-01-04-01

Cansino, J. M., Román, R., and Ordóñez, M. (2016). Main Drivers of Changes in CO2 Emissions in the Spanish Economy: A Structural Decomposition Analysis. *Energy Policy* 89, 150–159. doi:10.1016/j.enpol.2015.11.020

Chen, Y., and Tseng, C. L. (2008). Climate Policies and the Power Sector: Challenges and issues[J], *Journal of Energy Engineering* 134(2):31-32. doi:10.1061/(asce)0733-9402(2008)134:2(31)

Chen, Y., Jiang, P., Dong, W., and Huang, B. (2015). Analysis on the Carbon Trading Approach in Promoting Sustainable Buildings in China. *Renew. Energ.* 84, 130–137. doi:10.1016/j.renene.2015.06.062

Chèze, B., Chevallier, J., and Alberola, E. (2009). Emissions Compliances and Carbon Prices under the EU ETS: A Country Specific Analysis of Industrial sectors[J], *Journal of Policy Modeling* 31(3):446-462. doi:10.1016/j.jpolmod.2008.12.004

Dales, J. H. (2002). *Pollution, Property & Prices: An Essay in Policy-Making and economics[M]*. London UK: Edward Elgar Publishing.

Fu, H., Manogaran, G., Wu, K., Cao, M., Jiang, S., and Yang, A. (2020). Intelligent Decision-Making of Online Shopping Behavior Based on Internet of Things. *Int. J. Inf. Manag.* 50, 515–525. doi:10.1016/j.ijinfomgt.2019.03.010

IPCC (2014). Sobre el Cambio Climático P I. Cambio climático 2014: Impactos, Adaptación y Yulnerabilidad. Contribución del Grupo de Trabajo II al Quinto Informe de Evaluación del Grupo Intergubernamental de Expertos Sobre el Cambio Climático. Resumen para Responsables de Políticas[J]. 2014.

Jin, J., Zhang, X., Xu, L., Wen, Q., and Guo, X. (2021). Impacts of Carbon Trading and Wind Power Integration on Carbon Emission in the Power Dispatching Process. *Energ. Rep.* 7, 3887–3897. doi:10.1016/j.egyr.2021.06.077

Kumarappan, S., and Joshi, S. (2011). Trading Greenhouse Gas Emission Benefits from Biofuel Use in US Transportation: Challenges and Opportunities. *Biomass and Bioenergy* 35 (11), 4511–4518. doi:10.1016/j.biombioe.2011.09.018

Li, L., Sun, W., Hu, W., and Sun, Y. (2021a). Impact of Natural and Social Environmental Factors on Building Energy Consumption: Based on Bibliometrics. *J. Building Eng.* 37, 102136. doi:10.1016/j.jobe.2020.102136

Li, L., Wang, Y., Wang, M., Hu, W., and Sun, Y. (2021b). Impacts of Multiple Factors on Energy Consumption of Aging Residential Buildings Based on a System Dynamics Model--Taking Northwest China as an Example. *J. Building Eng.* 44, 102595. doi:10.1016/j.jobe.2021.102595

Li, W., Chien, F., Ngo, Q.-T., Nguyen, T.-D., Iqbal, S., and Bilal, A. R. (2021c). Vertical Financial Disparity, Energy Prices and Emission Reduction: Empirical Insights from Pakistan. *J. Environ. Manage.* 294, 112946. doi:10.1016/j.jenvman.2021.112946

Liu, J., Liu, Y., Yang, L., Liu, T., Zhang, C., and Dong, H. (2020). Climatic and Seasonal Suitability of Phase Change Materials Coupled with Night Ventilation for Office Buildings in Western China. *Renew. Energ.* 147, 356–373. doi:10.1016/j.renene.2019.08.069

Liu, W., and Dai, Y. (2004). A Review on the Emission Permits Trade of Carbon in China. *Probl. For. Econ.* 4, 001. doi:10.16832/j.cnki.1005-9709.2004.04.001

Luo, X., and Liu, Y. (2021). A Multiple-Coalition-Based Energy Trading Scheme of Hierarchical Integrated Energy Systems. *Sust. Cities Soc.* 64, 102518. doi:10.1016/j.scs.2020.102518

Luo, X., Liu, Y., Feng, P., Gao, Y., and Guo, Z. (2021). Optimization of a Solar-Based Integrated Energy System Considering Interaction between Generation, Network, and Demand Side. *Appl. Energ.* 294, 116931. doi:10.1016/j.apenergy.2021.116931

Luo, X., Liu, Y., Liu, J., and Liu, X. (2019). Energy Scheduling for a Three-Level Integrated Energy System Based on Energy Hub Models: A Hierarchical Stackelberg Game Approach. *Sust. Cities Soc.* 52, 101814. doi:10.1016/j.scs.2019.101814

Montgomery, W. D. (1972). Markets in Licenses and Efficient Pollution Control Programs. *J. Econ. Theor.* 5 (3), 395–418. doi:10.1016/0022-0531(72)90049-x

Perino, G., and Willner, M. (2017). EU-ETS Phase IV: Allowance Prices, Design Choices and the Market Stability reserve. *Clim. Pol.* 17 (7), 936–946. doi:10.1080/14693062.2017.1360173

Qi, S.-z., Zhou, C.-b., Li, K., and Tang, S.-y. (2021). The Impact of a Carbon Trading Pilot Policy on the Low-Carbon International Competitiveness of Industry in China: An Empirical Analysis Based on a DDD Model. *J. Clean. Prod.* 281, 125361. doi:10.1016/j.jclepro.2020.125361

Song, X., Lu, Y., Shen, L., and Shi, X. (2018). Will China's Building Sector Participate in Emission Trading System? Insights from Modelling an Owner's Optimal Carbon Reduction Strategies. *Energy policy* 118, 232–244. doi:10.1016/j.enpol.2018.03.075

Xu, L., and Wang, C. (2018). Sustainable Manufacturing in a Closed-Loop Supply Chain Considering Emission Reduction and Remanufacturing. *Resour. Conservation Recycling* 131, 297–304. doi:10.1016/j.resconrec.2017.10.012

Zhang, Y., Guo, S., Shi, X., Qian, X., and Nie, R. (2021). A Market Instrument to Achieve Carbon Neutrality: Is China's Energy-Consumption Permit Trading Scheme Effective?. *Appl. Energ.* 299, 117338. doi:10.1016/j.apenergy.2021.117338

Zorer Gedik, G., Yüğrük Akdağ, N., Kiraz, F., et al. (2017). Evaluation of Mass Housing Settlements in Terms of Wind and Noise Control: Istanbul and Diyarbakir as a Case[J]. *J. Environ. Eng. Landscape Manag.* 25 (4), 389–401. doi:10.3846/16486897.2017.1284667

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 30 August 2021
doi: 10.3389/fenrg.2021.709272

How to Promote Energy Transition With Market Design: A Review on China's Electric Power Sector

Liu Pingkuo[1]*, *Gao Pengbo*[1] *and Zhang Chen*[2]

[1]College of Economics and Management, Shanghai University of Electric Power, Shanghai, China, [2]State Grid Energy Research Institute Co., Ltd., Beijing, China

Energy transition, especially in the power industry, will lead to a significant promotion in energy sustainable development. Lots of emphases have been focused on the impact of policy on the energy transition; however, there were little studies on the role of the market. This paper will be devoted to the theoretical basis of market design comprehensively and discusses the obstacles restricting China's energy transition by using an Institution-Economics-Technology-Behavior (IETB) analysis framework (four dimensions including Institution, Economics, Technology, and Behavior). In addition, the paper provides an overview of research findings on some available market designs related to the energy transition. Of note, power spot market, power capacity market, power futures market, carbon emission market, and Tradable Green Certificate (TGC) market are highlighted and discussed with emphasis. And the effects of implementing each market on overcoming those obstacles in the energy transition process are analyzed. The review results show that the market design is as important as the policy-making; hence, it is unwise for energy transition to focus on policies and ignore markets, and the market design should be pertinent and objective. Finally, some policy recommendations and market design suggestions are put forward.

Keywords: energy transition, IETB analysis framework, obstacles to transition, market design, Sustainable development

OPEN ACCESS

Edited by:
*Chan Wang,
Guangdong University of Finance and Economics, China*

Reviewed by:
*Jay Zarnikau,
University of Texas at Austin, United States
Xiong Xiong,
Tianjin University, China*

***Correspondence:**
*Liu Pingkuo
pingoforever@sina.com*

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

***Received:** 13 May 2021*
***Accepted:** 23 July 2021*
***Published:** 30 August 2021*

Citation:
Pingkuo L, Pengbo G and Chen Z (2021) How to Promote Energy Transition With Market Design: A Review on China's Electric Power Sector. Front. Energy Res. 9:709272. doi: 10.3389/fenrg.2021.709272

INTRODUCTION

Many industrialized countries are pursuing energy transition, but their focuses are different, which has led to differences in the approaches they take. For example, the United States promotes its energy transition by making some preferential policies on the development of fossil energy (shale gas resources) and renewable energy, and the European countries are more inclined to implement a series of policies, plans, and schemes to develop a renewable economy, while Japan demonstrates a commitment to clean energy, such as the nuclear power and the offshore wind power, by improving the policy framework. Since the beginning of the 1990s, the major industrialized countries in the world have successively carried out a series of *Electricity Market Reform* or *Power Market Liberalization Reform* effectively in response to the obstacles to developing the energy and power sector (Grubb and Newbery, 2018; Letova et al., 2018). Since 2002, China has implemented two rounds of power system optimization and adjustment which are defined as China's Power System Reformation (Yang, 2015). Especially in the second round of China's Power System Reform, one of the priorities is to build a competitive market environment (Wang, 2019). While exploring ways to allocate power resources efficiently, China has ushered in another profound change—energy transition—a gradual and long-term process (Li and Wang, 2019). Currently, China is still in the low efficient and poor benefit Coal Age (Zhang and Jiao, 2018). Because of the difference with most other countries in the resource endowments, the economic-social development, and the goals of energy transition, China needs to achieve a leapfrog development from the *Coal Era* to the *Renewables Era* directly without experiencing the *Oil Era* (Li and Wang, 2019). Especially under the dual pressure of energy security and environmental protection, how to promote the sustainable energy transition has become a hot issue for China and even all the countries around the world (Sun, 2017; Yang et al., 2020). Meanwhile, the energy development mode with "sustainable transition" as the core has attracted the attention of governments, enterprises, and scholars of various countries (Shi and Wang, 2015; Staden, 2017; Safari et al., 2019). As the energy strategic thinking of "Four Revolutions" (Energy Consumption Revolution, Energy Supply Revolution, Energy Technology Revolution, and Energy System Revolution) has been improved since 2014, the Chinese government attaches great importance to the task of energy transition. In 2015, China put forward the five development concepts of "Innovation, Coordination, Green, Openness, and Sharing" which pointed out the direction for solving the worldwide problems of energy resources shortage and environmental constraints. From the perspective of institutional change, both market design and energy transition have become two parallel systems that China's power sector must adapt to at this stage. These two systems have brought both opportunities and challenges for the development of China's power industry from different levels.

In order to demonstrate the above problems, we first use the Institution-Economics-Technology-Behavior (IETB) analysis framework to study the obstacles to China's energy transition from the aspects of Institution, Economics, Technology, and Behavior (Liu and Wang, 2019; Zhang and Andrews-Speed, 2020). We also analyze the five market mechanisms including the power spot market, the power capacity market, the power futures market, the carbon emission market, and the Tradable Green Certificate (TGC) market and then consider the effects of implementing those five markets focusing on whether the five markets mentioned in this article can solve the obstacles encountered in China's energy transition process. At the same time, we hope that this research can provide some practical methods and approaches for the sustainable development of power industry.

LITERATURE REVIEW

Worldwide, there are many mechanisms for promoting the energy transition (especially for advancing clean energy development). Some of the experienced countries pin their hopes on the electric power market design since the issue of clean energy consumption has already been fully considered in the design process of power markets (Shi et al., 2017). However, most of the current research on the driving factors of energy transition just focuses on the supporting policies (Matthew and Jennie, 2017; Shi, 2017; Munro and Cairney, 2020). For example, in terms of investment and financing policies, Fan and Hao (2020) studied the relationship between investment and renewable energy consumption by the Vector Error-Correction Model, believing that targeted direct investment will make a significant boost on renewable energy and accelerate China's energy transition process (Fan and Hao, 2020). Will and Strachan (2012) focused on the relationship between energy investments and energy service demands by adopting the Two-stage Stochastic Energy System Model, pointing out that large energy investments will be required in the United Kingdom to meet the needs for new energy in the future development process (Will and Strachan, 2012). Based on the subsidy, by considering the 92 renewable energy listed enterprises of China between 2007 and 2016 as samples, Yang et al. (2019) used the Panel Threshold Effect Model to explore the effects and differences regarding both government subsidy types and enterprise sizes, proving that government subsidies are the main force supporting China's energy transition (Yang et al., 2019). Monasterolo and Raberto (2019) also had a discussion on the negative socioeconomic and environmental externalities associated with fossil fuel subsidies, finding that renewable subsidies contribute to foster the low-carbon transition (Monasterolo and Raberto, 2019). With respect to the tax policy, Lin and Jia (2019) used the dynamic recursive Computable General Equilibrium model to analyze the impact of the energy tax on the energy-economy-environment (3E) system, showing that taxes on energy production sectors may be an effective way to reduce CO_2 emissions, and promote clean energy development (Lin and Jia, 2019). Wang et al. (2019) used a Differential Game Model to conduct a research on the possibility of the carbon tax affecting the strategy and performance of low-carbon technology sharing among enterprises, believing that carbon tax policy is the key to China's emission reduction and energy transition (Wang et al., 2019a). In addition, some scholars discussed the impact of price support policies on energy transition as well. For example, Wei and Dong (2016) summarized the historical experience of energy transition in the past three decades, finding that the price of energy services played a crucial role in creating the incentives to stimulate energy transition (Wei and Dong, 2016). Li et al. (2018) exemplified China's eight economic zones, quantified the impact of energy prices on carbon emissions, and proved that energy prices can suppress carbon emissions through some relevant factors which include economic development, industrial structure, energy efficiency, energy investment, and energy consumption (Li et al., 2018).

To make the research objective clear, we must consider the following four points: 1) "Energy Transition" is aimed at solving the energy security and environmental protection issue to promote high-quality economic and social development (Jin, 2016). 2) "Energy Transition" is supposed to promote a steady increase in the shares of new energy production and consumption in the total energy output and the total consumption (Xie et al., 2017). 3) "Energy Transition" should rationally enhance the cost advantage or the competitive advantage of renewable energy (Sun, 2018). 4) While the process exhibits the attributes of

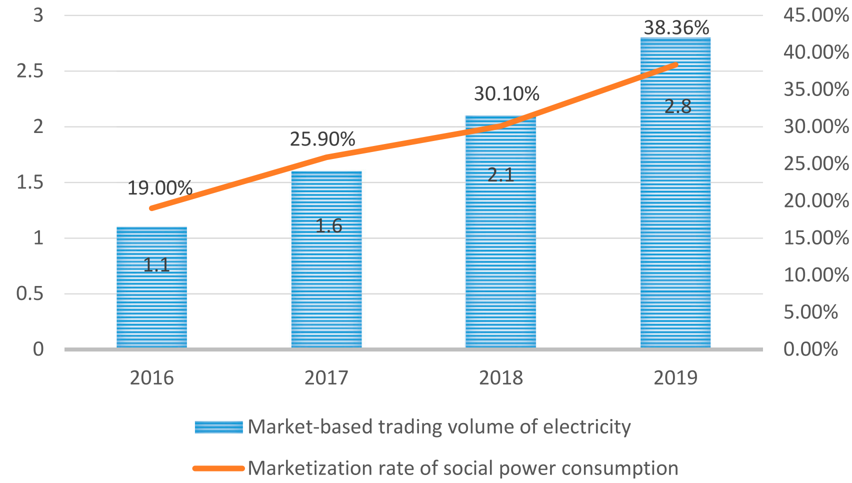

FIGURE 1 | 2016–2019 power market traded electricity and its share in the nation's power consumption (unit: trillion kWh, %).

permanency, systematicness, and complexity (Solano-Rodríguez et al., 2018), "Energy Transition" should also make a difference to a synergistic, orderly, and high-quality development of energy sector (Baležentis and Štreimikienė, 2019). In addition, even if we can effectively intervene in the transition through policies, China still faces problems, such as high power consumption, large infrastructure investment, unreasonable energy structure, and high reform costs (Shi et al., 2017), which directly lead to the difficulty of accelerating the pace in the short term. Therefore, a market-oriented optimization for adjusting energy structure, reducing inefficient supplies, and expanding effective demands will become the consensus. At the same time, from the long-term perspective of China's institutional changes and social development, both the market design and the related institutional arrangements have become an important tool to promote the power transition and advance the synergistic, orderly, and high-quality development.

The remainder of this paper is organized as follows: *Section 3* presents the development status of China's power market and some current obstacles to China's energy transition. The emphasis is laid in *Section 4* which discusses the five market mechanisms and their implementation effects to reflect the importance of market design on promoting the energy transition. At last, *Section 5* displays the conclusions and policy recommendations.

Current Situation

Development Status

The most active transaction mode in China has gradually shifted from the medium- and long-term contract transactions to the power spot (day-ahead) market transactions already. The transaction volume via China's power market (including power generation trading volume) totaled 2.1 trillion kWh with a 29% year-on-year growth in 2018 and reached 2.8 trillion kWh in 2019. **Figure 1** shows the transaction volume in China's power market from 2016 to 2019.

Power spot market: At the beginning of the *Reform*, the Chinese government tentatively selected eight provinces as the power spot market pilots which have been put into operation in June 2019. Among all the pilots, Guangdong Province has made the fastest progress, releasing its spot market design scheme in August 2018. China's cross-regional spot markets for renewable energy have started to operate since 2017, but the transaction scale of renewable energy is relatively small. In 2017, the spot market for renewable energy achieved 6.0 billion kWh of renewable power transaction (the electricity consumption of the whole society in 2017 was 6.3 trillion kWh). In particular, Gansu Province is the largest trader with electricity sales of 2.4 billion kWh in the first half of 2018.

Electricity capacity market: There are some countries, such as the United States, the United Kingdom, and France, which have launched the electricity capacity market transactions. At present, China is also actively building the power capacity market, starting from the basic national conditions of China's market construction (Chen et al., 2020). Therefore, China is trying to learn the successful experience from those industrialized countries and construct the capacity market as soon as possible. This is not only a solution to the reduction in the reform costs but also a requirement to ensure the long-term safe supply of electricity in the future (Chen, 2018).

Power futures market: At present, the development of China's power futures market is still in the preliminary stage. The common view in politics, academia, and business is that China's power futures market will be helpful to reduce the risk of energy transition. Currently, the focus on China's power futures market is mainly about the operation principle, unfortunately without enough research or practice on the power market futures trading mechanism, rules, or risk management (Du et al., 2018).

Carbon emissions market: In 2012, the Chinese department of National Development and Reform Commission (NDRC) decided to launch carbon emissions trading (ET) pilots across the country, and identified Beijing City, Tianjin City, Shanghai City, Chongqing City, Guangdong Province, Hubei Province, and Shenzhen City as the seven carbon ET pilots. In 2013, Shenzhen took the lead in launching actual transactions. Subsequently,

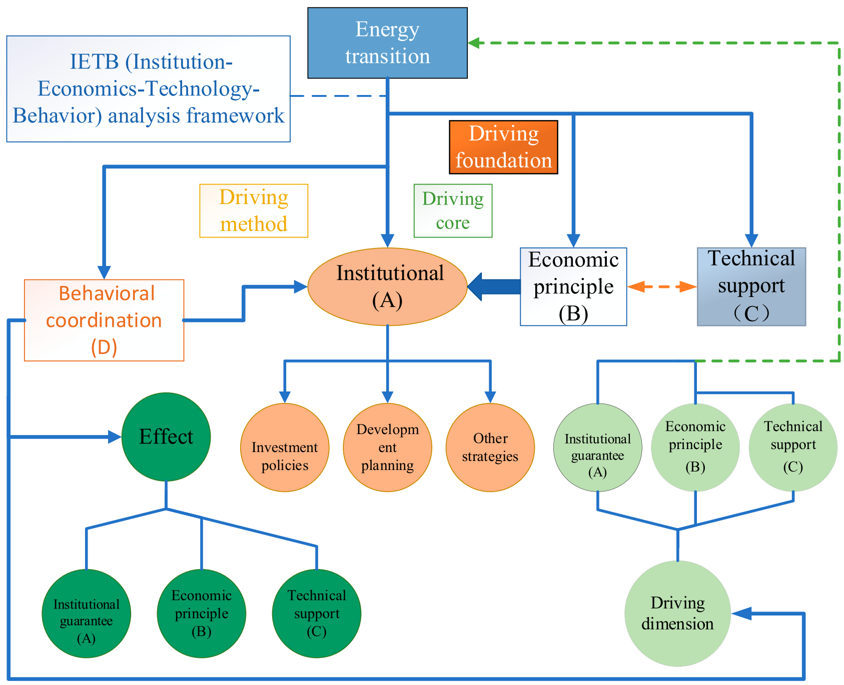

FIGURE 2 | IETB conceptual analysis framework.

other pilot provinces and cities also started the operation as well. As of the end of October 2019, the trading volume of carbon emission allowances in the pilots reached 347 million tons of carbon dioxide equivalent, with a transaction volume of approximately $1,077 million[1]. On December 19, 2017, the NDRC issued the "National Carbon Emissions Trading Market Construction Plan (Power Generation Industry)" which officially launched the construction process of the carbon ET market.

TGC market: As early as around 2012, China began to conceive of this market as well as the Renewable Portfolio Standard. In 2017, China established a voluntary subscription market for Green Certificates, but there was no renewable energy quota system supporting the voluntary subscription market. As of February 2020, China has issued a total of 27,161,607 green certificates. In particular, wind power projects issued a total of 23,315,779 wind power green certificates, and photovoltaic projects issued a total of 3,845,828 photovoltaic green certificates.

Barriers to Transition

Liu et al. (2019) built an IETB analysis framework (**Figure 2**) for discussing the energy transition issue (Liu et al., 2019). The institutional is the driving core for energy transition, which is mainly reflected in investment policies, development planning, and other strategies. In addition, the institutional guarantee also constitutes an important link connecting the technical support, the economic principle, and the behavioral coordination. The technical support and the economic principle form the driving foundation of energy transition, and both of them have a significant interaction relationship. The behavioral coordination, as the driving method of energy transition, not only can reflect the effect of the technical support, the economic principle, and the institutional guarantee but also can feedback the driving dimension of three of them.

Institutional Barrier

1) Supervision of industry is not sufficient (Ding, 2020). The "Renewable Energy Law of the People's Republic of China" (2006) stipulates the rights and obligations of the related government departments and the enterprises concerned (power grid enterprises, gas and heat pipe network enterprises, and oil sales enterprises). However, due to the ineffective supervision of the main responsibilities (Ding, 2020), it is difficult to impose fines on those irresponsible enterprises in the specific implementation. Since the implementation of this *Law*, no administrative penalty has been given to either the enterprises or the relevant departments for violation of the *Law*.
2) The enduring-effect system is not perfect (Li and Cai, 2016). At this stage, in the renewables' development, some renewables enterprises have always been pursuing high returns on investment blindly owing to the lag in electricity price adjustment and the deficiency in market function, which makes the irrational investment issues become increasingly prominent (Ding, 2020). Some localities have not effectively controlled the scale of renewable energy development in accordance with national plans, which leads to lots of

[1] 1 USD = 7.1315 RMB.

difficulties for some renewable energy enterprises to operate without government subsidies.

3) The ability to plan as a whole is poor (Cao and Zhou, 2017). Without constraints on renewables development goals or overall plans, some localities have been misled by not strictly following the national target for the development and utilization of renewables. Some development goals of local plans exceed the development goal of the superior plan. And even the construction scale, the industrial layout, and the development speed are also inconsistent with the superior planning (Ding, 2020). For example, the national "13th Five-Year Plan (2016–2020)" determined that the wind power development target in the Xinjiang Uygur Autonomous Region should be 18 million kilowatts, while the local "Xinjiang's Renewable Energy 13th Five-Year Plan" (2016–2020) determined that wind power development target should be 36.5 million kilowatts.
4) The interprovincial transactions are not smooth (Wu et al., 2019). The barriers are mainly formed by institution, system, and the like. The interprovincial barriers to power trading not only hinder the cross-regional flow of power resources but also lead to the bad phenomenon of local segregation and market blockade (Zhou, 2019). In 2017, the share of new energy curtailment caused by the interprovincial barriers accounted for more than 40% of the total curtailment. Specifically in 2018, the total electricity quantity traded in the national power market was about 2.1 trillion kWh. The electricity quantity traded in the provincial market was 1,688.5 billion kWh, while the quantity traded in the interprovincial (including the cross-regional) market was 347.1 billion kWh (accounting for 16.8% of the total quantity traded in the national market). Hence, there is still a large room for interprovincial electricity transactions. The interprovincial barriers have resulted in the division of power markets in various provinces, which is greatly restricting the unified development.

Economic Barrier

1) The government finance is overburdened (Cao and Zhou, 2017). The rapid increase in installed capacity of wind power and photovoltaic power has caused a huge gap in the renewable energy development fund. China's renewable energy subsidy gap has exceeded $9.815 billion in 2016, $14.022 billion in 2017, and $16.827 billion in 2018 and has further expanded in 2019. During 2016–2020, more than 90 percent of the subsidies for new renewables projects have not yet been implemented. Without the timely support of government transfer payment, the financial difficulties have plagued the survival and development of renewables enterprises, which makes the energy transition suffer badly.
2) The investment in power supply is insufficient (Zhang and Tang, 2016). There always are power shortages or power surpluses during the evolution of China's power system. Policymakers, businessmen, and experts always have certain concerns; that is, if the market system changes from fair dispatch to economic dispatch rapidly, the existing coal-fired power plants in the system will bear great pressure. Meanwhile, such a change may also lead to insufficient power investment in the future, and thus a systemic power shortage will occur again. China's power investment would be $743.182 billion during the "12th Five-Year Plan period" (2011–2015) and $813.229 billion during the "13th Five-Year Plan period" (2016–2020), which means that the "13th Five-Year Plan" investment increased just by 9.4% compared with the "12th Five-Year Plan" one. How to maintain sufficient investment in the power system with a high share of renewables is an important task to ensure the sustainability of China's energy transition.
3) The private capital is active without rational reasons (Lin, 2016). Since 2009, the Chinese government has continuously launched a series of support policies for new energy, which fully reflects the government's ambition to develop the new energy industry. However, these policies have also led to the rapid growth of private investment in the new energy sector, which has caused a disorderly development of new energy to a certain extent. For example, the great majority of investment projects are directly in the wind power plants and the solar power plants, while the minority of investment projects is in the biomass power and others. Enthusiastic private capital, in the absence of rational regulation, is easy to cause imbalance in the development and utilization of new energy (Zhao, 2016a).
4) The new mode of economic development could bring new challenges (Ma and Li, 2019). Data from 1991 to 2015 as a sample show that the growth of new energy consumption has a positive relationship with China's economic growth (Xu, 2017). China's economic development mode has shifted from the extensive growth of scale and speed to the intensive growth of quality and efficiency. And the economic growth rate has rationally slowed down. However, the new energy industry needs huge capital and labor input in the early stage of construction. Therefore, the high costs and low benefits will inevitably become the biggest obstacle restricting the further energy transition of China's new energy industry (Chen, 2015).

Technical Barrier

1) The ability of power system access and grid connection is still weak (Sun et al., 2017). China's current electricity pricing mechanism requires that the Grid Corporation should pay a local-benchmark electricity-price-based feed-in tariff to the grid-connected wind power plants and the photovoltaic power ones, and the governments make up the difference between the subsidized renewable electricity price and the coal-fired electricity price. Therefore, the Grid Corporation cannot increase its profitability by absorbing more renewables. On the contrary, receiving volatile renewable energy connecting the grid may affect the stability and safety of grid operation. Wind power and photovoltaic power generation have strong volatility and unpredictability. Hence, the wind/photovoltaic power generation technology conflicts with the current China's power system under strong constraints on power demand and transmission lines (Yin et al., 2015).

2) Power grid construction lags behind the renewable energy development (Li, 2019). The unsynchronized construction progress leads to the insufficient scale of transmission channels. Meanwhile, the capacity of some transmission channels has not reached the desired level, which hinders the output of renewable energy power (Guo et al., 2020). For example, at the end of 2018, the installed capacity of new energy in China's Three North Regions (Northeast China, North China, Northwest China) reached 230 million kilowatts. However, due to the limited local market, it was difficult to fully accommodate so much new energy power generation in the short term. Even though the load could be transmitted across regions, the transmission capacity was only 42 million kilowatts which accounted for only 18% of the total new energy installed capacity. And what was worse, the ratio of flexible power supply in power grid is unreasonably low, while the planning and construction of storage power stations is lagging, which affects not only the stability of power grid but also the accommodation of renewable energy (Ding, 2020).
3) The issue of new energy generation curtailment is outstanding in a bad way (Li and Wang, 2019). According to the data from the China Statistics Bureau (2019), on the power supply side, China's average wind curtailment rate reached 8.7% in 2018, solar curtailment rate 3.6%, and hydro curtailment rate 5.2%. In particular, the wind and the solar curtailment have become worst in Xinjiang Uygur Autonomous Region and Gansu Province. Yunnan and Sichuan provinces have the most serious water curtailment (with the rates reaching 37.6 and 20.2%, respectively). The nationwide renewable curtailment not only caused a huge waste of energy resources but also increased the cost of new energy power generation. It objectively impeded the progress of energy transition.

Behavioral Barrier

1) The contradiction between the central government and local governments has gradually emerged (Zhou, 2019). China's thermal power projects are mature in technology and efficient in economy; hence, lots of provinces are vigorously promoting the construction of thermal power projects, which makes the current coal-fired power generation capacity severely surplus. At the same time, these projects cannot be replaced by new energy power generation projects in a short time because the newly-built coal-fired power projects are still in the debt repayment period. Additionally, the unreasonable policy incentives system and the uneven distribution of interests among governments are also the main reasons for the large deviations between the central and local energy systems. Such policy deviations also make the energy transition difficult in terms of national planning, local dispatching, and energy pricing (Cao and Zhou, 2017).
2) The conflict of interests between enterprises and governments is unsettled (Xie et al., 2014). Usually, the local governments will transfer the contradiction to the power enterprises. The sharp rise in coal prices has compressed the profitability of coal-fired power plants, thereby further increasing the contradiction between coal-fired power generation enterprises and renewable energy power generation enterprises (Ni, 2018). Some local power grid firms refused to get the new energy access to the grid just to reduce short-term investment, resulting in the fact that the nonfossil energy power output cannot be used timely and effectively. Due to the information asymmetry, some of the renewable energy power generation could get subsidized without being consumed, which not only wasted national finances but also violated the original intention of subsidy policy.

ANALYSIS AND DISCUSSION

Energy clean transition is a huge systematic project, which requires us to give full play to the role of the market in resource allocation and jointly promote the transformation of energy production and consumption patterns. By constructing a reasonable power market mechanism, it can fully tap the entire grid's consumption space, encourage traditional thermal power to undergo flexible transformation, release power-side regulation capabilities, change users' energy consumption habits, promote clean energy consumption, and promote energy-efficient transformation (Niu et al., 2014). This section will focus on analyzing the practical significance of the following five power market trading mechanisms, and discussing how market mechanisms can solve the obstacles in the process of China's energy transition.

Power Spot Market

The power spot market (**Figure 3**) in the market design framework is the core module, referring to a resource allocation platform where power suppliers and demanders search the power price and the equilibrium quantity (Gong et al., 2018). The power spot market operation system is mainly composed of the day-ahead market, balance mechanism, market risk control, and system management subsystems. It can provide an auxiliary service market subsystem, which is suitable for areas that develop auxiliary service markets such as frequency modulation and backup. Established on the basis of certain economic transactions, the power spot market design must strictly abide by the principles of mutual benefit and fair competition (Tang and Zhang, 2020). Since this type of power trading venue in the power system can connect the transmission side, distribution side, and power consumption side effectively, the power spot market will be able to guarantee the demand for energy transition in terms of new energy accommodation and energy structure adjustment (Zhou et al., 2019).

1) **Breaking down the interprovincial trading barriers and solving the volatility issue of new energy access to grid:** The main role of the intraday market in the power spot market system is to provide a trading platform for market participants. After the closure of the day-ahead market, the intraday market can fine-tune the power generation plan. In addition, the intraday market can cope with various intraday forecast deviations and unplanned problems, although the

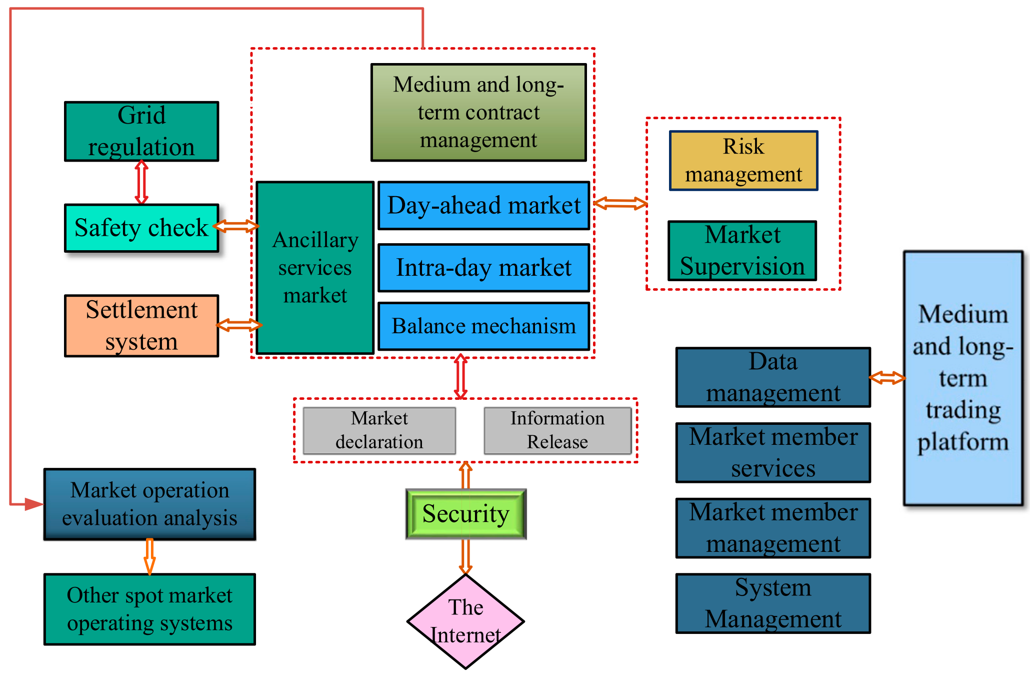

FIGURE 3 | Operating system diagram of the power spot market.

transaction size is often small (Ma et al., 2019). As more intermittent renewable energy sources are connected to power grid, the uncertainty of the renewable power generation capacities within the day will also increase greatly. The existence of the intraday market can provide institutional support for such renewable energy to participate in market competition (Zhou et al., 2019). A market-oriented renewable energy utilization mechanism can be formed by improving the mechanism design of spot market and expanding the scale of renewable energy power transactions (Ge et al., 2019). At the same time, the power spot market plays a decisive role in the allocation of resources. It can not only fully explore the interprovincial accommodation capacity of renewable energy through market competition but also alleviate the more serious problems of renewable curtailment (Zhang et al., 2018). Since the State Grid Corporation officially launched the interregional and interprovincial surplus renewable energy power spot trading pilot (2017), China's renewable energy spot market has traded six billion kW hours of renewable energy power generation in 2017. And by the end of 2018, the cumulative trading volume exceeded nine billion kWh. Hence, the power spot market can provide a commercial platform for the cross-provincial flow of new energy as well.

2) **Adjusting the energy structure:** The power spot market is an important module of a complete power market transaction system and also a vital measure of price discovery and resource optimization (Gong, 2018). At the end of 2017, the NDRC announced that the FIT for photovoltaic power trading in the market was \$0.091 to \$0.119/kWh, and the FIT for wind power trading was \$0.056 to \$0.08/kWh. In contrast, the FIT of thermal power was generally maintained at \$0.042–0.07/kWh. In such a situation, the renewable power plants selling photovoltaic or wind power at higher prices naturally would rather generate more clean electricity after ensuring that their generation can be sold through the spot market. Hence, the power spot market can achieve the purpose of expanding a clean energy market and squeezing the thermal power market, which has already been proven that the power spot market can promote the development of energy structure toward a green and clean direction through the price-driven user interaction (Peng and Tao, 2018).

Power Capacity Market

The power capacity market becomes the assistant module designed to ensure the available power load capacity during the market design. In that case, the power capacity market is an incentive mechanism (Ashokkumar Parmar and Pranav B Darji, 2020) in which a reliable power supply commitment can be offered by load demanders providing stable contract payments to capacity providers to encourage the continued investment in capacity at an affordable price (**Figure 4**). The structure design of the capacity market includes five stages: capacity quota, qualification and auction, transaction, delivery, and payment. The government conducts market guidance in the capacity quota and delivery stage, and the realization of qualifications, auctions, and transactions is completely subject to market competition. Theoretically, the power capacity market will promote a sustainable energy transition by meeting the needs of power investment incentives and promoting the optimal

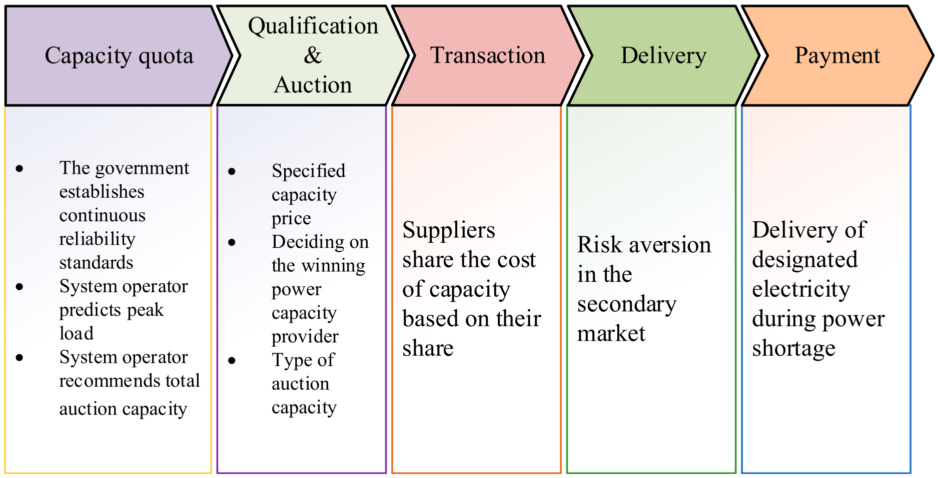

FIGURE 4 | Capacity market stage diagram.

allocation of incremental power generation resources (Chen et al.,2020).

1) **Meeting the needs of power investment incentives:** It will lead to huge power generation risks if the electric quantity market is used to regulate the shortfall of power generation capacity without the coordination with the capacity market (Li et al., 2019). The advantages of capacity market are characterized by using the investment as a variable and replacing the short-term prices with the long-term equilibrium costs, which can effectively reduce market risks (Lockwood et al., 2019). The capacity market is a mechanism that grants certain subsidies and investment recovery based on the generation capacity of power generation enterprises. Such a market mechanism is able to ensure sufficient investment in power generation capacity, avoid the risk of investment uncertainty caused by the long power construction period, and correspondingly increase the investment enthusiasm of power generation enterprises (Brown, 2018). The United Kingdom's transmission grid operator, National Grid Great Britain, needs to determine the capacity demand 3 years in advance. In December 2014, the National Grid Great Britain auctioned the 1-year reserve capacity demand starting from October 2018. In this auction, the United Kingdom government obtained 49.26 GW of capacity at a clearance price of \$24.39/(kW a)[2]. Such a mechanism stimulates new investment to build new capacities (Hou et al., 2015). As a lesson learned from the successful experience of the United Kingdom's capacity market, the power capacity market can provide solutions and ideas for solving the problem of insufficient investment in the energy transition process.

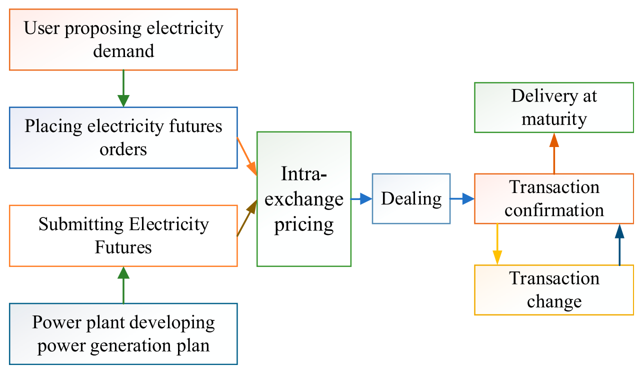

FIGURE 5 | Trading process in the power futures market.

2) **Optimizing the incremental resource allocation and solving the power safety problem caused by the connection of volatile new energy to the grid:** For a long time, China's power generation resource allocation has mainly relied on the planned economy mode. Even the "Plant-Grid Separation" scheme was basically realized during 2005–2012, the FIT of power generation enterprises still generally implemented a benchmark electricity pricing mechanism or an approved pricing model. The existence of such a situation not only makes the power generation industry blindly seek investment regardless of its own needs and interests but also objectively leads to a phased excess production capacity of power supply. On the contrary, introducing market competition through the construction of a sound capacity market will help discover the true cost of incremental power generation resources, guide the incremental power generation resources for optimal allocation, and ultimately achieve the goal of saving the overall energy cost of society. In addition, by scientifically and rationally planning the total amount and structure of power capacity demand, the capacity market is also able to

[2]1 USD ≈ 0.7954 GBP.

guide the transition of power supply to a green and low-carbon direction (Chen, 2018). The rapid development of renewable energy sources has put forward higher requirements for the system's reserve capacity of power supply, so the capacity market is one of the mainstream methods to optimize the allocation of power generation resources and increase the share of volatile new energy in power generation resources (Ashokkumar Parmar and Pranav B Darji, 2020).

Power Futures Market

The power futures transaction is a secondary market expressed as a type of risk management mechanism in which a specific quantity and quality of electricity commodity standard contracts can be delivered (**Figure 5**). In the trading process of power futures trading, auction trading is often used, which is also the basic trading method in the process of power futures trading. In the process of bidding transactions, a large number of trading members, including both sellers and buyers, are gathered on the trading platform. Then, under the guidance of the rules and regulations of the exchange, bidding transactions are completed separately for various types of power futures. Developed on the basis of electricity forward contract transactions, the power futures contracts are highly standardized during power futures trading (Spodniak and Bertsch, 2020). An advanced power futures market always has comprehensive functions of price discovery, resource allocation optimization, and risk aversion (Matthäus, 2010; Kalantzis and Milonas, 2013), and thus, it will guarantee China's energy transition in terms of energy structure optimization and market risk control (Zhang and Farnoosh, 2019).

1) **Controlling the risks and ensuring the energy security:** A mature and perfect power market should include the power futures market which is an effective supplement to the existing wholesale and retail power markets (Wang et al., 2019b). The power futures market can provide a platform for the price fluctuation management and the risk reduction in power market transactions (Nakajima, 2019). Of note, the development of futures trading in the power market will play a positive role in the risk management and control, which can help enterprises avoid risks to a certain extent through hedging and other applications (Du et al., 2018). The power futures market has the market function of price discovery which can guide the power market investment rationally (Nakajima, 2019). In addition, both the electricity producers and the consumers can have a relatively accurate estimate of both the future production costs and the future consumption costs since participants can sign long-term power futures contracts in advance. This trading mechanism reduces the risks of production and consumption to a certain extent and will help improve the safety of the entire power system. For example, Singapore Power Futures has helped competitive electricity users reduce the cost of retail electricity contracts by more than 10% since it began operations in April 2015. At the same time, the construction of power futures market is of great significance to the energy security.

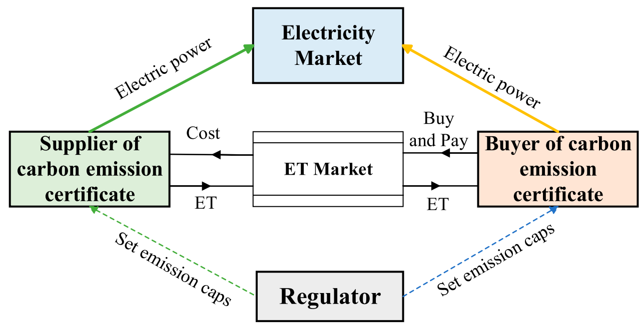

FIGURE 6 | Operation process of the carbon emissions emission mechanism.

2) **Optimizing the energy structure:** A single price in the spot market can easily deviate from its actual value, and it cannot achieve the effects of energy conservation, emission reduction, and resource allocation optimization efficiently (Stephanía and Nursimulu, 2019). The power grid system can use the price discovery function of the power futures market to scientifically and reasonably budget and plan the future power spot market (Kallabis et al., 2016). In the context of overall oversupply in the power market, low-efficiency generators can still obtain some of the planned power generation, which prevents those high-efficiency environment-protection generators from obtaining chances with a high power generation when the overall electricity consumption decreases. As a result, the utilization rate of efficient coal-fired generators is reduced. In the power futures market, the high-efficiency generators have the attributes of low coal consumption, low fuel costs, and advantages in the quotations, so they will be given priority in concentrated bidding transactions. The transaction order of low-efficiency generators should be in the back, and their transaction volume is not guaranteed, which make the low-efficiency generators gradually withdraw from the market competition (Ren, 2019). This shows that the power futures market can finally achieve the purpose of saving coal, reducing emissions, and optimizing power structure through market-oriented means.

Carbon Emission Market

The carbon emission market in the market design framework is a kind of auxiliary module in which the carbon emission right accepting the guidance and supervision with specific environmental protection objectives can be exchanged and circulated as valuable assets and scarce commodities (**Figure 6**). In the carbon emission market, carbon emission regulators set relevant carbon dioxide emission cap standards for thermal power manufacturers. Among thermal power manufacturers, those whose carbon emissions are lower than the upper limit of carbon dioxide emissions prescribed by the regulator are suppliers of carbon emission rights certificates;

those whose carbon emissions are higher than the upper limit of carbon dioxide emissions prescribed by the regulators are those who demand carbon emission rights certificates. Suppliers of carbon emission rights certificates sell their surplus carbon emission rights certificates and obtain corresponding benefits at the same time, while carbon emission rights certificate demanders must choose to purchase corresponding carbon emission rights certificates in the carbon emission rights certificate market to meet the requirements of regulators. The essence of carbon ET is to realize the re-distribution of carbon emission responsibilities in a market-oriented way (Lin and Jia, 2020). The carbon emission market is of great significance for advancing the adjustment of energy structure and promoting the accommodation of new energy (Weng and Xu, 2018).

1) **Adjusting the energy structure:** The establishment of the carbon trading mechanism not only helps to mobilize the enthusiasm of enterprises to produce clean power but also can promote the continuous increase in the share of clean energy power generation (Zhu, 2019). In terms of the carbon emission right, the implementation of carbon emission right trading system can increase the generation costs of traditional energy power generation plants, which in turn will reduce the investment in the traditional energy sector (Feng, 2016). Accordingly, the carbon emission market is conducive to the energy transition by adjusting the power supply structure and reducing carbon emissions. Some evidence suggests that the implementation of carbon trading can significantly promote the structural transformation of high-carbon energy markets and the carbon emission market can also gradually reduce the coal consumption (Yi et al., 2019). With the reduction in low-efficiency coal resource consumption and the widespread use of clean energy, the efficiency of energy use will be further improved, which is more conducive to achieving the goal of energy-saving as well as emission reduction and promoting the energy market reform (Zhang et al., 2020).

2) **Promoting the accommodation of new energy:** In the carbon trading mechanism, enterprises using traditional fossil energy are required to pay carbon emission taxes which can force high-energy-consuming enterprises to use clean energy to a certain extent. This mandatory carbon emission tax payment mechanism can also control the total regional energy consumption and transform the energy demand into clean energy consumption (Feng, 2016; Lin and Jia, 2020; Zhang et al., 2020). Shanghai Stock Exchange is the largest carbon trading exchange in China. In 2012, the Shanghai Stock Exchange realized a carbon trading volume of more than $981.5 million. In particular, the number of individual accounts opened for voluntary carbon emission reduction projects exceeded 210,000, and the trading volume accounted for about 70% of the national trading market. As of the end of 2018, China's cumulative carbon ET volume was close to 800 million tons, and its cumulative carbon ET volume exceeded $1.542 billion. The successful implementation of the carbon emission market will help the traditional fossil energy consumers transform their energy needs into clean energy (Wang et al., 2019c).

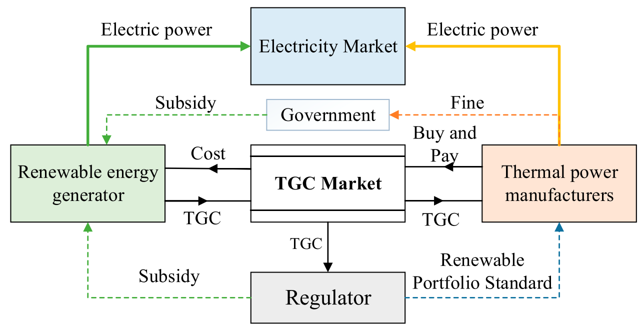

FIGURE 7 | Operation process of TGC trading mechanism.

TGC Market

The TGC market is another auxiliary module in which the TGC issued by the government is to realize both the renewable power production and the consumption as planned and expected (Song et al., 2020). Generally, a green certificate trading system is composed of green certificates, issuing agencies, transaction management agencies, management systems, and registration agencies. In the trading system, the regulator first stipulates the relevant quota standards for thermal power manufacturers, and then renewable energy generators put green certificates equivalent to their own electricity production on the green certificate market for sales; in order to meet the quota requirements of the regulatory agencies, thermal power manufacturers can either choose to purchase a corresponding number of green certificates in the green certificate market or choose to pay a certain fine to the government. Through the voluntary subscription transactions of TGC, power enterprises can complete their obligations in the TGC market (**Figure 7**) based on the Renewable Portfolio Standard (RPS) (Hustveit et al., 2015). Theoretically, the TGC market will help promote China's energy transition by reducing the government's financial burden and optimizing resource allocation (Finjord et al., 2018).

1) **Reducing the government's financial burden:** Both the implementation of RPS and the establishment of the TGC market are conducive to reducing the regulatory costs and reducing the government's financial burden (Zhao, 2016b). The introduction of market-based measures can enable the TGCs to be traded freely, which means that the government no longer needs to directly transfer the financial subsidies to support the renewable energy industry (An et al., 2019). The TGC system is a major measure to improve some renewable energy support policies and even construct some renewables development mechanisms (Tang, 2017). The TGC market not only is conducive to promoting the efficient use of clean energy and reducing the direct subsidy intensity of national

financial funds but also has a positive significance for consolidating social consensus and promoting energy transition. Some research results showed that the TGC program can not only achieve the goal of renewable electricity but also reduce both the regulatory costs and the financial burden (Ciarreta et al., 2017). As of the end of May 2018, the cumulative number of China's TGC issued was 22 million, and the cumulative number of subscriptions reached 27,190. Such an achievement directly helped the government retain $0.645 million by saving the renewable energy subsidies.

2) **Optimizing the resource allocation and alleviating the contradiction between coal-fired power generation and renewable one**: If the government only adopts the RPS system without implementing the TGC transactions to stimulate the development of renewable energy market, this kind of imperfection will lead to a significant increase in the cost of enterprises. In a policy system simply implementing the RPS, all related enterprises and market entities will be assigned consistent quotas but not allowed to trade them. At this time, different power enterprises with different marginal costs will inevitably cause terrible waste, market inefficiency. After the establishment of the TGC market, the external costs of the power industry will be internalized, and the total cost becomes the sum of production costs and external costs (Liu, 2017). Meanwhile, the equilibrium price in the power market can truly reflect the actual value of electricity commodities, which can effectively solve the problem of inefficient resource allocation. The mutual conversion of renewable energy power generation and TGCs will be able to encourage the enthusiasm of those superior renewable energy enterprises and make those disadvantaged renewable energy enterprises complete the quotas at a lower cost (Jiang et al., 2014). In addition, the very small scale of mandatory quotas can easily cause the underutilization of resources. On the contrary, the TGC market can accurately avoid such a problem and ease the contradiction between the coal-fired plants and the renewable ones. The establishment of a TGC market can promote the accommodation of renewables and increase the revenue of power generators significantly (Helgesen and Tomasgard, 2018). According to the real-time statistics of the TGC's subscription platform, as of May 31, 2019, in China, a total of 2,138 participants had subscribed for a total of 33,140 TGCs, and each TGC representing 1,000 kWh green electric power came from either the onshore wind power project or photovoltaic power plant project.

CONCLUSION AND POLICY IMPLICATION

This article comprehensively analyzed the theoretical basis of market design for promoting the energy transition and then discussed the goals and the obstacles related to China's energy transition. Accordingly, the function and role of market design have been discussed on five typical markets. In summary, the conclusions are as follows:

1) The market design is as important as the policy-making; hence, it is unwise for energy transition to focus on policies and ignore markets. The energy transition is characterized by permanency, systematicness, and complexity. The Chinese government has already successively issued a series of policies; however, China's energy transition still lack the necessary market incentives due to the imbalance in the distribution of energy endowments, the expansion of fiscal subsidy gap, the high cost of new energy technology, and especially the difficulty in implementing the policies. Many scholars and enterprises have proved the role of market design which shows a much more stable and durable effect than the role of policy-making. Of note, the market design for energy transition in electric power industry is not only to promote the vigorous development of new energy (such as the power spot market, the power futures market, and the TGC market) but also to advance the sustainable and clean evolution of traditional energy (such as the power capacity market and the carbon emission market).
2) Market design should be pertinent and objective; hence, there are at least five types of markets that can promote the energy transition of electric power sector. There are four main sources of obstacles to China's energy transition. In particular, the institutional barriers have always been the principal contradictions, and the economic barriers and the technical barriers are the core troubles, while the behavioral barriers are the important links. The spot market is an effective way to solve the volatility of new energy and realize the economic dispatch of renewables in the meantime and it can fully exploit the interprovincial accommodation space through market competition to alleviate the increasingly serious issue of renewable curtailment. The power capacity market can meet the needs of power investment incentives and promote the optimal allocation of incremental power generation resources. The power futures market is able to optimize the energy structure and control risks. The carbon emission market is an effective way to arrange the energy structure scientifically and promote the accommodation of new energy rationally. The TGC market can reduce the government's financial burden and optimize the resource allocation.
3) As far as the current situation of China's energy development is concerned, it is still far from the achievement of China's energy development goals. China should pay more attention to promoting the energy transition to not only innovate on the basis of the characteristics of its own development but also draw on the advanced experience of other industrialized countries in the field of market design. The share of nonfossil energy in primary energy consumption is a very core indicator in the process of China's energy transition, and the realization of that indicator mainly depends on the nonfossil energy power generation in the power system. Therefore, to achieve the goal of China's national energy transition, the power system must be sustainably transformed first.

Based on the conclusions above, we offer the following recommendations:

In the market design, China firstly should explore the establishment of a diversified market structure that includes a competitive power market, a cross-regional and interprovincial power trading market, and an ancillary service market. Secondly, sufficient market choices and space should be provided for the profitability of both the new energy and the conventional power sources. Finally, the design should be to promote the energy transition in electric power industry in light of a high share of new energy access. In the design of specific market rules, the volatility, uncertainty, and marginal cost of new energy power generation should be fully considered. On the one hand, it is possible to mobilize the enthusiasm of various types of power investment, especially of the flexible power supply investment, through a reasonable investment protection mechanism to ensure the long-term, safe, and reliable operation of the power system. On the other hand, the potential of flexible resources can be fully mobilized through the design of rules during the operation phase. The research on the market design is supposed to help the energy transition by providing some management, mechanism, and policy guarantees in building a formal and unified power market trading system.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

LP: supervision, conceptualization, methodology, writing, and editing. GP: data collection, writing, and reviewing. ZC: investigation and reviewing.

FUNDING

This paper is supported by the National Natural Science Foundation of China (Grant No. 72103128) and the Key Projects in Soft Science Research of Shanghai Science and Technology Commission (Grant No. 21692109400). This study received funding from the Technological Project of State Grid Corporation of China. The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

REFERENCES

An, X., Zhang, S., Li, X., and Du, D. (2019). Two-stage Joint Equilibrium Model of Electricity Market with Tradable green Certificates. *Trans. Inst. Meas. Control.* 41 (6), 1615–1626. doi:10.1177/0142331217718619

Ashokkumar Parmar, A., and Pranav B Darji, B. (2020). Capacity Market Functioning with Renewable Capacity Integration and Global Practices[J]. *Electricity J.* 33 (2), 106708. doi:10.1016/j.tej.2019.106708

Baležentis, T., and Štreimikienė, D. (2019). Sustainability in the Electricity Sector through Advanced Technologies: Energy Mix Transition and Smart Grid Technology in China[J]. *Energies* 12 (6), 1–21. doi:10.3390/en12061142

Brown, D. P. (2018). Capacity Payment Mechanisms and Investment Incentives in Restructured Electricity Markets[J]. *Energ. Econ.* 74. doi:10.1016/j.eneco.2018.05.033

Cao, L. P., and Zhou, F. Q. (2017). Research on Challenges and Countermeasures of Energy System Transition in China in the Context of Energy Revolution[J]. *Chin. J. Environ. Manage.* 9 (05), 84–89. doi:10.16868/j.cnki.1674-6252.2017.05.084

Chen, H. (2015). Analysis of the Development of China's New Energy Industry under the New normal [J]. *China Stat.* 405 (09), 55–56.

Chen, Y. G., Zhang, X., and Zhang, L. (2020). Discussion on Mechanism Design of Southern China (Starting from Guangdong) Power Capacity Market[J]. *Guangdong Electric Power* 33 (02), 45–53. doi:10.3969/j.issn.1007-290X.2020.002.006

Chen, Z. (2018). *Electricity Industry Capacity Market Urgently Needs to Be Established [N]*. Beijing: CHINA ENERGY NEWS. 2018-01-29(004).

Chen, Z., Zhang, X., and Ma, Z. M. (2020). A Capacity Market Design Guiding the Long-Term Effective Balance of Power Supply and Demand[J/OL]. Electric Power:1-7[2020-02-17]. Available at: http://kns.cnki.net/kcms/detail/11.3265.TM.20190905.1134.008.html. doi:10.11930/j.issn.1004-9649.201906029

Ciarreta, A., Espinosa, M. P., and Pizarro-Irizar, C. (2017). Optimal Regulation of Renewable Energy: A Comparison of Feed-In Tariffs and Tradable Green Certificates in the Spanish Electricity System. *Energ. Econ.* 67 (67), 387–399. doi:10.1016/j.eneco.2017.08.028

Ding, Z. L. (2020). Report of the Law Enforcement Inspection Group of the Standing Committee of the National People's Congress on the Inspection of the Implementation of the "Renewable Energy Law of the People's Republic of China"-December 15, 2019 at the 15th Meeting of the Standing Committee of the 13th National People's Congress [J]. *The People's Congress of China* (02), 11–16.

Du, J., Dong, C., and Di, P. Y. (2018). Analysis and Application of Futures Trading in Electricity Market [J]. *Mech. Electr. Inf.* 564 (30), 114–115+117.

Fan, W. Y., and Hao, Y. (2020). An Empirical Research on the Relationship Amongst Renewable Energy Consumption, Economic Growth and Foreign Direct Investment in China[J]. *Renew. Energ.* 146, 598–609. doi:10.1016/j.renene.2019.06.170

Feng, T. T. (2016). *Coupling Induction Analysis Model of Tradable Green Certificate and Carbon Emission Trading Acting on Electricity Market in China[D]*. Beijing): North Chinese Electronic Power University.

Finjord, F., Hagspiel, V., Lavrutich, M., and Tangen, M. (2018). The Impact of Norwegian-Swedish green Certificate Scheme on Investment Behavior: A Wind Energy Case Study. *Energy Policy* 123 (DEC), 373–389. doi:10.1016/j.enpol.2018.09.004

Ge, R., Chen, L. X., and Tang, J. (2019). Design and Practice of Cross-Regional Incremental Spot Market for Renewable Energy[J]. *electric power construction* 40 (1), 11–18. doi:10.3969/j.issn.1000-7229.2019.01.002

Gong, G. J. (2018). Spot Market Accelerates Service Change[J]. *China Power Enterprise Manage.* (27), 1.

Gong, G. J., Wang, H., Zhang, T., and Chen, Z. (2018). Research on Electricity Market about Spot Trading Based on Blockchain[J]. *proceedings see* 38, 6955–6966. (in Chinese). doi:10.13334/j.0258-8013.pcsee.172645

Grubb, M., and Newbery, D. (2018). *UK Electricity Market Reform and the Energy Transition: Emerging Lessons[J]*. United States: Cambridge Working Papers in Economics.

Guo, L., Wu, C., and Chen, L. (2020). Analysis on Transmission Congestion Mechanism of Cross-Region Renewable Energy Integration in Receiving-End Power Grid[J]. *Electric Power Construction* 41 (2), 21–29. (in Chinese). doi:10.3969/j.issn.1000-7229.2020.02.003

Helgesen, P. I., and Tomasgard, A. (2018). An Equilibrium Market Power Model for Power Markets and Tradable green Certificates, Including Kirchhoff's Laws and Nash-Cournot Competition[J]. *Energ. Econ.* 70, 270–288. doi:10.1016/j.eneco.2018.01.013

Hou, F. R., Wang, X. L., and Suo, T. (2015). Capacity Market Design in the United Kingdom and Revelation to China's Electricity Market Reform[J]. *Automation Electric Power Syst.* 39 (24), 1–7. doi:10.7500/AEPS20150322002

Hustveit, M., Frognerj, S., and Fleten, S. (2015). "Toward a Model Forthe Sw Edish-Norw Egian Electricity Certificate Market[C]," in 2015 12thInternational Conference on the European Energy Market (EEM) (New York,USA: IEEE).

Jiang, J. J., Ye, B., and Ma, X. M. (2014). The Construction of Shenzhen's Carbon Emission Trading Scheme. *Energy Policy* 75 (dec), 17–21. doi:10.1016/j.enpol.2014.02.030

Jin, L. Q. (2016). The Goal and Path of Energy Structure Transformation: Comparison and Enlightenment from America and Germany[J]. *Inq. into Econ. Issues* (2), 166–172.

Kalantzis, F. G., and Milonas, N. T. (2013). Analyzing the Impact of Futures Trading on Spot price Volatility: Evidence from the Spot Electricity Market in France and Germany. *Energ. Econ.* 36 (Mar.), 454–463. doi:10.1016/j.eneco.2012.09.017

Kallabis, T., Christian, P., and Christoph, W. (2016). The Plunge in German Electricity Futures Prices – Analysis Using a Parsimonious Fundamental Model [J]. *Energy Policy* 95, 280–290. doi:10.1016/j.enpol.2016.04.025

Letova, K., Yao, R., Davidson, M., and Afanasyeva, E. (2018). *A Review of Electricity Markets and Reforms in Russia[J]*, 53. United Kingdom: Utilities Policy. doi:10.1016/j.jup.2018.06.010

Li, J. F., and Cai, Q. M. (2016). Discussion on the Key Problems and Policy Suggestions of Energy Transformation in China [J]. *Environ. Prot.* 44 (09), 16–21.

Li, J. J., and Wang, N. (2019). China's Energy Transition and Path Selection[J]. *Adm. Reform* 117 (05), 65–73.

Li, L. S. (2019). *Research on Dispatching and Planning of Integrated Energy Systems Considering Differences of Multiple Functional Areas [D]*. Zhejiang: Zhejiang University.

Li, P., Huang, L., and Chen, H. Y. (2019). Enlightenment of Japan's Power Market Construction to China [J]. *South. Power Syst. Technol.* 13 (09), 67–74. doi:10.13648/j.cnki.issn1674-0629.2019.09.011

Li, W., Sun, W., Li, G. M., Jin, B., Wu, W., Cui, P., et al. (2018). Transmission Mechanism between Energy Prices and Carbon Emissions Using Geographically Weighted Regression[J]. *Energy Policy* 115, 434–442. doi:10.1016/j.enpol.2018.01.005

Lin, B., and Jia, Z. (2020). Why Do We Suggest Small Sectoral Coverage in China's Carbon Trading Market?. *J. Clean. Prod.* 257, 120557. doi:10.1016/j.jclepro.2020.120557

Lin, B. Q., and Jia, Z. J. (2019). *How Does Tax System on Energy Industries Affect Energy Demand, CO 2 Emissions, and Economy in China?*, 84. Netherlands: Elsevier B.V. doi:10.1016/j.eneco.2019.104496

Lin, F. P. (2016). *Research on Legal Issues of My Country's New Energy Market Access System [D]*. Jiangxi: Jiangxi University of Science and Technology.

Liu, D. N. (2017). Coordinated Development of Electricity Market, Carbon Emission Rights Market and green Certificate Market [J]. *China Electr. Equipment Industry* (07), 44–46. doi:10.3969/j.issn.1009-5578.2017.07.014

Liu, P. K., Peng, H., and Luo, S. (2019). Research on Structural Characteristics of Driving Forces of China Energy Transition[J. *J. China Population, Resour. Environ.* 29 (12), 45–56. (in Chinese). doi:10.12062/cpre.20190811

Liu, P. K., and Wang, Z. W. (2019). Is it Reasonable for China to Promote "Energy Transition" Now? ——An Empirical Study on the Substitution-Complementation Relationship Among Energy Resources [J]. *China Soft Sci.* 344 (8), 19–135.

Lockwood, M., Mitchell, C., and Hoggett, R. (2019). Unpacking 'regime Resistance' in Low-Carbon Transitions: The Case of the British Capacity Market. *Energ Res. Soc. Sci.* 58, 101278, 2019 . ISSN 2214-6296. doi:10.1016/j.erss.2019.101278

Ma, H., Liu, W. T., and Chen, Y. (2019). Power Market Mechanism Design and System Architecture Adapted to My Country's National Conditions [J]. *Electric Age* (05), 78–81.

Ma, Q. L., and Li, Q. (2019). Case Study on Relationship between CHINA'S Economic Growth and New/Traditional Energies [J]. *Resour. Industries* 452 (02), 85–94.

Matthäus, P. (2010). "Risk Premia in the German Electricity Futures Market[C]," in International Conference on Energy & Environment (IEEE).

Matthew, J. B., and Jennie, C. S. (2017). Energy Democracy: Goals and Policy Instruments for Sociotechnical Transitions[J]. *Energ. Res. Soc. Sci.* 33, 35–48. doi:10.1016/j.erss.2017.09.024

Monasterolo, I., and Raberto, M. (2019). The Impact of Phasing Out Fossil Fuel Subsidies on the Low-Carbon Transition[J]. *Energy Policy* 124, 355–370. doi:10.1016/j.enpol.2018.08.05

Munro, F. R., and Cairney, P. (2020). A Systematic Review of Energy Systems: The Role of Policymaking in Sustainable Transitions[J]. *Renew. Sustain. Energ. Rev.* 119, 109598.1–109598.10. doi:10.1016/j.rser.2019.109598

Nakajima, T . (2019). Expectations for Statistical Arbitrage in Energy Futures Markets[J]. *J. Risk Financial Manage.* 12 (1). doi:10.3390/jrfm12010014

Ni, W. D. (2018). Improving Coal Power Operation Cost and Promoting the Marketization of New Energy Generation [J]. *Electric Power Equipment Manage.* 24 (09), 5.

Niu, W. J., Li, Y., and Wang, B. B. (2014). Demand Response Based Virtual Power Plant Modeling Considering Uncertainty[J]. *Proc. CSEE* 34 (22), 3630–3637. (in Chinese). doi:10.13334/j.0258-8013.pcsee.2014.22.007

Peng, X., and Tao, X. (2018). Cooperative Game of Electricity Retailers in China's Spot Electricity Market. *Energy* 145, 152–170. doi:10.1016/j.energy.2017.12.122

Ren, M. Y. (2019). Impact of Electricity Futures Market on Thermal Power Enterprises [J]. *China Power Enterprise Manage.* 559 (10), 78–79.

Safari, A., Das, N., Langhelle, O., Roy, J., and Assadi, M. (2019). Natural Gas: A Transition Fuel for Sustainable Energy System Transformation? *Energy Sci. Eng.* 7 (4), 1075–1094. doi:10.1002/ese3.380

Shi, D. (2017). Supply-Side Solutions to China's Energy Transition[J]. *China Economist* (01), 82–99.

Shi, D., and Wang, L. (2015). Energy Revolution and its Effects on Economic Development [J]. *Ind. Econ. Res.* (1), 1–8. doi:10.13269/j.cnki.ier.2015.01.001

Shi, L. J., Zhou, L., Pang, B., Yan, Y., Zhang, F., and Liu, J. (2017). Design Ideas of Electricity Market Mechanism to Improve Accommodation of Clean Energy in China[J]. *Automation Electric Power Syst.* 41 (24), 83–89. doi:10.7500/AEPS20170614002

Solano-Rodríguez, B., Pizarro-Alonso, A., Vaillancourt, K., and Martin-del-Campo, C. (2018). "Mexico's Transition to a Net-Zero Emissions Energy System: Near Term Implications of Long Term Stringent Climate Targets," in *Limiting Global Warming to Well below 2°C: Energy System Modelling and Policy Development.* Germany: Springer, 315–331. doi:10.1007/978-3-319-74424-7_19

Song, X. H., Han, J. J., Shan, Y. Q., Zhao, C., Liu, J., and Koub, Y. (2020). Efficiency of Tradable green Certificate Markets in China[J]. *J. Clean. Prod.* 264, 121518. doi:10.1016/j.jclepro.2020.121518

Spodniak, P., and Bertsch, V. (2020). Is Flexible and Dispatchable Generation Capacity Rewarded in Electricity Futures Markets? A Multinational Impact Analysis[J]. *Energy* 196, 117050.1–117050.11. doi:10.1016/j.energy.2020.117050

Staden, M. V. (2017). Sustainable Energy Transition: Local Governments as Key Actors[J]. *Towards 100% Renewable Energy*. Germany: Springer, 17–25.

Stephanía, M. L., and Nursimulu, A. (2019). Drivers of Electricity price Dynamics: Comparative Analysis of Spot and Futures Markets[J]. *Energy Policy* 126, 76–87. doi:10.1016/j.enpol.2018.11.020

Sun, L. L. (2018). Research on Power Generation Cost———Based on the analysis of life cycle assessment theory [J]. *Price: Theor. Pract.* 407 (05), 153–156.

Sun, X. Y. (2017). *Research on China's Energy Transition and Policies[D]*. Beijing): China University of Petroleum.

Sun, Y. Z., Bao, Y., Xu, J., Zha, X. M., Li, X., Ke, D. P., et al. (2017). Discussion on strategy of stabilizing high proportion of renewable energy power fluctuation [J]. *Chin. Sci. Bull.* (10), 111–121. doi:10.1360/N972016-00484

Tang, C., and Zhang, F. (2020). Mechanism of wind power and solar photovoltaic power participation in the electricity spot market considering the guaranteed capacity factor. *IOP Conf. Ser. Earth Environ. Sci.* 446, 022031. doi:10.1088/1755-1315/446/2/022031

Tang, J. P. (2017). The Impact of green power certificate trading on the operation and development of new energy power generation Enterprises[J]. *Solar Energy* (05), 16–18+22.

Wang, F. (2019). History of China's power industry regulatory Reform[J]. *China Collective Economy* (23), 57–58.

Wang, H., Chen, Z. P., and Wu, X. Y. (2019). Can a carbon trading system promote the transformation of a low-carbon economy under the framework of the porter hypothesis? —Empirical analysis based on the PSM-DID Method[J]. *Energy Policy* 129, 930–938. doi:10.1016/j.enpol.2019.03.007

Wang, M. Y., Li, Y. M., Li, M. M., and Shi, W. (2019). Will carbon tax affect the strategy and performance of low-carbon technology sharing between enterprises?[J]. *J. Clean. Prod.* 210, 724–737. doi:10.1016/j.jclepro.2018.10.321

Wang, X., Hong, Z. Z., and Pang, J. Y. (2019). Formation and Development of Singapore Electricity Future Market [J]. *Zhejiang Electric Power* 38 (09), 22–26. doi:10.19585/j.zjdl.201909004

Wei, W., and Dong, A. P. (2016). The Mechanism Analysis and Policy Recommendations of Energy Taxation to Promote the Development of Renewable Energy. *Old District Construction 000* 014, 8–10.

Weng, Q., and Xu, H. (2018). A review of China's carbon trading market. *Renew. Sustain. Energ. Rev.* 91 (aug), 613–619. doi:10.1016/j.rser.2018.04.026

Will, U., and Strachan, N. (2012). Critical mid-term uncertainties in long-term decarbonisation Pathways[J]. *Energy Policy* 433, 444–619. doi:10.1016/j.enpol.2011.11.004

Wu, J., Chang, L., and Cao, B. (2019). Design and Implementation of Renewable Energy Inter-regional Spot Market Operation Support System[J]. *Shandong Electric Power* 046 (003), 13–18. doi:10.3969/j.issn.1007-9904.2019.03.004

Xie, X. X., Ren, D. M., and Zhao, Y. Q. (2014). Initial Analysis of Promoting China's Energy Revolution System and Mechanism Reform [J]. *Energy of China* 36 (04), 16–19+44. doi:10.3969/j.issn.1003-2355.2014.04.004

Xie, Z. M., Yan, K., and Zhou, L. M. (2017). Research of Long-run Equilibrium between Economic Growth/Energy Transformation and CO2 Emissions——An Empirical Study Based on Provincial Panel Data Analysis [J]. *Theor. Pract. Finance Econ.* 38 (06), 116–121. doi:10.3969/j.issn.1003-7217.2017.06.018

Xu, Y. (2017). An Empirical Study on the Relationship between New Energy Consumption and China's Economic Growth [J]. *Econ. Rev.* (05), 69–74. doi:10.16528/j.cnki.22-1054/f.201705069

Yang, N. (2015). Thoughts on Deepening the Reform of China's Electric Power System[J]. *Enterprise Reform Manage.* 268 (23), 194+196. doi:10.13768/j.cnki.cn11-3793/f.2015.5927

Yang, T., Zhao, L. Y., Li, W., and Zomaya, A. Y. (2020). Reinforcement learning in sustainable energy and electric systems: a Survey[J]. *Annu. Rev. Control.* 49, 145–163. doi:10.1016/j.arcontrol.2020.03.001

Yang, X. L., He, L. Y., Xia, Y. F., and Chen, Y. (2019). Effect of government subsidies on renewable energy investments: The threshold Effect[J]. *Energy Policy* 132, 156–166. doi:10.1016/j.enpol.2019.05.039

Yi, L., Bai, N., and Yang, L. (2019). Evaluation on the Effectiveness of China's Pilot Carbon Market Policy[J]. *J. Clean. Prod.* 246, 119039. doi:10.1016/j.jclepro.2019.119039

Yin, G. L., Zhang, X., Cao, D. D., and Liu, J. (2015). Determination of Optimal Spinning Reserve Capacity of Power System Considering Wind and Photovoltaic Power Affects[J]. *Power Syst. Technol.* 39 (No.38512), 191–198. doi:10.13335/j.1000-3673.pst.2015.12.025

Zhang, k., and Jiao, Y. (2018). Strategy of China's Diversified and Flexible Energy Structure: Evidences from the Alternation of Energy Eras and the Gas Shortage [J]. *Sino-Global Energy* 023 (006), 1–19.

Zhang, L. Z., and Tang, C. P. (2016). Applicability Analysis of British Capacity Market Mode in China[J]. *Electric Power Construction* 37 (03), 124–128. doi:10.3969/j.issn.1000-7229.2016.03.019

Zhang, S., Andrews-Speed, P., and Li, S. (2018). To what extent will China's ongoing electricity market reforms assist the integration of renewable energy?. *Energy Policy* 114 (mar), 165–172. doi:10.1016/j.enpol.2017.12.002

Zhang, S., and Andrews-Speed, P. (2020). State versus market in China's low-carbon energy transition: An institutional perspective. *Energ. Res. Soc. Sci.* 66, 101503. doi:10.1016/j.erss.2020.101503

Zhang, W., Li, J., and Li, G. X. (2020). Emission reduction effect and carbon market efficiency of carbon emissions trading policy in China[J]. *Energy* 196, 117117.1–117117.9. doi:10.1016/j.energy.2020.117117

Zhang, Y., and Farnoosh, A. (2019). Analyzing the dynamic impact of electricity futures on revenue and risk of renewable energy in China[J]. *Energy Policy* 132, 678–690.

Zhao, Q. Y. (2016). *Research on the Renewable Energy Quota System in China [D]*. Liaoning: LIAONING UNIVERSITY.

Zhao, T. Y. (2016). New energy industry over-investment phenomenon and governance suggestions [J]. *Enterprise Reform Manage.* (8X), Beijing, 173–173. doi:10.13768/j.cnki.cn11-3793/f.2016.3160

Zhou, M., Wu, Z. Y., and He, Y. h. (2019). A day-ahead electricity market-clearing model considering medium- and long-term transactions and wind producer Participation[J]. *scientia sinica (informationis)*. (in Chinese) 49 (8), 1050–1065.

Zhou, X. (2019). *Research on the Formation Mechanism of Interprovincial Barriers in Electricity Market [D]*. Zhejiang: Zhejiang University of Finance & Economics.

Zhu, M. (2019). *The Carbon Trading Market Is of Great Significance for Promoting Energy Structure Adjustment [N]*. Beijing: China Economic Times. -06-21(005).

Conflict of Interest: Author ZC was employed by company State Grid Energy Research Institute Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article or claim that may be made by its manufacturer is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 13 October 2021
doi: 10.3389/fenrg.2021.752592

Analysis of the Fee-to-Tax Reform on Water Resources in China

Zi-Rui Chen[1], *Yuan Yuan*[2]* and *Xu Xiao*[3]*

[1]School of Marxism, South China Normal University, Guangzhou, China, [2]School of Mathematical Sciences, South China Normal University, Guangzhou, China, [3]School of Economics and Management, Beihang University, Beijing, China

The Resource Tax Law was officially implemented on September 1, 2020, in China. This law presents the "Fee-to-Tax" reform of water resources. This article compares the effects of the "Fee-to-Tax" reform under asymmetric duopoly conditions with perfect information. The mechanisms of the two policies are different when all firms simultaneously respond to water resources: the water resource fee affects output by reducing market size, while the water resource tax reduces output by amplifying the weighted cost difference effects between companies. Water resource taxes work better than fees for eliminating backward production capacity. A comparison of the situation when companies respond sequentially is also carried out. When a low-cost firm is in the leading position, the collection of fees actually reduces the output difference, whereas the tax improves it. When a high-cost firm acts as a leader, the effects depend on the cost difference. When the cost difference between firms is small, the first-move advantage of high-cost firms dominates the cost advantages of low-cost firms. Therefore, a higher tax rate yields a smaller output difference. When cost differences are relatively larger, the cost advantage of low-cost firms dominates the first-move advantage of high-cost firms. As the operational cost for reducing water consumption increases, the reduced water consumption first increases and then decreases.

Keywords: fee-to-tax reform, policy effect, asymmetric duopoly, water resource tax, water consumption

OPEN ACCESS

Edited by:
Yong-Cong Yang, Guangdong University of Foreign Studies, China

Reviewed by:
Minxing Jiang, Nanjing University of Information Science and Technology, China
You-Hua Chen, South China Agricultural University, China

***Correspondence:**
Yuan Yuan
yyuan2102@m.scnu.edu.cn
Xu Xiao
xuu_xiao@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *03 August 2021*
Accepted: *27 September 2021*
Published: *13 October 2021*

Citation:
Chen Z-R Yuan Y and Xiao X (2021) Analysis of the Fee-to-Tax Reform on Water Resources in China. Front. Energy Res. 9:752592. doi: 10.3389/fenrg.2021.752592

INTRODUCTION

On August 26, 2019, after the twelfth meeting of the Standing Committee of the Thirteenth National People's Congress, the Resource Tax Law was officially adopted and was officially implemented on September 1, 2020. For the first time, the Resource Tax Law explicitly levies water resource taxes on a trial basis for industries and individuals who use surface water or groundwater. As the water resource tax is levied, the collection of water resource fees will cease. China's water resources are very scarce, and the per capita water resources are only one-fourth of the world average. Water resources are unevenly distributed in space and time, and there are problems such as water pollution, waste, the excessive exploitation of groundwater, and weak citizen protection awareness. With the development of the construction of an ecological civilization, the importance of water resources to human society is constantly increasing; therefore, a general trend is to include water resources in the scope of resource tax collection.

China began collecting water resource fees in 1980. In 1988, China officially promulgated and implemented the "Water Law of the People's Republic of China", which explicitly included the collection of water resource fees into the legal scope. The collection of water resource fees has serious problems, such as multisector collection, low actual collection rates, and irregular use management.

To promote the construction of resource-saving and environmentally friendly cities, increase citizens' awareness of water resource protection and water efficiency, and improve water resources, China has included water resources in the scope of resource tax collection.

Although country characteristics must necessarily shape practical policy advice, theory provides some fairly specific guidance. This paper aims to analyze the theoretical basis that underlies the Fee-to-Tax reformation of water resources.

When studying the effect of the reform of water resource fees and taxes, scholars hold different opinions. Mushtaq et al. (2008) questioned the effectiveness and feasibility of a water Fee-to-Tax reform and noted that this reform is likely to cause serious difficulties in agricultural production. Ma, Zhao and Ni (2018) indicated that tax reform is conducive to reducing not only arbitrary charges but also the burden on enterprises, and the collection and use of a water resource tax is more reasonable and transparent, which is helpful for the state to control the source and use of the water resource tax and to reduce corruption. Some researchers established the computable general equilibrium model (CGE) of the economy with water as an explicit factor of production. Qin et al. (2012) used the CGE model to assess the economic impact of water pricing in China. Li et al. (2019) calculated a reasonable tax rate of water resources in Yunnan Province with the CGE model; Tian (2021) also calculated the optimal tax rate of water resources in Hebei Province. Beyond these studies, there are few articles on the economic principles of water resource tax fee shifting.

To avoid increasing the corporate tax burden, a general rule is presented that the tax fee after the reform equals the original water resource fee in the Fee-to-Tax reform. In this particular situation, the collection of water resource fees can be seen as a special type of unit tax before the Fee-to-Tax reform. Considering this, the model that studies ad valorem and unit taxes can be adapted to analyze the effect of the Fee-to-Tax reform on water resources.

The comparison between these two types of taxes is a classic topic that has been the subject of ongoing discussion and development in public finance (Skeath, 1994; Blackorby and Murty, 2007; Vetter, 2017). The study of differentiated duopolies or oligopolies was developed by Dixit (1979), Singh and Vives (1984), Häckner (1999) and other scholars. Wang and Zhao (2007) compared the welfare effects of cost reductions in differentiated Bertrand and Cournot oligopolies but did not take taxation into account. It was indicated that in asymmetric and differentiated oligopolies, unit taxation could be welfare-superior to ad valorem taxation if the goods are sufficiently differentiated under either Cournot or Bertrand competition (Wang and Zhao, 2009). Lapan and Hennessy (2011) extended the analysis to multimarket oligopolies. For a linear demand system, it is also demonstrated that the marginal cost of public funds for ad valorem taxes is generally lower than that for unit taxes (Häckner and Herzing, 2016). Arguably, policy designers favor the use of ad valorem taxes over unit taxes in oligopolies. However, the anticompetitive effects of the two taxes on firms' strategic interactions favor unit taxes over ad valorem taxes (Vetter, 2014). Given decreasing returns to scale, an ad valorem tax regime unambiguously Pareto dominates a unit tax regime (Hoffmann and Runkel, 2016). Griffith and Nesheim et al. (2018) noted that by considering the use of tax policy, utility is linear in the consumption of the outside good. A specific tax results in larger reductions than an ad valorem tax but at a greater cost to consumers.

The vast majority of applications focus on how these theories help us to explain economic situations in real life (Nie and Chen, 2012; Nie et al, 2018; Tao et al, 2018). Such theories are also applied to discuss clean and dirty technology competition (Chen et al, 2015; Acemoglu et al, 2016), the impacts of subsidies and taxation (Chen et al, 2017; Golosov et al, 2014; Wang et al, 2017; Yang et al, 2018; Dong et al, 2018), and other related social economic issues (Bloch and Demange, 2018; Fuest et al, 2018; Wang and Wright, 2017).

In this paper, the model of ad valorem and unit taxes is further developed to study the effect of the Fee-to-Tax reform under an asymmetric duopoly by investigating the total outputs and the difference in the outputs in the two collection regimes.

The remainder of this paper is organized as follows. ***Model Establishment*** introduces the model. The model is discussed in ***Model Analysis*** under two different circumstances: (1) all firms simultaneously respond to the policy; (2) different firms respond to policy change sequentially. Finally, concluding remarks are presented in ***Concluding Remarks***.

MODEL ESTABLISHMENT

By taking water resource policy into account, a duopoly model is adopted for the following study. In an industry, two asymmetric firms exist (the marginal production costs are different) that compete in quantity. For convenience, denote the two firms as $\{A, B\}$. The marginal costs of the two firms are constants, $c_i, i \in \{A, B\}$, which satisfies $c_A < c_B$. Assume that the two firms' outputs are $q_i, i \in \{A, B\}$ and that prices are $p_i, i \in \{A, B\}$. The inverse demand function satisfies

$$p_i = \alpha - q_i - \gamma q_j, i, j \in \{A, B\}, i \neq j. \tag{1}$$

In **Eq. 1**, $\alpha > 0$ means that the market size and $\gamma \in [0, 1]$ represents product substitutability. High product substitutability manifests in similar functions offered by the products of the two firms. A larger γ means higher product substitutability; thus, in the extreme case, $\gamma = 1$ indicates that the products of the two firms have the same function, whereas $\gamma = 0$ means that each firm has a monopoly on a different product. This type of inverse demand function is widely adopted in economics and in industrial organizations (Chen et al, 2018a; Chen et al, 2018b). Considering the water resource policy, both firms' profits are listed as follows:

$$\pi_i = (p_i - c_i)q_i - T(\tau, p_i; \kappa, q_i). \tag{2}$$

In **Eq. 2**, $\tau \geq 0$ is the collection rate based on price when the water resource fee is collected, and $\kappa \geq 0$ is the taxation rate according to the outputs when the water resource tax is collected (Lapan and Hennessy, 2011). For **Eq. 2**, the term $(p_i - c_i)q_i$ is revenues, and $T(\tau, p_i; \kappa, q_i)$ is payment for water resources. When the water resource fee is collected, $T = \kappa q_i$. When the water resource tax is collected, $T = \tau p_i q_i$. We do not consider subsidies and always assume the taxation intensity to be nonnegative. (1) and (2), along with the tax function and fee function, constitute the asymmetric duopoly model with water resource usage payments.

In the following section, the above model is used to analyze the economic and environmental effects of the Fee-to-Tax reform in the situation when all firms respond to the policy change simultaneously and sequentially.

MODEL ANALYSIS

Firms Respond to the Policy Simultaneously

First, we are concerned with the case in which all firms respond to the policy simultaneously, and then the model is discussed under Cournot competition.

When the water resource fee is collected, **Eq. 2** is also concave, and the unique equilibrium is determined by the first-order optimal condition. The equilibrium is outlined by the following equations:

$$\frac{\partial \pi_i}{\partial q_i} = \left(\alpha - \gamma q_j - 2q_i\right) - c_i - \kappa = 0, i, j \in \{A, B\}, i \neq j. \quad (3)$$

The equilibrium is

$$q_A^{*,F} = \frac{(2-\gamma)(\alpha-\kappa) - (2c_A - \gamma c_B)}{(4-\gamma^2)},$$
$$q_B^{*,F} = \frac{(2-\gamma)(\alpha-\kappa) - (2c_B - \gamma c_A)}{(4-\gamma^2)}. \quad (4)$$

When water resource fees are collected, both firms reduce outputs, and the two firms reduce output identically. The output gap and corresponding price and profits are

$$\Delta q^{*,F} = q_A^{*,F} - q_B^{*,F} = \frac{c_B - c_A}{(2-\gamma)}. \quad (5)$$

$$p_A^{*,F} = \frac{\alpha}{2+\gamma} + \frac{\kappa(1+\gamma)}{2+\gamma} + \frac{(2-\gamma^2)c_A + \gamma c_B}{(4-\gamma^2)},$$
$$p_B^{*,F} = \frac{\alpha}{2+\gamma} + \frac{\kappa(1+\gamma)}{2+\gamma} + \frac{(2-\gamma^2)c_B + \gamma c_A}{(4-\gamma^2)}. \quad (6)$$

$$\pi_A^{*,F} = \left[\frac{(2-\gamma)(\alpha-\kappa) - (2c_A - \gamma c_B)}{(4-\gamma^2)}\right]^2,$$
$$\pi_B^{*,F} = \left[\frac{(2-\gamma)(\alpha-\kappa) - (2c_B - \gamma c_A)}{(4-\gamma^2)}\right]^2. \quad (7)$$

Before the Fee-to-Tax reform, the water resource fee reduced the total outputs and producer surplus. The corresponding price increases with the fee collection intensity. The output difference remains constant regardless of the amount of payment per unit, which means that such a policy places an identical effect on the outputs of the two firms. From **Eq. 4**, we have $\left|\frac{\partial q_B^{*,F}}{\partial \kappa}\right| = \left|\frac{\partial q_A^{*,F}}{\partial \kappa}\right|$. Therefore, it is also found that higher product substitutability yields a larger output gap.

When the water resource tax is collected, the payment is $T(\tau, p_i; \kappa, q_i) = \tau p_i q_i$. Thus, the equilibrium is outlined by the following equations:

$$\frac{\partial \pi_i}{\partial q_i} = (1-\tau)\left(\alpha - \gamma q_j - 2q_i\right) - c_i = 0, i, j \in \{A, B\}, i \neq j. \quad (8)$$

The equilibrium is

$$q_A^{*,T} = \frac{(2-\gamma)(1-\tau)\alpha - (2c_A - \gamma c_B)}{(4-\gamma^2)(1-\tau)},$$
$$q_B^{*,T} = \frac{(2-\gamma)(1-\tau)\alpha - (2c_B - \gamma c_A)}{(4-\gamma^2)(1-\tau)}. \quad (9)$$

To measure the cost difference, we refer to the definition of WCD (weighted cost difference) combined with product substitutability.

Definition 1. WCD (weighted cost difference) is defined as $2c_i - \gamma c_j$.

According to **Eq. 9** and $c_A < c_B$, both firms reduce outputs under $2c_A - \gamma c_B > 0$. Moreover, when the cost difference is small, the high-efficiency firm reduces fewer outputs than the low-efficiency firm. Under $2c_A - \gamma c_B < 0$, the water resource tax improves the outputs of high-efficiency firms and reduces the outputs of low-efficiency firms. The output gap is

$$\Delta q^{*,T} = q_A^{*,T} - q_B^{*,T} = \frac{c_B - c_A}{(2-\gamma)(1-\tau)}. \quad (10)$$

The corresponding price and profits are given as follows:

$$p_A^{*,T} = \frac{\alpha}{2+\gamma} + \frac{(2-\gamma^2)c_A + \gamma c_B}{(4-\gamma^2)(1-\tau)}, p_B^{*,T} = \frac{\alpha}{2+\gamma} + \frac{(2-\gamma^2)c_B + \gamma c_A}{(4-\gamma^2)(1-\tau)}, \quad (11)$$

$$\pi_A^{*,T} = (1-\tau)\left[\frac{(2-\gamma)(1-\tau)\alpha - (2c_A - \gamma c_B)}{(4-\gamma^2)(1-\tau)}\right]^2,$$
$$\pi_B^{*,T} = (1-\tau)\left[\frac{(2-\gamma)(1-\tau)\alpha - (2c_B - \gamma c_A)}{(4-\gamma^2)(1-\tau)}\right]^2. \quad (12)$$

From **Eq. 9**, we have $\left|\frac{\partial q_B^{*,T}}{\partial \tau}\right| > \left|\frac{\partial q_A^{*,T}}{\partial \tau}\right|$. Therefore, the water resource tax has a greater effect on high-cost firms than on low-cost firms. Moreover, $\frac{\partial \Delta q^{*,T}}{\partial \gamma} > 0$. Higher product substitutability yields a larger output gap. Thus, we draw the following conclusions about subsidies.

Proposition 1. When all firms respond to the policy change simultaneously, (1) The water resource fee does not change the output difference. (2) The water resource tax reduces total outputs and increases the output gap. (3) With small cost differences, the water resource tax reduces the outputs and profits of both firms. (4) Under large cost differences, the water resource tax improves the outputs and profits of high-efficiency firms while reducing the outputs and profits of low-efficiency firms.

Proof. See in **Supplementary Appendix SA**.

Remarks. Based on the above analysis, we argue that the implementation of water resource taxes improves prices while reducing total output and product surplus. Higher taxes mean higher prices and lower outputs.

Obviously, product substitutability increases the opponent's costs in the WCD. When $\gamma = 0$, the opponent's costs have no effect on the firm's decisions. This definition reflects the interaction of both the opponent's costs and product substitutability. In practice, firms care much more about the WCD than the cost difference.

Based on Definition 1, we can intuitively draw the following conclusions. Under Cournot competition, collecting the water resource fee affects equilibrium by reducing the market size, while collecting the water resource tax affects equilibrium by amplifying the effects of the WCD. Both the water resource fee and tax affect the market equilibrium, and the affecting mechanisms differ. Water resource fees reduce the market size and then reduce firms' outputs and profits. In contrast, collecting a tax amplifies the effects of the WCD and then affects the output difference and profits. The above conclusions capture the action mechanism of the different taxes.

When conducting the Fee-to-Tax reform, a general rule is assumed that the amount of payment remains unchanged during the reform. Thus, a comparison of the outputs is conducted under this basic rule. That is,

$$\begin{aligned}\kappa\left(q_A^{*,F}+q_B^{*,F}\right) &= \kappa\frac{2(\alpha-\kappa)-(c_A+c_B)}{(2+\gamma)}\\ &= \tau p^{*,T}q_A^{*,T}+\tau p_B^{*,T}q_B^{*,T}\\ &= \tau\left[\frac{\alpha}{2+\gamma}+\frac{(2-\gamma^2)c_A+\gamma c_B}{(4-\gamma^2)(1-\tau)}\right]\frac{(2-\gamma)(1-\tau)\alpha-(2c_A-\gamma c_B)}{(4-\gamma^2)(1-\tau)}\\ &+\tau\left[\frac{\alpha}{2+\gamma}+\frac{(2-\gamma^2)c_B+\gamma c_A}{(4-\gamma^2)(1-\tau)}\right]\frac{(2-\gamma)(1-\tau)\alpha-(2c_B-\gamma c_A)}{(4-\gamma^2)(1-\tau)}.\end{aligned} \tag{13}$$

Eq. 13 is restated as

$$\begin{aligned}&\frac{\tau\alpha}{2+\gamma}\frac{2(1-\tau)\alpha-(c_A+c_B)}{(1-\tau)}+\tau\alpha\frac{(2-\gamma^2+\gamma)(c_A+c_B)}{(4-\gamma^2)(1-\tau)}\\ &-\tau\left[\frac{(2-\gamma^2)c_A+\gamma c_B}{(4-\gamma^2)(1-\tau)}\right]\frac{(2c_A-\gamma c_B)}{(2-\gamma)(1-\tau)}\\ &-\tau\left[\frac{(2-\gamma^2)c_B+\gamma c_A}{(4-\gamma^2)(1-\tau)}\right]\frac{(2c_B-\gamma c_A)}{(2-\gamma)(1-\tau)}=\kappa[2(\alpha-\kappa)-(c_A+c_B)].\end{aligned} \tag{14}$$

For the output effects of the two types of policy, we have the following relationship:

$$\begin{aligned}q_A^{*,T}-q_A^{*,F} &= \frac{\kappa}{(2+\gamma)}-\frac{\tau(2c_A-\gamma c_B)}{(4-\gamma^2)(1-\tau)},\\ q_B^{*,T}-q_B^{*,F} &= \frac{\kappa}{(2+\gamma)}-\frac{\tau(2c_B-\gamma c_A)}{(4-\gamma^2)(1-\tau)}.\end{aligned} \tag{15}$$

Under a fixed total amount of payment, we draw the following conclusions. Proposition 2 (1)$q_A^{*,T}-q_A^{*,F}>q_B^{*,T}-q_B^{*,F}$, $p_A^{*,T}-p_A^{*,F}<p_B^{*,T}-p_B^{*,F}$. **(2)** Under $\frac{\kappa}{\tau}\leq\frac{\alpha}{2+\gamma}+\frac{(2-\gamma^2)c_A+\gamma c_B}{(4-\gamma^2)(1-\tau)}$, the water resource fee yields more output than the water resource tax yield. Otherwise, the water resource fee leads to fewer outputs than the water resource tax.

Proof. See **Supplementary Appendix SB**.

Remarks. This proposition demonstrates that low-cost firms experience a larger loss in outputs than high-cost firms experience. After the reform, it is more advantageous to phase out backward production capacity. By levying water resource taxes, the government participates in the distribution of benefits from the development of state-owned water resources, can also adjust the distribution of benefits between resource occupiers and nonresource occupiers, and at the same time promote equal competition among water companies.

Interestingly, the distinguishing effects on the output difference are the result of the two policies' action mechanisms. Collecting the water resource fee affects the equilibrium by reducing the market size. Such a tax affects outputs by amplifying the effects of the WCD. After using tax leverage to increase the cost of water use, companies will naturally adjust their production behavior to promote water conservation.

Firms Respond to the Policy Sequentially: Low-Cost Firm as the Leader

Next, this article discusses the second case: assuming that not all firms respond to the policy synchronously, then the model is discussed under Stackelberg competition. Once the outputs are obtained, the analysis of prices and profits under Stackelberg competition is similar to that under Cournot competition. Thus, in the following section, we mainly focus on outputs. We first address the case in which the low-cost firm plays the leading position, and the high-cost firm acts as a follower.

By taking a backward induction approach, we immediately obtain the following equilibrium when the water fee is collected.

$$\begin{aligned}q_A^{*S1,F} &= \frac{(2-\gamma)(\alpha-\kappa)-(2c_A-\gamma c_B)}{2(2-\gamma^2)},\\ q_B^{*S1,F} &= \frac{(4-2\gamma-\gamma^2)(\alpha-\kappa)-(4-\gamma^2)c_B+2\gamma c_A}{4(2-\gamma^2)}.\end{aligned} \tag{16}$$

The output gap of the two firms is

$$\begin{aligned}\Delta q^{*S1,F} &= q_A^{*S1,F}-q_B^{*S1,F}\\ &= \frac{\gamma^2(\alpha-\kappa)-(4-2\gamma)c_A+(4-\gamma^2+2\gamma)c_B}{4(2-\gamma^2)}.\end{aligned} \tag{17}$$

Under Stackelberg competition, collecting the water resource fee affects the output gap, which is different from the result under Cournot competition. Moreover, $q_A^{*S1,F}>q_A^{*,F}>q_B^{*,F}>q_B^{*S1,F}$.

After the Fee-to-Tax reform, the equilibrium is given as follows.

$$\begin{aligned}q_A^{*S1,T} &= \frac{(2-\gamma)(1-\tau)\alpha-(2c_A-\gamma c_B)}{2(2-\gamma^2)(1-\tau)},\\ q_B^{*S1,T} &= \frac{1}{2}\alpha-\frac{c_B}{2(1-\tau)}-\frac{\gamma}{2}\frac{(2-\gamma)(1-\tau)\alpha+\gamma c_B-2c_A}{2(2-\gamma^2)(1-\tau)}\\ &= \frac{2(2-\gamma^2)(1-\tau)\alpha-2(2-\gamma^2)c_B-\left[(2-\gamma)(1-\tau)\gamma\alpha+\gamma^2c_B-2\gamma c_A\right]}{4(2-\gamma^2)(1-\tau)}\\ &= \frac{(4-2\gamma-\gamma^2)(1-\tau)\alpha-(4-\gamma^2)c_B+2\gamma c_A}{4(2-\gamma^2)(1-\tau)}.\end{aligned} \tag{18}$$

Similarly, the output gap is

$$\Delta q^{*S1,T} = q_A^{*S1,T} - q_B^{*S1,T} = \frac{\gamma^2(1-\tau)\alpha + (4+2\gamma-\gamma^2)c_B - (4+2\gamma)c_A}{4(2-\gamma^2)(1-\tau)}. \quad (19)$$

$$q_A^{*S1,T} > q_A^{*,T} > q_B^{*,T} > q_B^{*S1,T}.$$

Based on the above analysis, we have the following conclusions.

Proposition 3. Collecting the water resource fee reduces the output difference between firms. When a low-cost firm acts as the leader, the output difference is larger than that under the circumstance when the water resource fee is collected. Based on the above conclusion, high-cost firms may prefer water resource fees, and low-cost firms may favor water resource taxes.

Proof. See **Supplementary Appendix SC**.

Remarks. The output difference when not all firms respond simultaneously is larger than the output difference under the Cournot game. Accordingly, when low-cost firms respond first to the policy reform, these firms possess both cost and first-move advantages. These advantages yield larger output differences than those when firms act at the same time. First, on the basis of their own cost advantages, the first mover has the opportunity to limit its competitor to achieve sales and achieve cost advantages through economies of scale and learning effects. Second, the forerunner creates switching costs for customers who use it, and it is difficult for the latecomer to seize it from the forerunner. Third, the first-move company can build important brand loyalty, but the latter is difficult to break. In all, when firms do not respond simultaneously, the effects of the policy reform that supports phasing out of backward production capacity are strengthened.

Furthermore, an analysis of the environmental benefits of the "Fee-to-Tax" reform will be discussed. For the ith firm under consideration: $c_i = PC_i + OC_i$, where PC_i means the present value of the original production cost; OC_i means the increased operational cost (i.e., cost increased as a result of renewed technology for reducing water consumption).

To measure the reducing water consumption, we introduce the definition of RWC (reducing water consumption) combined with the increased operational cost: $RWC_i = \delta \cdot OC_i \cdot q_i$, in which $\delta \cdot OC_i$ stands for the ratio of reducing water consumption over the original water consumption per unit product.

When the low-cost firm (firm A) plays the leading position, its production cost increases: $c_A = PC_A + OC_A$. The cost of high-cost firm (firm B) stays unchanged.

By taking a backward induction approach, we immediately obtain the following equilibrium when the water fee is collected.

$$q_A^{*S1,F} = \frac{(2-\gamma)(\alpha-\kappa) - [2c_A - \gamma c_B + 2(1-\kappa\delta)OC_A]}{2(2-\gamma^2)},$$

$$q_B^{*S1,F} = \frac{\alpha - \gamma q_A^{*S1,F} - c_B - \kappa}{2}. \quad (20)$$

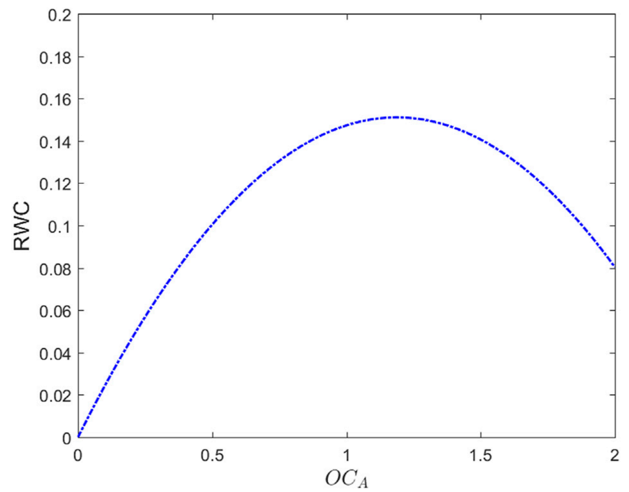

FIGURE 1 | Numerical simulations of RWC_A ($\gamma = 0.5, \tau = 0.2, \delta = 0.15, \alpha = 5, c_A = 1.1, c_B = 1.9.$).

$$RWC_A^{*S1,F} = \delta \cdot OC_A \cdot q_A = \frac{[(2-\gamma)(\alpha-\kappa) - (2c_A - \gamma c_B)]\delta \cdot OC_A - 2(1-\kappa\delta)\delta \cdot OC_A^2}{2(2-\gamma^2)}. \quad (21)$$

After the tax reform, the water tax was collected.

$$RWC_A^{*S1,T} = \delta \cdot OC_A \cdot q_A^{*S1,T} = \frac{[(2-\gamma)(1-\tau)\alpha - (2c_A - \gamma c_B)]\delta \cdot OC_A - 2\delta \cdot OC_A^2}{2(2-\gamma^2)(1-\tau)}. \quad (22)$$

Proposition 4. As the operational cost for saving water consumption increases, the reducing water consumption increases at first, and then decreases.

Remarks. The first-move company invests in water saving technology. Thus, the actual cost of its product includes the original cost and the increased operational cost for reducing water consumption. As a company increases its investment in saving water, the reduced water consumption increases as well. However, when the operational cost increases beyond the extreme point, the actual cost will become so high that it will cause the sales of the product to decline dramatically, hinder the company's commercial competition, and thus eventually decrease the reducing water consumption. **Figure 1** shows numerical simulations of RWC_A when $\gamma = 0.5, \tau = 0.2, \delta = 0.15, \alpha = 5, c_A = 1.1, c_B = 1.9.$ This figure shows that RWC_A first increases and then decreases as the operational cost for saving water of the leader firm increases, which is consistent with Proposition 4.

Firms Respond to the Policy Sequentially: High-Cost Firm as the Leader

Then, we consider the other case in which the high-cost firm leads, while the low-cost firm follows.

When a high-cost firm (firm B) acts as a leader, the problem is also solved by a backward induction approach. We first consider the situation when the water resource fee was collected.

$$q_B^{*S2,F} = \frac{(2-\gamma)(\alpha-\kappa)-(2c_B-\gamma c_A)}{2(2-\gamma^2)},$$
$$q_A^{*S2,F} = \frac{(4-2\gamma-\gamma^2)(\alpha-\kappa)-(4-\gamma^2)c_A+2\gamma c_B}{4(2-\gamma^2)}. \quad (23)$$

The output gap is

$$q_A^{*S2,F} - q_B^{*S2,F} = \frac{-\gamma^2(\alpha-\kappa)+(4+2\gamma)c_B-(4-\gamma^2+2\gamma)c_A}{4(2-\gamma^2)}. \quad (24)$$

Similar conclusions to those drawn in ***Concluding Remarks*** also hold. That is,

$$q_B^{*,F} < q_B^{*S2,F} \text{ and } q_A^{*S2,F} < q_A^{*,F}. \quad (25)$$

Moreover, a small cost difference between the two firms implies that $q_A^{*S2,F} < q_B^{*S2,F}$, and a large cost difference indicates that $q_A^{*S2,F} > q_B^{*S2,F}$. Thus, we draw the following conclusion. When a high-cost firm acts as the leader, with a small cost difference, the first-move advantage of firm B dominates the cost advantages of firm A. Therefore, for small cost differences, a higher tax rate yields a smaller output difference. When cost differences are relatively larger, the cost advantage of firm A dominates the first-move advantage of firm B, and a higher fee rate yields larger output differences. In this way, the water resource fee promotes output differences. Moreover, the total outputs under the water resource fee satisfy the relationships

$$q_B^{*S2,F} + q_A^{*S2,F} = \frac{(8-4\gamma-\gamma^2)(\alpha-\kappa)-(4-2\gamma)c_B-(4-\gamma^2-2\gamma)c_A}{4(2-\gamma^2)},$$
$$q_A^{*S1,F} + q_B^{*S2,F} = \frac{(8-4\gamma-\gamma^2)(\alpha-\kappa)-(4-2\gamma)c_A-(4-\gamma^2-2\gamma)c_B}{4(2-\gamma^2)}.$$

Apparently, $q_A^{*S1,F} + q_B^{*S1,F} > q_B^{*S2,F} + q_A^{*S2,F}$. Similarly, we also have the relationship $q_A^{*S1,F} + q_B^{*S1,F} > q_B^{*S2,F} + q_A^{*S2,F} > q_A^{*,F} + q_B^{*,F}$.

In the situation when the water resource tax is collected, the equilibrium is given as follows:

$$q_B^{*S2,T} = \frac{(2-\gamma)(1-\tau)\alpha-(2c_B-\gamma c_A)}{2(2-\gamma^2)(1-\tau)},$$
$$q_A^{*S2,T} = \frac{(4-2\gamma-\gamma^2)(1-\tau)\alpha-(4-\gamma^2)c_A+2\gamma c_B}{4(2-\gamma^2)(1-\tau)}. \quad (26)$$

Similarly, the output gap is

$$\Delta q^{*s,T} = q_A^{*s,T} - q_B^{*s,T} = \frac{-\gamma^2(1-\tau)\alpha-(4+2\gamma-\gamma^2)c_A+(4+2\gamma)c_B}{4(2-\gamma^2)(1-\tau)}. \quad (27)$$

Based on **Eq. 26**, we have the relationships $q_A^{*S2,T} < q_A^{*,T}$ and $q_B^{*,T} < q_B^{*S2,T}$. The corresponding price is

$$p_B^{*S2,T} = \frac{(2-\gamma)\alpha}{4} + \frac{2c_B+\gamma c_A}{4(1-\tau)},$$
$$p_A^{*S2,T} = \frac{(4-2\gamma-\gamma^2)\alpha}{4(2-\gamma^2)} + \frac{(4-3\gamma^2)c_A+2\gamma c_B}{4(2-\gamma^2)(1-\tau)}. \quad (28)$$

Based on the above analysis, we obtain the following conclusions:

Proposition 5. When the high-cost firm leads the investment in water savings according to the "Fee-to-Tax" reform, the output of the high-cost firm is higher than its output under the situation when two firms respond simultaneously. The outputs of the latecomer are lower than the outputs under other circumstances. The total output of two firms is higher than the output when two firms respond simultaneously. More specifically, the proposition can be delivered in the following inequality:

$$q_A^{*S2,T} < q_A^{*,T} < q_A^{*S1,T} < q_B^{*S2,T} > q_B^{*,T} > q_B^{*S1,T} \text{ and } q_A^{*,T} + q_B^{*,T} < q_A^{*S2,T} + q_B^{*S2,T} < q_A^{*S1,T} + q_B^{*S1,T}.$$

Proof. See **Supplementary Appendix SD**.

Remarks. Under the Stackelberg game, firm A possesses both a cost advantage and a second-move disadvantage. This disadvantage yields a smaller output difference than that under the Cournot game. Furthermore, the total outputs when the low-cost firm plays a leading position are higher than the total outputs when the high-cost firm acts as a leader. The outputs under Stackelberg competition are higher than the outputs under Cournot competition because the leading firm produces more under Stackelberg than under Cournot to hinder entrants. High outputs are regarded as a strategy.

Accordingly, the implementation of the tax reduces the outputs of both firms. The tax reduces the outputs of high-cost firms more than the outputs of low-cost firms. When two firms respond at the same time, collecting water resource fees reduces outputs symmetrically. However, the implementation of a water resource tax has an asymmetric reduction effect on firms' output. In other cases, when two firms do not respond to the policy reform simultaneously, both policies have an asymmetric reduction effect on firms' outputs. However, the effect of taxes on the leading firm in such situations is more severe than the effect of taxes on the corresponding firm when they respond simultaneously.

CONCLUDING REMARKS

This article addresses the effects of the "Fee-to-Tax" reform of China's water resources under asymmetric duopoly conditions. The impacting mechanisms of water resource taxes and water resource fees differ. Collecting water resource fees reduces the market size, while taxes amplify the WCD (weighted cost difference) effects between industries. When all firms in the market respond to the policy simultaneously, the water resource fee reduces firms' outputs identically, while the water resource tax affects high-cost firms more than low-cost firms. Furthermore, when firms respond sequentially, the implementation of fees asymmetrically affects the equilibrium of firms. However, the tax affects the leading firm more than it affects the corresponding firm when all firms act synchronously. Additionally, the effect of the tax is more severe for leading firms than for followers. Surprisingly, it is also proven that the outputs are higher under Stackelberg competition than under Cournot competition because the leading firm under Stackelberg produces more than the leading firm under Cournot produces to hinder entrants. As the operational cost for reducing water consumption increases, the reduced water consumption first increases and then decreases. Therefore, the "Fee-to-Tax" reform provides some benefits to maintain the environmental development of some water mining or related industries.

Based on the above analysis, taxes can act as an efficient regulative tool to support and shape industrial development. Some policy implications can be proposed according to the findings in this analysis. Specifically, the adoption of special taxes in some industries can help to eliminate backward production capacity. Because the collection of taxes has asymmetric effects on output, it works better to phase out backward production capacity than the collection of fees. Additionally, when the government decides on a tax pattern, the market characteristics of different firms should be fully considered.

In this article, the effect of the "Fee-to-Tax" reform under asymmetric duopoly conditions with perfect information is discussed. Some further research topics arise. On the one hand, the market response under incomplete information is worth discussing. Incomplete information deters both government and industry decisions, and it is also important to study the mechanisms in such situations. On the other hand, in analyzing tax reforms, it is worth considering deterring the different production characteristics of different industries. In this way, an optimal tax regime can be proposed. It is crucial to design a tax regime that considers the long-term effects for some industries with externalities that involve energy, the environment and food safety. Chen and Nie, 2016.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

XX and Z-RC conceived the idea and supervised the project. Z-RC designed the model and wrote the manuscript. YY performed the mathematical studies. All authors approved the manuscript before submission to the journal.

FUNDING

This work is partially supported by the Guangdong Planning Office of Philosophy and Social Science (GD20YYJ01).

ACKNOWLEDGMENTS

Z-RC especially wishes to thank Mr. Jun Gong, whose song brought her joy and delight.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.752592/full#supplementary-material

REFERENCES

Acemoglu, D., Akcigit, U., Hanley, D., and Kerr, W. (2016). Transition to Clean Technology. *J. Polit. Economy* 124 (1), 52–104. doi:10.1086/684511

Blackorby, C., and Murty, S. (2007). Unit versus Ad Valorem Taxes: Monopoly in General Equilibrium. *J. Public Econ.* 91 (3-4), 817–822. doi:10.1016/j.jpubeco.2006.10.003

Bloch, F., and Demange, G. (2018). Taxation and Privacy protection on Internet Platforms. *J. Public Econ. Theor.* 20 (1), 52–66. doi:10.1111/jpet.12243

Chen, Y.-h., He, Q., and Paudel, K. P. (2018a). Quality Competition and Reputation of Restaurants: the Effects of Capacity Constraints. *Econ. Research-Ekonomska Istraživanja* 31 (1), 102–118. doi:10.1080/1331677x.2017.1421996

Chen, Y.-h., Huang, S.-j., Mishra, A. K., and Wang, X. H. (2018b). Effects of Input Capacity Constraints on Food Quality and Regulation Mechanism Design for Food Safety Management. *Ecol. Model.* 385, 89–95. doi:10.1016/j.ecolmodel.2018.03.011

Chen, Y.-h., Wen, X.-w., Wang, B., and Nie, P.-y. (2017). Agricultural Pollution and Regulation: How to Subsidize Agriculture? *J. Clean. Prod.* 164, 258–264. doi:10.1016/j.jclepro.2017.06.216

Chen, Y. H., Nie, P. Y., and Wang, X. H. (2015). Asymmetric Doupoly Competition with Innovation Spillover and Input Constraints. *J. Business Econ. Manage.* 16 (6), 1124–1139. doi:10.3846/16111699.2013.823104

Chen, Z.-y., and Nie, P.-y. (2016). Effects of Carbon Tax on Social Welfare: A Case Study of China. *Appl. Energ.* 183, 1607–1615. doi:10.1016/j.apenergy.2016.09.111

Dixit, A. (1979). A Model of Duopoly Suggesting a Theory of Entry Barriers. *Bell J. Econ.* 10, 20–32. doi:10.2307/3003317

Dong, B., Wei, W., Ma, X., and Li, P. (2018). On the Impacts of Carbon Tax and Technological Progress on China. *Appl. Econ.* 50 (4), 389–406. doi:10.1080/00036846.2017.1316826

Fuest, C., Peichl, A., and Siegloch, S. (2018). Do higher Corporate Taxes Reduce Wages? Micro Evidence from Germany. *Am. Econ. Rev.* 108 (2), 393–418. doi:10.1257/aer.20130570

Golosov, M., Hassler, J., Krusell, P., and Tsyvinski, A. (2014). Optimal Taxes on Fossil Fuel in General Equilibrium. *Econometrica* 82 (1), 41–88. doi:10.3982/ecta10217

Griffith, R., Nesheim, L., and O'Connell, M. (2018). Income Effects and the Welfare Consequences of Tax in Differentiated Product Oligopoly. *Quantitative Econ.* 9 (1), 305–341. doi:10.3982/qe583

Häckner, J. (1999). A Note on Price and Quantity Competition in Differentiated Oligopolies. *J of Econ*, 15, 546-554. doi:10.1006/jeth.2000.2654

Häckner, J., and Herzing, M. (2016). Welfare Effects of Taxation in Oligopolistic Markets. *J. Econ. Theor.* 163, 141–166. doi:10.1016/j.jet.2016.01.007

Hoffmann, M., and Runkel, M. (2016). A Welfare Comparison of Ad Valorem and Unit Tax Regimes. *Int. Tax Public Finance* 23 (1), 140–157. doi:10.1007/s10797-015-9355-2

Lapan, H. E., and Hennessy, D. A. (2011). Unit versus Ad Valorem Taxes in Multiproduct Cournot Oligopoly. *J. Public Econ. Theor.* 13 (1), 125–138. doi:10.1111/j.1467-9779.2010.01495.x

Li, M., Liu, C., and Xu, S. (2019). "Simulation and Analysis on the Optimal Tax Rate of Water Resources in Yunnan Province. *IOP Conf. Ser. Earth Environ. Sci.* 267, 062034. doi:10.1088/1755-1315/267/6/062034

Ma, Z., Zhao, J., and Ni, J. (2018). Green Tax Legislation for Sustainable Development in China. *Singapore Econ. Rev.* 63 (04), 1059–1083. doi:10.1142/s0217590817420103

Mushtaq, S., Khan, S., Dawe, D., Hanjra, M. A., Hafeez, M., and Asghar, M. N. (2008). Evaluating the Impact of Tax-For-Fee Reform (Fei Gai Shui) on Water Resources and Agriculture Production in the Zhanghe Irrigation System, China. *Food Policy* 33 (6), 576–586. doi:10.1016/j.foodpol.2008.04.004

Nie, P.-y., and Chen, Y.-h. (2012). Duopoly Competitions with Capacity Constrained Input. *Econ. Model.* 29 (5), 1715–1721. doi:10.1016/j.econmod.2012.05.022

Nie, P.-y., Wang, C., Chen, Z.-y., and Chen, Y.-h. (2018). A Theoretic Analysis of Key Person Insurance. *Econ. Model.* 71, 272–278. doi:10.1016/j.econmod.2017.12.020

Qin, C., Jia, Y., Su, Z., Bressers, H. T. A., and Wang, H. (2012). The Economic Impact of Water Tax Charges in China: a Static Computable General Equilibrium Analysis. *Water Int.* 37 (3), 279–292. doi:10.1080/02508060.2012.685554

Singh, N., and Vives, X. (1984). Price and Quantity Competition in a Differentiated Duopoly. *RAND J. Econ.* 15, 546–554. doi:10.2307/2555525

Skeath, S. E., and Trandel, G. A. (1994). A Pareto Comparison of Ad Valorem and Unit Taxes in Noncompetitive Environments. *J. Public Econ.* 53 (1), 53–71. doi:10.1016/0047-2727(94)90013-2

Tao, A., Wang, X. H., and Yang, B. Z. (2018). Duopoly Models with a Joint Capacity Constraint. *J. Econ.*, 125, 1–14. doi:10.1007/s00712-018-0597-1

Tian, G.-l., Wu, Z., and Hu, Y.-c. (2021). Calculation of Optimal Tax Rate of Water Resources and Analysis of Social Welfare Based on CGE Model: a Case Study in Hebei Province, China. *Water Policy* 23 (1), 96–113. doi:10.2166/wp.2020.118

Vetter, H. (2014). Ad Valorem versus Unit Taxes in Oligopoly and Endogenous Market Conduct. *Public Finance Rev.* 42 (4), 532–551. doi:10.1177/1091142113496129

Vetter, H. (2017). Commodity Taxes and Welfare under Endogenous Market Conduct. *J. Econ.* 122 (2), 137–154. doi:10.1007/s00712-017-0538-4

Wang, C., Nie, P.-y., Peng, D.-h., and Li, Z.-h. (2017). Green Insurance Subsidy for Promoting Clean Production Innovation. *J. Clean. Prod.* 148, 111–117. doi:10.1016/j.jclepro.2017.01.145

Wang, X. H., and Zhao, J. (2009). On the Efficiency of Indirect Taxes in Differentiated Oligopolies with Asymmetric Costs. *J. Econ.* 96 (3), 223–239. doi:10.1007/s00712-008-0046-7

Wang, X. H., and Zhao, J. (2007). Welfare Reductions from Small Cost Reductions in Differentiated Oligopoly. *Int. J. Ind. Organ.* 25 (1), 173–185. doi:10.1016/j.ijindorg.2006.02.003

Wang, Z., and Wright, J. (2017). Ad Valorem Platform Fees, Indirect Taxes, and Efficient price Discrimination. *RAND J. Econ.* 48 (2), 467–484. doi:10.1111/1756-2171.12183

Yang, Y.-c., Nie, P.-y., Liu, H.-t., and Shen, M.-h. (2018). On the Welfare Effects of Subsidy Game for Renewable Energy Investment: Toward a Dynamic Equilibrium Model. *Renew. Energ.* 121, 420–428. doi:10.1016/j.renene.2017.12.097

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

PERSPECTIVE
published: 15 November 2021
doi: 10.3389/fenrg.2021.734010

Research on the National New Energy Strategy From the Perspective of Political Economics

Hao Pan[1], Shichang Xu[2]*, Zidi Wang[3], Zijian Liang[4] and Lingdong Zeng[4]

[1]Engaged in the Study of the Sinicization of Marxism, Administrative Management Teaching and Research Section, Party School of Jiangmen Municipal Committee of the Communist Party of China, Jiangmen, China, [2]Engaged in Open Economic Strategy and Political Economics Research, School of Marxism, Sun Yat-sen University, Guangzhou, China, [3]Institute of Enterprises Research, Sun Yat-Sen University, Guangzhou, China, [4]School of Economics and Trade, Guangdong University of Foreign Studies, Guangzhou, China

Based on the perspective of political economics analysis, this article conducts research on the national new energy strategy as the economic situation changes differently from the past. Under the socialist market economy system with Chinese characteristics, the new energy strategy is not only an inevitable choice for China as a responsible major country, but also a key measure to promoting high-quality economic development. Through the analysis of the main dilemmas faced by China's implementation of new energy strategy, this article proposes to design policies in terms of core technology research, innovative industry financing, cultivating professional talents, and continuous expansion of opening up, to originate a high-quality development path for China.

Keywords: political economics, new energy strategy, energy crisis, low-carbon economy, high-quality development, development path

Edited by:
Chan Wang, Guangdong University of Finance and Economics, China

Reviewed by:
Jingtian Huang, University of Macau, China
Wei Wanqing, Guangxi University, China
Qi Chen, Humboldt University of Berlin, Germany

Correspondence:
Shichang Xu
wzd13932397801@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *30 June 2021*
Accepted: *26 October 2021*
Published: *15 November 2021*

Citation:
Pan H, Xu S, Wang Z, Liang Z and Zeng L (2021) Research on the National New Energy Strategy From the Perspective of Political Economics. Front. Energy Res. 9:734010. doi: 10.3389/fenrg.2021.734010

CHAPTER 1. NATIONAL POLITICAL ECONOMICS OF NEW ENERGY STRATEGY

On September 22, 2020, Chinese President Xi Jinping made a statement at the general debate of the 75th session of the United Nations General Assembly, stressed that: "China will scale up its Intended Nationally Determined Contributions by adopting more vigorous policies and measures. We aim to have CO2 emissions peak before 2030 and achieve carbon neutrality before 2060."[1] This is a major strategic decision made by China based on the internal requirements of promoting a shared future for building a human community and achieving sustainable development. Afterwards, at the Third Paris Peace Forum, the Twelfth Meeting of the Leaders of the BRICS Countries, the Leaders' Side Event on Safeguarding Planet of G20 Riyadh Summit, and the World Economic Forum Virtual Event of the Davos Agenda, General Secretary Xi has mentioned the goal of achieving carbon peak and carbon neutralization many times, reflecting China's determination to actively respond to climate change.

As showed in **Figure 1**, since the 21st century, global carbon emissions have increased rapidly. From 2000 to 2019, the emissions of carbon dioxide increased by 40%. According to the data from the "World Energy Statistical Yearbook (70th Edition)" released by BP, global carbon emissions have continued to grow since 2013. In 2019, this indicator even reached 34.36 billion tons, hitting a

[1]Source: Full text of Xi's statement at the General Debate of the 75th Session of the United Nations General Assembly: http://www.xinhuanet.com/english/2020-09/23/c_139388686.htm.

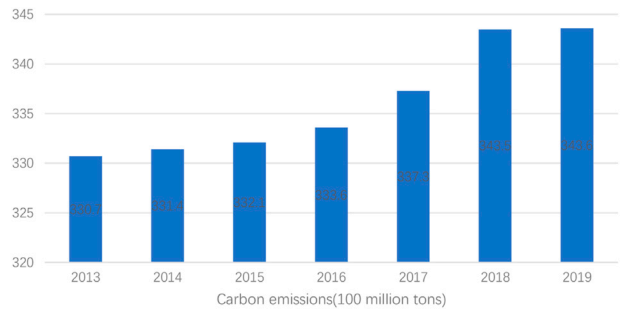

FIGURE 1 | Trends in global carbon emissions (2013–2019). Data Sources: BP "World Energy Statistical Yearbook (70th Edition)".

historical high. As the world's largest developing country, China should shoulder the responsibility of energy saving and emission reduction in the world economic development, actively respond to climate change, and look forward to global cooperation.

At the same time, China's 14th Five-Year Plan listed carbon peaking and carbon neutrality as important tasks for China's economic and social development in the next 5 years. 2021–2025 is a critical period and window period for carbon peaking, the "14th Five-Year Plan (2021–2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035" clearly states that China should implement the nationally determined contribution target for climate change in 2030 with a more active attitude, and specifically formulate action plans for peak carbon emissions to reduce carbon emission intensity, support qualified localities and industries to take the lead in reaching the peak of carbon emissions, improve the carbon sink capacity of the ecosystem, and strive to achieve carbon neutrality by 2060. To this end, the "14th Five-Year Plan" also noted that China should focus on the development of new energy and other strategic emerging industries, promote the application of core technologies, and cultivate new growth momentum for industrial development.

New energy industry is also an important engine to promote the establishment of a "dual circulation" development pattern. The main characteristics of this pattern is that it has two circulations, the domestic economic cycle plays a leading role and the domestic and international economic cycles mutually encourage each other. From the perspective of internal circulation, China's economy is gradually transforming from high-speed development to high-quality development. The transformation and upgrading of the energy structure will help ensure domestic energy security (Andrew, 2010), and deepen supply-side reforms, and create a dynamic balance of demand-driven supply and supply-creating demand. From the perspective of external circulation, Europe is currently China's second largest trading partner, the most important source of imports and the second largest export destination. The upgrading process of the European new energy industry is in line with China's improvement of the strategic position of the new energy industry, which will help the two parties become important strategic partners, promote the strengthening of the chain of China's new energy industry, expand the opening up against the background of the external economic cycle, and form a strong attraction to global resource elements.

Under the socialist market economy system with Chinese characteristics, it is not only a national strategy to promote the development of the new energy industry, but also an important starting point for accelerating high-speed and high-quality economic development. The growth of the new energy industry helps to alleviate the impact on China's healthy operation of the economy caused by the limited traditional energy reserves and large price fluctuations; at the same time, in order to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060, form new international competitive advantages and create new economic growth points, China should continue to stimulate the development of a low-carbon economy and place new energy industries in an important strategic position for economic growth (Xiliang et al., 2016). Finally, new energy industries can help moderate the over-reliance on petroleum and coal for the advancement of various industries for a very long time, and rationalize the industrial structure. Transformation and upgrading will help areas that are currently relatively underdeveloped to adapt to local conditions, give full play to the advantages of solar and wind energy, form economies of scale, and drive regional economic development.

CHAPTER 2. NEW ENERGY STRATEGY BOOSTS HIGH-QUALITY ECONOMIC DEVELOPMENT

Respond to the Energy Crisis Actively

There are three aspects of main problems exists in China's energy currently.

Firstly, China's energy is relatively scarce, and the reserves of traditional energy are limited, which cause the serious insufficiency per capita. Based on the situation, China is facing a severe energy crisis and challenge. If new energy industry can't be developed and utilized as soon as possible, China's economic structure and development will be greatly affected.

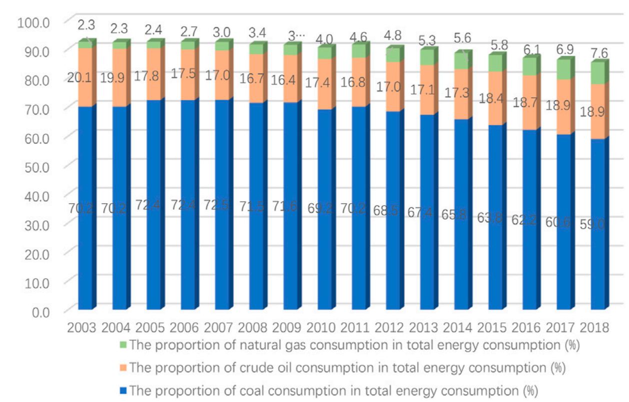

FIGURE 2 | The percentage of China's energy consumption (2003–2018). Data Sources: China Statistical Yearbook 2004–2019.

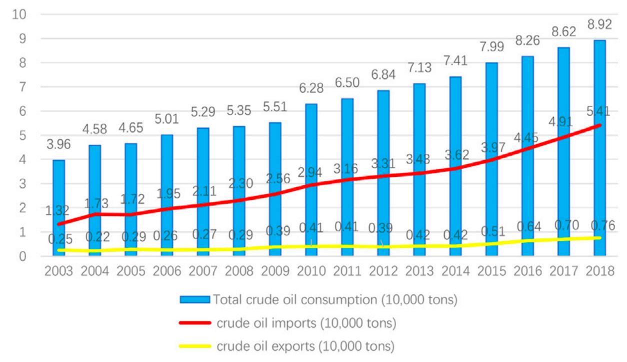

FIGURE 3 | China's crude oil consumption, import and export data (2003–2018). Data Sources:China Statistical Yearbook 2004–2019.

Secondly, China is provided with unbalanced energy structure. Most of the energy used in China is coal, which create a condition that overall utilization of traditional energy is inefficient, making it difficult to meet the needs of high-quality economic development in the new era (Xiangzhong and Yue, 2019).

Figure 2 shows the proportion of coal, crude oil and natural gas consumption in total energy consumption of China from 2003 to 2018. As the most important energy source for China's economic development, coal consumption accounts for more than 50% of total energy consumption in the past 16 years, in particular years, 2005 and 2006, this proportion was as high as 72.4%. In recent years, with the proposing of requirements about developing high-quality economic, China's dependence on coal energy has been reduced, and the proportion of coal consumption in total energy consumption fell below 60% for the first time in 2018. Corresponding to the reduction is the increase in the proportion of natural gas energy consumption, but this increase is lower than the decline in coal consumption, which indicate that China's consumption of other alternative energy sources is also increasing. On the whole, although the proportion of coal consumption is declining, China's economic development is still restricted by the heavy dependence on coal energy. It means that China needs to implement a new energy strategy to promote high-quality economic development urgently.

Thirdly, China lacks the dominance over energy prices. As the second largest oil consumer in the world, China does not have a dominant advantage in oil trading and pricing. It will not only bring a large unknown risk to the country, but also transmit the influence to the domestic bulk market and related energy industries through the price linkage mechanism, affecting the speed of the development of various domestic industries and hinder the growth of GDP.

It can be seen from **Figure 2** that the proportion of China's crude oil consumption to total energy consumption remained basically unchanged from 2003 to 2018, and has maintained at about 20%. Combined with the total oil consumption shown in **Figure 3**, the consumption of crude oil in China is increasing year by year, which shows that with the development of economy, China's energy demand is also expanding. However, reviewing the quantity of import and export of China's petroleum resources from 2003 to 2018, this paper found out that about 50% of China's crude oil consumption needs to be obtained from abroad. These data reveal the fact that China does not have a dominant advantage in oil trade and pricing, and the domestic economic development could be easily affected by fluctuations in international oil prices.

The development of new energy is an effective way to solve the problem of energy shortages and restriction. China needs to resolutely promote reforms in the energy sector, accelerate the establishment of systems and mechanisms which is conducive to the development of energy science and technology, improve the energy development environment, and advance changes in energy production and utilization methods (Ying, 2021). The development of new energy can play an important role in adjusting energy structure, reducing greenhouse gas emissions, and promoting the development of strategic emerging industries. New energy resources are rich in reserves, have renewable characteristics, and can be used permanently by humankinds, besides, new energy resources do not contain carbon or have a small carbon content, which make them more environmentally friendly. Therefore, the development of new energy industries can not only open up different energy supply channels and effectively increase the purveyance of energy, but also reduce environmental pollution, promoting economic green and low-carbon development (Qiao and Hongtao, 2021). At the same time, the development of new energy will help reduce the proportion of fossil energy in China's energy demand, solve the problem of China's economic development's heavy dependence on imported energy, relieve energy pressure, diversify the energy structure, reduce the risks brought by the weakening of the inherent energy structure, ensure national energy security, and fundamentally solve China's energy problems.

Promote the Development of Low-Carbon Economy

Low-carbon economy is conducive to enhancing core competitiveness. The essence of low-carbon economy is an economic system of efficient use of energy, development of clean energy, and pursuit of green GDP. Its core characteristics lie in the innovation of energy technology and emission reduction technology, the innovation of industrial structure and systems, and the fundamental transformation of the concept of human survival and development. A low-carbon economy is an inevitable choice to achieve economic development and protect resources and the environment. The development of low-carbon economy and the smooth advancement of energy conservation and emission reduction are inseparable from technical support (Yan and Lian, 2013). With the adjustment of energy supply and consumption structure, the intensity of China's demand for green, low-carbon, smart energy and new technologies will continue to grow.

Compared with developed countries, China has a certain gap in some advanced core technologies, carbon storage technologies and other key new energy technologies such as energy saving and emission reduction technologies. However, in other areas, such as solar and wind energy development and commercial operations, China is in a leading position in the world. At the same time, China's relatively abundant labor force makes it more cost-effective to develop a low-carbon economy. With the help of

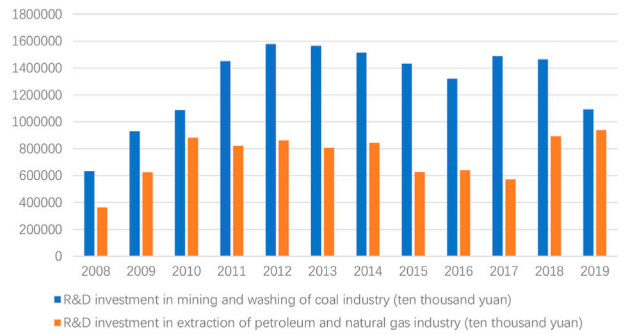

FIGURE 4 | R&D investment in mining and washing of coal, extraction of petroleum and natural gas industries (2008–2019). Data Sources: China Statistical Yearbook 2009–2020.

the development in the fields mentioned above, China will form a new competitive advantage in international competition, thereby changing the low-end image of the "world factory", starting to move towards the production of high value-added industries, and enhancing home country's core competitiveness.

In order to promote the development of the low-carbon economy, China has continuously increased its R&D investment in mining and washing of coal, extraction of petroleum and natural gas industries in recent years. As shown in **Figure 4**, with the exception of slight declines in some years, the overall upward trend in R&D expenditures for the two types of industries is obvious. This fact indicate that China is increasing investment in key new energy technologies such as advanced core technologies and carbon storage technologies, which shows China's determination to develop a low-carbon economy and implement a new energy strategy.

A low-carbon economy can help to realize the leapfrog development of China's economy. In the process of development, the low-carbon economy can continuously improve its own institutional framework, related policies and measures to promote the research and development, practice of energy-efficient science and technology, energy-saving and renewable energy technologies, and greenhouse gas emission reduction technologies. Moreover, the development of a low-carbon economy is bound to change the past extensive economic growth mode, optimize and upgrade the industrial structure and economic structure, avoid the influence of the "lock-in effect", and promote the development of related industries such as the new energy and the promotion and application of its products (Ming and Xiaowen, 2015). In addition, the rapid development of low-carbon technology in developed countries will push low-carbon products to the market, stimulate the progress of China's low-carbon technology, and further optimize China's economic development structure (Jing et al., 2016). The development of a large number of new energy projects in China will create more jobs, promote green employment, reduce China's employment pressure, ease social contradictions, industrial structure transformation and economic development model adjustments will be promoted, and China's economic development will achieve leapfrog development.

The rapid development of a low-carbon economy in the international community will prompt the establishment of new rules for the world's economic pattern. It is an urgent requirement and strategy for achieving scientific, harmonious, green and low-cost development to develop a low-carbon economy, build a low-carbon society, and encourage the fundamental transformation of China's economic development from a high-carbon energy economy to a low-carbon and carbon-free energy economy (Caineng, 2021)· At present, although China has late-comer advantages in the aspects of globalization, institutional arrangements, industrial structure, and technological revolution, it still also be constrained by the dominant international rules of developed countries. In order to Break through the constraints, China should develop the low-carbon economy to cooperate with developed countries in terms of new technology research and development (Zheng-Xin et al., 2017), enjoy the latest technological achievements, and get the opportunity to discuss and formulate new rules of the game, grasp the initiative of the country's low-carbon economic development, and promote the sustained and rapid development of the country's economy.

Contribute to the High-Quality Development of the National Economy

China's economy has shifted from a stage of rapid growth to a brand-new level of high-quality development. Under the background of achieving carbon peaking and carbon neutrality goals, the rapid growth of the new economy represented by the new energy industry has accelerated the release of the huge potential of economic development and continued to consolidate China's economic growth. The foundation of high-quality development has made China's economy more solid in its green transition.

It can be seen from **Figure 5** that as China's GDP continues to increase, the value of contract deals of new energy and power saving in domestic technical markets has also increased, that is, there is a positive correlation between China's GDP and the output value of new energy and high-efficiency energy-saving industries. In 2010, the turnover of the contract deals of new energy and power saving in domestic technical markets in China was 544,696.9 billion yuan. By 2019, it has grown to 28,135,523,

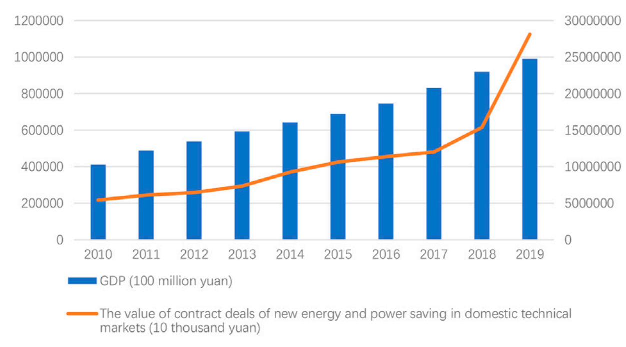

FIGURE 5 | China's GDP and the value of contract deals of new energy and power saving in domestic technical markets (2010–2019). Data Sources: China Statistical Yearbook 2011–2020.

achieving a growth rate of 416.54%. Therefore, in the process of China's economic transition to high-quality development, the new energy industry is also facing the historic development opportunities, and its potential value is closely connected with China's economy.

Developing new energy industry will bring about greater economic benefits. The rise of new energy has greatly promoted the development and upgrading of China's new energy companies, while technological research and development and manufacturing of advanced equipment require a large amount of comprehensive consumption of human and material resources, will help stimulate domestic consumption growth and provide more jobs Vacancies for the society. That is, the development of emerging industries such as new energy can add new breakthrough points and growth points to the country's economic growth (Dingbang, 2020; Qian, 2021). At the same time, environmental pollution control is a long-term process. High cost and insignificant effect are the difficulties for countries to control environmental pollution, which have always hindered the economic development of a country, while the characteristics of renewable, pollution-free, and low emissions that new energy could be used to solve the problem of environmental pollution. Gradually, new energy will reduce the state's investment in environmental governance, and promote economic development to a certain extent. Finally, new energy is an important guarantee for the national energy security strategy in the new era. It has a broad international market and the market-oriented development of the new energy industry will inevitably produce huge economic benefits, playing a vital role in the country's economic growth.

New energy industry will contribute to sustainable economic development. The development of new energy, replacing biochemical resources with new energy, and give birth to a new industrial revolution, is not only out of consideration of protecting the environment and coping with climate change (Chu et al., 2020), but also for the purpose of achieving sustainable development of the national economy. Due to its geographical location and topographic features, China has favorable conditions for the development of new energy sources such as hydropower, solar energy, and wind energy, which has laid a solid foundation for the use of new energy sources to achieve high-quality economic development. The development of the economy requires the drive of the industry, and the production of the different industries must consume a variety of energy, so after the extensive and in-depth use of new energy, when the economic production capacity remains in the same level of production compared with normal years, the lower energy cost will inevitably increase economic output in a Continuously stable way. The development and application of new energy belongs to the development of sustainable energy, and because of the high reuse rate of sustainable energy, after long-term use, energy development costs will be greatly reduced, economic energy consumption costs will be diluted, and the average cost of energy consumption will be hugely cut down, which means a substantial increase in the ratio of production capacity, and the profit margin of economic production capacity will be significantly improved. Moreover, in China's energy consumption, with the increase in the proportion of new energy sources and the progress of energy-saving technologies produced, the ability of China's economic sustainable development will be gradually improved (Bin and Boqiang, 2017).

New energy accelerates the pace of upgrading the national industrial structure (Xiaoxiao, 2015). New energy is the strategic commanding height of the new round of international competition. Developed countries and regions in the world regard the advancement of new energy as an important measure to conform to the trend of science and technology and promote the adjustment of industrial structure. The development and utilization of new energy will not only affect the energy consumption structure and production structure of the enterprise, promoting the transformation of the production mode of the enterprise, but will also stimulate the development of emerging industries in the "new energy economy". As a result, the improvement of the current industrial structure and economic structure dominated by heavy chemical industry has played an important role in driving the development of a series of related industries and improving the ability of economic operation to resist risks (Yu, 2020). Moreover, vigorously promoting the development of new energy economy is an important development strategy opportunity. Cultivating new energy industries into characteristic industries and new economic growth points will effectively motivate the healthy, rapid development of China's economy. And developing new energy industry will become an important way to effectively respond to challenges and seize development opportunities (Ahmed and Ozturk, 2018). In addition, in social and economic activities, the development of new energy industries can greatly limit and improve the production and operation of China's existing high-energy-consuming and high-polluting enterprises, prompting traditional enterprises to move closer to the development path of energy conservation and environmental protection, achieving the revolution of high energy consumption smoothly, and transforming and implement China's industrial restructuring policy.

CHAPTER 3. DEVELOPMENT PATH OF CHINA'S NEW ENERGY STRATEGY

Strengthen International Cooperation

Set up the system of exchanges and cooperation about new energy technology with other countries around the world by Taking the building of a human community with a shared future of mankind as starting point.

Form a normalized high-end theme forum to demonstrate China's attitude and sense of responsibility for participating in international ecological environment governance.

Improve Independent Innovation Capabilities

Encourage enterprises to increase investment in basic and core technology research and development, to form a batch of core technologies and independent brands with strong international competitiveness in the global economy.

Give a full play of market forces to develop constructions such as key laboratories, engineering research centers, industrial innovation centers, and enterprise technology centers.

Promote joint innovation of industry, university and research and encourage upstream and downstream enterprises to set up a joint innovation platform to stimulate the coordinated development of innovation across the industry chain and increase the conversion rate of scientific and technological achievements.

Improve Financing Channels

Innovative financial services and develop targeted financial support methods according to the rules of new energy industry technology research and development.

Strengthen cooperation between various financial institutions from the perspective of the entire industry chain, give full play to the expertise of different financial institutions in the fields of credit, trust, insurance, etc. Innovate financial products creatively to achieve full coverage of financial products in the new energy industry chain and to boost the development of the new energy industry through improving Economic efficiency.

ENHANCE TALENT TRAINING

Strengthen the talent cultivation. optimize the professional setting of universities and the new energy talent training plan. And improve the vocational qualification certification system from all aspects of every level.

Advance the introduction of talents. introduce outstanding talents from all over the world actively, and provide talents with more powerful Incentives from equity, salary and benefits.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

HP is responsible for conceiving the full-text framework and the research focus; SX (Co-Author) is responsible for organization implementation and research data collection; ZW is responsible for data and literature analysis; ZL is responsible for data and literature analysis; LZ is responsible for data and literature analysis.

REFERENCES

Ahmed, K., and Ozturk, I. (2018). What New Technology Means for the Energy Demand in China? A Sustainable Development Perspective. *Environ. Sci. Pollut. Res.* 25 (29), 29766–29771. doi:10.1007/s11356-018-2957-3

Andrew, B. K. (2010). China's New Energy-Security Debate. *Survival* 52 (3), 137–158. doi:10.1080/00396338.2010.494881

Bin, X., and Boqiang, L. (2017). Assessing the Development of China's New Energy Industry. *Energ. Econ.* 70, 116–131. doi:10.1016/j.eneco.2018.01.001

Caineng, Z. (2021). The Connotation and Path of the World Energy Transition and its Significance to Carbon Neutrality. *Acta Petrolei Sinica* 42 (02), 233–247. doi:10.7623/syxb202102008

Chu, W., Löschel, A., and Managie, S. (2020). Recent Advances in Energy Demand Research in China. *China Econ. Rev.* 63, 101517. doi:10.1016/j.chieco.2020.101517

Dingbang, C. (2020). Research on Two-Stage Economic Growth Path Based on Energy Substitution and Environmental Pollution Control. *Chin. J. Manage. Sci.* 28 (09), 146–153. doi:10.7623/syxb202102008

Jing, W., KHuangYang, S., Li, Y., Hu, T., and Zhang, Y. (2016). Driving Forces Analysis of Energy-Related Carbon Dioxide Emissions in Beijing: an Input–Output Structural Decomposition Analysis. *J. Clean. Prod.* 163, 58–68. doi:10.1016/j.jclepro.2016.05.086

Ming, L., and Xiaowen, Y. (2015). The Measurement and Dynamic Mechanism of China's Low-Carbon Economic Growth—based on the analysis of unexpected DEA and panel VAR model. *Econ. Sci.* 37 (02), 44–57. doi:10.19523/j.jjkx.2015.02.004

Qian, L. (2021). Quantitative analysis of new energy industry policy and its environmental protection effect. *J. Beijing Inst. Techn. (Social Sci. Edition)* 23 (04), 30–39. doi:10.1016/j.enpol.2021.112161

Qiao, W., and Hongtao, Y. (2021). New energy demonstration program and China's urban green economic growth: Do regional characteristics make a difference?. *Energy Policy* 151. 112161. doi:10.1016/j.enpol.2021.112161

Xiangzhong, Z., and Yue, G. (2019). FDI and China's energy efficiency: what role does the government play. *World Economy Stud.* (07), 78–89+135. doi:10.13516/j.cnki.wes.2019.07.006

Xiaoxiao, D. (2015). Energy efficiency, industrial structure and economic growth—an empirical study based on the perspective of matching. *Res. Econ. Manage.* 36 (05), 13–21. doi:10.3969/j.issn.1000-7636.2015.05.002

Xiliang, Z., Karplus, V. J., Qi, T., Zhang, D., and He, J. (2016). Carbon emissions in China: How far can new efforts bend the curve. *Energ. Econ.* 54, 388–395. doi:10.1016/j.eneco.2015.12.002

Yan, M., and Lian, W. (2013). Theoretical and empirical analysis of the mechanism of Low-Carbon Technology on Low-Carbon Economy—Based on the Perspective of Marx's Theory of Social Product Value. *J. Finance Econ.* 39 (11), 80–89. doi:10.16538/j.cnki.jfe.2013.11.004

Ying, X. (2021). Energy issues and ecological civilization construction in China' s industrialization. *Macroeconomic Manage.* 37 (02), 51–58. doi:10.19709/j.cnki.11-3199/f.2021.02.011

Yu, D. (2020). Research on the dynamic correlation between industrial economic growth and energy consumption. *J. Ind. Technol. Econ.* 39 (07), 100–106. doi:10.3969/j.issn.1004-910X.2020.07.012

Zheng-Xin, W., Zheng, H. H., Pei, L. L., and Jin, T. (2017). Decomposition of the factors influencing export fluctuation in China's new energy industry based on a constant market share model. *Energy Policy* 109, 22–35. doi:10.1016/j.enpol.2017.06.050

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 17 December 2021
doi: 10.3389/fenrg.2021.701719

Coal Supply Sustainability in China: A New Comprehensive Evaluation Methodology

Pin Li[1,2], Hongyuan Yu[3], Jinsuo Zhang[4]*, Meiyang Du[5]* and Jing Xiong[1]*

[1]China Institute of Urban Governance, Shanghai Jiao Tong University, Shanghai, China, [2]School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai, China, [3]Shanghai Institutes for International Studies, Shanghai, China, [4]School of Economics and Management, Yan'an University, Yan'an, China, [5]Antai College of Economics and Management, Shanghai Jiao Tong University, Shanghai, China

Coal is a major source of energy in China. Quantifying China's coal supply sustainability is essential to track China's efforts towards sustainable development and achieve carbon neutrality goals. In this research, in addition to availability, economic sustainability, environmental sustainability and technological sustainability, we specially considered health and security, and transport sustainability of China's coal supply. We select 19 indicators from the above six dimensions to build a coal supply sustainability index and construct a novel optimized comprehensive evaluation model with level difference maximization to evaluate China's coal supply sustainability. The results showed that the policies issued by the Chinese government have effectively improved coal supply sustainability. China's coal supply sustainability level has improved significantly, with the figure nearly doubling from 0.338 in 2000 to 0.7004 in 2019. To improve the sustainability of China's coal supply further fundamentally, it is still necessary to improve energy diversification. Since phasing out China's coal reliance requires considerable time, the Chinese government needs to introduce more positive and effective policies to such as increase the research and development support for carbon capture, utilization and storage technology, etc. to improve the sustainability of coal supply. The results of this research presented in this paper will have reference value for both promoting the sustainable development of China and other coal-consuming countries in the world.

Keywords: coal supply, sustainability, optimization, comprehensive evaluation, carbon neutral

OPEN ACCESS

Edited by:
You-hua Chen, South China Agricultural University, China

Reviewed by:
Dongxiao Yang, Hunan University of Technology and Business, China
Peng Sun, Hainan University, China

***Correspondence:**
Jinsuo Zhang
mark56zhang@163.com
Meiyang Du
meiyang.du@sjtu.edu.cn
Jing Xiong
bearnear@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *28 April 2021*
Accepted: *29 October 2021*
Published: *17 December 2021*

Citation:
Li P, Yu H, Zhang J, Du M and Xiong J (2021) Coal Supply Sustainability in China: A New Comprehensive Evaluation Methodology. Front. Energy Res. 9:701719. doi: 10.3389/fenrg.2021.701719

INTRODUCTION

Climate change is regarded as one of the greatest challenges that human society is facing in the 21st century. Facing increasingly severe climate situation, the Paris Agreement in 2016 proposed to control the global temperature rise within 2°C comparing with the level before industrialization, and do utmost to limit within 1.5°C (Wei et al., 2020). China aims to reach CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060, Chinese President Xi Jinping said to United Nations General Assembly on September 22nd in 2020 (Wang and Zhang, 2020). Carbon neutrality has great significance in improving the ecological environment, coping with climate change, and promoting high-quality development.

Coal is the foundation of China's energy security, as well as the key to achieve carbon neutrality. Up to now, the quantity of China's carbon emissions accounts for 30% of global total and China generates more than 50% global coal-fired power (Oberschelp et al., 2019; Duan et al., 2021; Cui et al., 2021; Oberschelp et al., 2019; Cui et al., 2021; Duan et al., 2021). Although many policies has adopted to limit coal consumption for years, Chinese government has also imposed stricter requirements on coal consumption control after the carbon neutral target was put forward. However, China will not eliminate coal in the short term and coal will still play an important role in ensuring China's energy security for a long period of time in the future (Zhang et al., 2020). Over the years, the Chinese government has put forward a number of measures such as the Guidance on Deepening the Reform of the Coal Marke to ensure the safety of coal supply (Yang et al., 2018). In July 2021, the National Development and Reform Commission held a special meeting on the establishment of a long-term coal supply guarantee mechanism, in this meeting the Chinese government required all localities and central enterprises to stick to the bottom line thinking, focus on building a long-term coal supply guarantee mechanism, continue to accelerate the construction of government coal reserve facilities, and promote the formation of a coal reserve system with flexible adjustments and strong guarantees. This fully reflects the importance the Chinese government attaches to ensuring the balance of coal supply and demand in China. China has more than 200 new coal-fired power stations planned or under construction that coal-fired power is an important strategic reserve in China's energy transition (Mallapaty, 2020). To achieve the goal of carbon neutrality, it is necessary to transform the development model of coal industry in order to achieve low-carbon, decarbonized, and clean development, as well as safe and sustainable development. Therefore, studying the sustainability of China's coal supply is significant in achieving the goal of carbon neutrality to China as well as to the world.

LITERATURE REVIEW

Since the concept of sustainable development was introduced, the issue of sustainable energy has attracted the attention of many organizations and scholars. It has also achieved rich and systematic research results. Coal is an important component of the energy supply system in China and in the world, and has also been the focus of many scholars' interest over the years. However, compared with the study of energy sustainability, coal supply sustainability research is still relatively lacking. Therefore, this section presents a systematic review of energy sustainability research as well as research on the sustainability issues of coal.

From the perspective of energy sustainability research, the term "sustainable energy" derives from the concept of sustainable development used in the Brantland Commission report (Our Common Future, 1987). "Sustainable development" and "resources" have become the two most common keywords related to the concept of green economy in scientific literature from 1990 (Merino-Saum et al., 2018). Munasinghe (1994) introduced the concept of sustainable energy development. They believe that the implementation of a series of energy supply and demand management policies can ultimately lead to the realization of the sustainable development of energy (sustainable Energy Development, 1995). Following these seminal work, organizations and scholars started focusing on the environmental sustainability of energy security and the relationship between energy security and energy sustainability. The European Commission (2001) stressed the importance of sustainability and environmental concerns related to energy security (Green, 2001). In 2004, the "Global Energy Assessment" published by the United Nations introduced the concept of sustainability into energy security, emphasizing environmental sustainability (Meghan, 2013). (Sovacool et al., 2011) points out that energy security is almost synonymous with energy sustainability (Sovacool et al., 2011). According to the World Energy Council (2013) (Wyman, 2013) energy security, energy equity, and environmental sustainability are the three major challenges to global energy sustainability. With more and more in-depth and extensive research, scholars construct different energy sustainability indexes that incorporate various dimensions to evaluate the sustainability of the energy system in recent years (listed in **Table 1**).

Table 1 shows that the comprehensive evaluation method is a representative method for scholars to study the sustainability of the energy system. In addition to its environmental sustainability, factors such as equity, efficiency, economy, and society are also included in the study of energy sustainability. Energy technology sustainability, energy ecurity sustainability, and energy development sustainability have all been studied thoroughly by scholars. However, few scholars have thus far considered factors such as health, security, and transportation. Moreover, there is a lack of in-depth research on the sustainability of specific energy systems, such as coal, oil, or natural gas.

From the perspective of coal sustainability research, the concept of coal sustainability rarely concerned scholars and social organisations before 2000. In 2000, while Joyce and Thomson clarified social permission, the broader concept of sustainable development started attracting attention in the mining industry Since then, sustainable development has become the main management objective of the global mining industry. With the deepening of energy sustainability research, scholars started paying attention to the relationship between coal and sustainable development from 2000 to 2010 (Breaking, 2002) (Botin, 2009). Many of these scholars proposed the importance of considering the factors related to sustainable development in the mining sector (Corder et al., 2010). After 2010, more in-depth research on risk management and the social impact on the process of coal mining was done. Risk management and accident prevention in coal mining became the foremost concerns of scholars. (Kowalska, 2014) and (Kemp et al., 2016) both assessed the social risks of the coal mining process and the operation mode of social risk in the coal industry based on a case studies method and a literature review, respectively (Kowalska, 2014; Kemp et al., 2016). (Wang et al., 2013a) used a modified curve-fitting model to forecast China's coal production capacity (CPC), and analyzed its influence on China's economy and CO_2 emissions. (Yuan et al., 2016) and (Feng et al., 2018) quantify the rational capacity and potential investment of coal power in China, and analyzed their influence on China's

TABLE 1 | Selected research on energy sustainability comprehensive evaluation.

No	Source	Year	Themes	Name of sustainability index	Dimension	No. of countries	Time frame	No. of indicators	Assessment model
1	Brown and Sovacool, (2007)	2007	Energy policy, Energy sustainability	Energy sustainability index (ESI)	Oil security, Electricity reliability, Energy efficiency, Environmental quality	1	10	12	—
2	Mondal and Denich, (2010)	2010	Renewable energy, Sustainability	—	Solar energy, Wind energy, Biomass potential, Hydro resource potential	1	—	—	GIS-based GeoSpatial Toolkit (GsT), Hybrid System
3	Tsai. (2010)	2010	Sustainable development, Renewable energy	Taiwan sustainable development indicator (TSDI)	Social, Economic, Environmental, Ecology	1	9	3	weighted-sum method
4	Raza et al. (2014)	2014	Renewable energy, Sustainability	Sustainability index	Cost, Reliability, Load response, Efficiency and life, Capacity variation, Risk factors, Environmental externalities, Energy density	1	9	9	Weighting and Aggregation
5	Kumar and Katoch, (2014)	2014	Hydropower Sustainability Indicators	Sustainability indicators	Social, Environmental, Economic	1	1	50	—
6	Mainali and Silveira, (2015)	2015	Energy technology sustainability	Energy technology sustainability index	Technical, Economic, Social, Environmental, Institutional Sustainability	3	7	11	Multicriteria analysis, PCA (principal component analysis), Weighting and Aggregation
7	Iddrisu and Bhattacharyya, (2015)	2015	Energy Sustainability	Sustainable Energy Development Index (SEDI)	Technical Sustainability, Economic Sustainability, Social Sustainability, Environmental Sustainability, Institutional Sustainability	20	1	11	Economic model
8	Narula and Reddy, (2016)	2016	Energy Supply, Energy sustainability	Sustainable energy security index	Availability, Affordability (Economic dimension), Efficiency, Acceptability	15	3	6	Scoring matrix, Weighting matrix, sensitivity analysis
9	Radovanović et al. (2017)	2017	Energy security, Sustainable approach	Energy Security Index	Energy intensity, Energy consumption, External dependence, Per capita GDP, Carbon intensity, Renewable energy share	28	23	6	PCA (principal component analysis), Weighting and Aggregation
10	Martín-Gamboa et al. (2017)	2017	Energy sustainability	Review	Technical, Economic, Environmental, Social, Mixed	—	—	—	—
11	Pavlović et al. (2018)	2018	Energy supply security	The Composite index (CI)	Energy Import Dependency Index, Energy Intensity, Gross Inland Consumption, Index of National Economy Dependence on Natural Gas, Herfindahl-Hirschman Index, Shannon-Wiener Index	1	15	6	Weighting and Aggregation
12	Sovacool and Walter, (2018)	2018	Sustainable development, Energy security	—	Security, Poverty, Development, Fiscal responsibility, Governance	5	20	5	—
13	Marquez-Ballesteros et al. (2019)	2019	Urban energy sustainability	Urban Energy Sustainability Index (UESI)	Solid waste recycling, Renewable energy power generation, Energy	2	6	4	Scenario anal

(Continued on following page)

TABLE 1 | (*Continued*) Selected research on energy sustainability comprehensive evaluation.

No	Source	Year	Themes	Name of sustainability index	Dimension	No. of countries	Time frame	No. of indicators	Assessment model
					affordability, Power supply quality				
14	Chen and Wu, (2020)	2020	Gas supply reliability	Consumer satisfaction index (CSI), Continuity indexes (CI)	Demand, Supply, loss gas amount for users, frequency that gas supply shortages happen, the time when the gas supply is insufficient	1	1	5	Monte Carlo method
15	Jie et al. (2021)	2021	Coal supply in China	—	Coal resource, import, export, final demand	—	—	—	Scenario analysis

low-carbon energy transition. Wang et al. (2018a) proposes a system dynamic (SD) model to forecast the change of China's coal production capacity CPC in three scenarios. (Chen et al., 2015) and (Wang et al., 2018b) respectively studied the phased evaluation framework of coal mine safety production and impact mechanism of safe mining (Chen et al., 2015; Wang et al., 2018b). In recent years, the environmental and health losses ascribable to coal mining have also been a foremost topic addressed by scholars. Li and Chen (2018) develops a 30-province energy system optimization model (China TIMES-30P) to simulate China's Carbon emissions during coal transportation. (Liu et al., 2018) develop an optimization model based on an appropriate index system evaluated the carbon dioxide emissions during coal transportation in China. (Zhang et al., 2018) established Hicks-neutral and Solow-neutral models to assess the coal capacity considering the technical progress, and applied the decoupling index to analyze the effect of coal CU on China's economic growth. (Liu et al., 2019) evaluated the ecological efficiency of coal mining areas in Shanxi Province based on a DEA model (Liu et al., 2019). (von der Goltz and Barnwal, 2019) used micro-data from approximately 800 mines in 44 developing countries to assess the impact of mining on health and wealth (von der Goltz and Barnwal, 2019). (Wang et al., 2020a) estimated and predicted the health loss of coal workers due to pneumoconiosis in China, while (Rauner et al., 2020) found that coal exports also have an impact on both people's health and the environment (Wang et al., 2020a; Rauner et al., 2020). Liu X (2021) estimated the potential environmental benefits of the widespread adoption of ULE in the Jing-Jin-Ji Region used atmospheric model (Liu et al., 2021). (Yan et al., 2021) studied the gas temperature and different emission gas concentration in the main combustion zone under different coal mixing ratio (Yan et al., 2021). (Zhu et al., 2021) proposed a new alternative fuel YSI value prediction model (BMKL) by using bayesian multi-core learning method (Zhu et al., 2021).

Existing research mentioned above provides important reference for this study. However, compared with energy sustainability research, coal sustainability still lack of comprehensive and systematic study. First of all, the existing coal supply sustainability research is more focused on specialized research on one or more aspects in social, environmental, safety and health impacts of coal mining. Standard in coal supply sustainability has not been established yet that it is hard to fully reflect the sustainability of coal. Secondly, coal supply is the origin of coal-related sustainable development that there is no comprehensive evaluation for coal supply sustainability. Thus, it is difficult to provide a comprehensive and systematic reference in theory and data for the sustainable development of coal under the constraints of the carbon neutral target. Thirdly, the current evaluation method is also based on a single approach with certain limitations. Therefore, the research goal of this article is to develop a more sustainable methodology to explore the sustainability of China's coal supply and to further comprehensively evaluate the policy effects and key issues of China's coal industry, in order to provide scientific guidance for the further improvement of relevant policies of China's coal industry under the constraints of carbon neutral targets in the future.

Accordingly, the remarkable contributions of this paper can be clearly illustrated as follows: First, we select coal, China's least sustainable energy source, to evaluate its sustainability. This research perspective is highly innovative and the research results of this study will have important reference value for improving the sustainability of China's coal system and achieving carbon neutrality goals. Second, we propose a comprehensive evaluation index for the sustainability of China's coal supply that can reflect China's coal industry policy objectives more comprehensively. This index could also provide a reference for other countries to evaluate their coal supply sustainability in the future. Third, contrary to the traditional comprehensive evaluation method, this study constructs a new optimized comprehensive evaluation model to assess China's coal supply sustainability, which can comprehensively reflect the advantages of subjective and objective weights. This model can also serve to solve other multi-objective attribute problems.

METHODOLOGY

China's coal supply sustainability is a multi-attribute decision-making conundrum; therefore, a comprehensive evaluation index is an important tool to quantify this problem. When utilising an evaluation index, each indicator is first given a certain weight

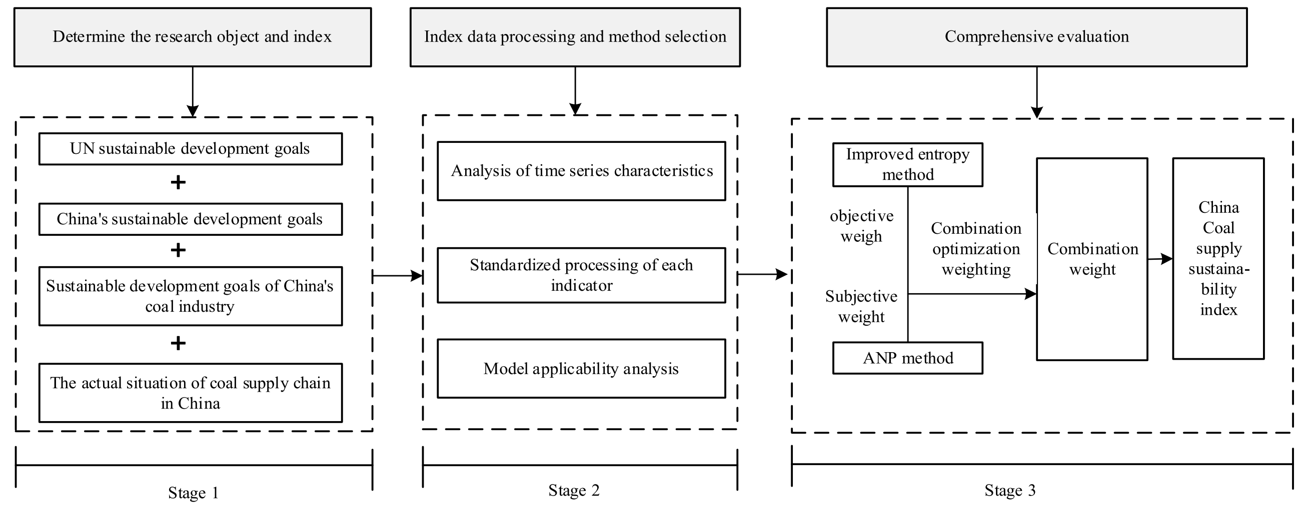

FIGURE 1 | The main research framework of this paper.

according to its perceived importance. They are then combined to create an index, using an appropriate aggregation technique. However, sustainable development indicators have high complexity and dynamic characteristics. This means that it is difficult to use an original indicator system to track the entire process of energy sustainable development. Further, directly embedding a set of original indicators flexibly into the coal system to assess the sustainability of China's coal supply system would not be effective either. Therefore, proposing a new indicator system to construct a comprehensive evaluation index that is suitable for China's coal supply sustainable development is crucial. To obtain more scientifically accurate evaluation results, different from previous scholars' research, in this paper, we put forward an 'policy objective analysis—index construction—comprehensive valuation model construction' method with three stages to perform an analysis (**Figure 1**).

China's Coal Supply Sustainability Index Design

An index is an important tool for evaluating the effectiveness of policies. The purpose of building China's coal supply sustainability index is to track the progress of China's coal supply sustainable development policies in several aspects. It can also become an operational tool to improve China's coal supply sustainability. Therefore, this study focuses on the consistency of the selected indicators and policy objectives. Considering the process of indicator selection, on the one hand, policy objectives are attached to specific indicators that can be measured by unbiased standards and are determined according to China's coal industry development policy goals and the country's actual coal supply process. The goals mentioned include "Guiding Opinions on the High-quality Development of China's coal industry in the 14th Five-Year Plan," "research on China's medium and long-term carbon emission reduction strategy target" and so on. On the other hand, it is also necessary to ensure that international goals are considered when choosing indicators. These include "Transforming our World: The 2030 Agenda for Sustainable Development," "World energy sustainable development index" and so on (Ang et al., 2015; Radovanović et al., 2017). Thus, the indicators are formulated considering global sustainable development goals. Ultimately, this study proposes the research idea of "overall goal-detailed goals -implementation path-specific indicators." As part of this research idea, in addition to availability, economic sustainability, environmental sustainability and technological sustainability, we specially considered health and security, and transport sustainability, subdivide the overall goal into six detailed goals: availability, economic sustainability, environmental sustainability, technological sustainability, health and security, transport sustainability. These six detailed goals are summarised into 17 implementation paths to design the China's coal supply sustainability index (CCSSI) (See **Figure 2**).

Tracking or interpreting changes in such a vast number of policy goals can be a problem. Furthermore, the choice of the final indicators depends upon both their complexity and ease of use. First, from the perspective of availability, coal resource endowment and coal exploration ability are the key factors affecting the sustainable supply of coal (Stefanova, 2012). The greater the reserve-production ratio, the longer the sustainable supply of coal resources and the stronger the ability to deal with coal supply risks. Additionally, the higher the self-sufficiency rate, the stronger the self-protection ability of coal resources. Coal supply per capita represents the equity of China's coal supply.

Second, from the perspective of economic sustainability, the stability of the coal price and market concentration is very important to ensure the stability of the coal supply market (Iddrisu and Bhattacharyya, 2015). Specifically, referring to the increase in China's coal imports in recent years, the influence of the international market on China's coal market cannot be

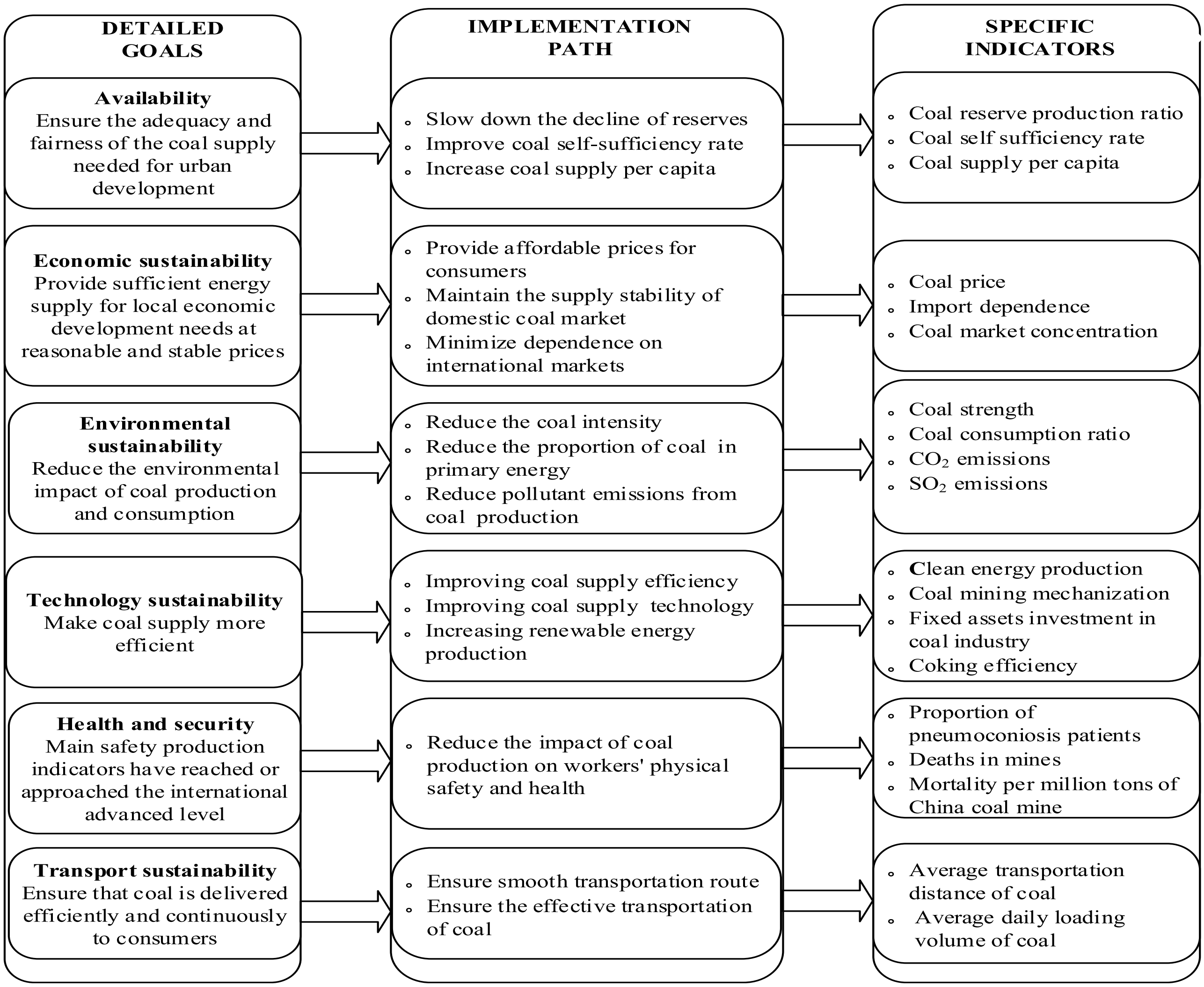

FIGURE 2 | Summary of China's coal supply sustainable goals and quantification measurements.

ignored. Therefore, this study also takes into account the indicator of external coal dependence.

Third, we address environmental sustainability. This dimension aims to reduce the negative impact of coal production and coal use on society and to increase the positive impacts. Coal resources have adverse effects on the environment during both the mining and the consumption process (Wirl, 1995). Both coal intensity and the proportion of coal supply in primary energy consumption determine the impact of coal on the environment (Laponche and Tillerson, 2001). This impact is specifically reflected by indicators such as carbon dioxide emissions, nitrogen oxide emissions, and sulphur dioxide emissions.

Fourth, from the perspective of technological sustainability, successful achievement of the United Nations' sustainable development goals requires the full use of mineral technologies (Ali et al., 2017). On a national level, government support for sustainability and investment in science and technology can effectively promote national sustainable development (Xu et al., 2020). Moreover, good infrastructure is a prerequisite for stabilising coal supply. Improved coal supply technology, systems, and practices can reduce coal demand, reduce coal intensity, and increase the sustainability level of coal supply. Technologies that improve coking efficiency and reduce the use of coal are regarded as the main policies for improving coal supply sustainability (Kemmler and Spreng, 2007; Hughes, 2009; Wei et al., 2018).

Fifth, regarding health and safety, this dimension emphasises the impact of the coal mining process on the health of workers, or production safety. Representative indicators are: proportion of pneumoconiosis patients, deaths in mines, and mortality per million tons. Finally, from the perspective of transport sustainability, the obvious imbalance of China's coal transportation market and the distribution, production, and consumption characteristics of coal resources determine the national transportation pattern of "transferring coal from the

TABLE 2 | Evaluation indexes of China's coal supply sustainability.

Criterion	Indicator	No	Attribute	Equation	Unit	Variable description	Data sources
Availability	Reserve production ratio	C1	Positive	$\frac{c_r}{c_p}$	Year	c_rAnnual reserves of coal, c_pTotal annual production of coal	Yang and Fan, (2005); Xu and Wang, (2021); Guo and Wang, (2010); Tian and Zhao, (2015)
	Coal self sufficiency	C2	Positive	$\frac{c_p}{c_c}$	%	c_pTotal coal production, c_cTotal coal consumption	Wang et al. (2013b); Fang and Zhang, (2013)
	Coal supply per capita	C3	Positive	—	—	—	—
Economic sustainability	Coal price	C4	Negative	—	—	Coal price index	Guo and Wang, (2010); Fang and Zhang, (2013); Tian and Zhao, (2015)
	Coal dependence	C5	Negative	$\frac{Q_c}{Q_i}$	—	Q_c–Coal supply in primary energy, Q_i–Net import of coal in primary energy	Xu and Wang, (2021)
	Market concentration	C6	Negative	$CR_{4=} \sum_{i=1}^{4}$, 其中 S_i $(\ⅈ = 1,2,3,4), S_i = \frac{q_i}{Q_{,,}}, \mathrm{Q} = \sum_{i=1}^{N} q_i$	—	Q Represents the sales volume of manufacturers in the market,q_i (i = 1.2, . . . , N) Represents the sales volume of the i th manufacturer,N Represents the number of manufacturers in the market.	Ai De. (2008); Tian and Zhao, (2015); Chen and Zhou, (2010); Guo and Wang, (2010); Tian and Zhao, (2015)
Environmental sustainability	Coal strength	C7	Negative	$\frac{c_c}{GDPP}$, GDPP = $\frac{GDP}{POP}$	Ten thousand tons of standard coal/yuan	*GDP*-gross domestic product *POP*-Total population	Guo and Wang, (2010); Tian and Zhao, (2015); Xu and Wang, (2021)
	Coal consumption	C8	Negative	—	%	Coal consumption proportion in primary energy	Xu and Wang, (2021); Guo and Wang, (2010)
	CO_2 emissions	C9	Negative	—	—		Jing and Jiang,

(Continued on following page)

TABLE 2 | (*Continued*) Evaluation indexes of China's coal supply sustainability.

Criterion	Indicator	No	Attribute	Equation	Unit	Variable description	Data sources
						Carbon dioxide emissions from coal industry	(2006); Guo and Wang, (2010); Wang et al. (2013b); Wang and li, (2013)
	SO_2 emissions	C10	Negative	—	%	Contribution rate of sulfur dioxide in coal industry	Jing and Jiang, (2006); Guo and Wang, (2010); Wang et al. (2013b); Wang and li, (2013)
Technological sustainability	Clean energy consumption	C11	Positive	—	%	Proportion of clean energy power consumption in total national energy generation	Jing and Jiang, (2006)
	Coal mining mechanization degree	C12	Positive	—	%	Coal mining mechanization degree	Jing and Jiang, (2006); Guo and Wang, (2010); Wang et al. (2013b); Wang and li, (2013)
	Coal Investment	C13	Positive	—	100 million yuan	Annual fixed assets investment in coal industry	Yang and Fan, (2005); Tian and Zhao, (2015); Guo and Wang, (2010); Wang et al. (2013b)
	Coking efficiency	C14	Positive	—	%	Coking efficiency	
Health and security	Proportion of pneumoconiosis patients	C15	Negative	—	%	Proportion of pneumoconiosis patients in the total number of occupational diseases	Jing and Jiang, (2006); Wang and li, (2013)
	Deaths in mines	C16	Negative	—	人	Total number of deaths per year due to mine accidents	Jing and Jiang, (2006); Wang and li, (2013); Tian and Zhao, (2015)

(Continued on following page)

TABLE 2 | (*Continued*) Evaluation indexes of China's coal supply sustainability.

Criterion	Indicator	No	Attribute	Equation	Unit	Variable description	Data sources
	Mortality per million tons	C17	Negative	—	%	Mortality per million tons of China coal mine	Jing and Jiang, (2006); Wang and li, (2013); Tian and Zhao, (2015)
Transport sustainability	Coal transportation distance	C18	Positive	—	Kilometre	Average railway transportation distance of coke	—
	Coal transportation volume	C19	Positive	—	Vehicle/ day	Daily average railway loading vehicles	—

west to the east" and "transporting coal from the north to the south." As a result, transportation has become another key factor restricting China's coal supply sustainability. China's coal is mainly transported by railway. Therefore, coal transportation distance and railway coal transportation volume are typical representative indicators. Based on the analysis mentioned above and to fully consider the availability of data and refer to relevant expert opinions in the field, 19 indicators are constructed. The source of each indicator and operation process of some complex indicators are shown in **Table 2**.

Optimal Combination Weight Model Construction

Among the numerous weighting methods in sustainability assessment, ANP(Analytic Network Process)and the entropy method (EM) are most commonly used weighting methods (Wang et al., 2009; Zhao et al., 2020). ANP is an effective, accurate and practical subjective evaluation method, which can effectively use the hypermatrix to analyze the influencing factors and synthesize the relationship between them. The entropy method (EM) can directly use the data information of the indicators themselves to determine their weight, completely avoided the deviation caused by subjective factors. This method does not have high requirements on the amount of sample data, it has a good calculation effect in the statistical analysis of small sample data, and it is a commonly used objective weighting method in the research of economics, energy, and other fields (Liu and Lin, 2019; Wu et al., 2019; Gong et al., 2021). Both methods have achieved good results in solving the weights of comprehensive evaluation indicators. However, subjective weight is better than objective weight in reflecting the importance of the indicator itself, and the objective weight is better than the subjective weight in reflecting the indicator data information level. If we only use one method for weighting, it is likely to lead to the problem of index weight bias due to the selected weight calculation methods are different. Therefore, after seriously considered the attribute of indicators for CCSSI, we develop a optimal combination weight model of level difference maximization.

This model is a subjective and objective combination weighting model which takes single index as combination unit. The method is to determine the reasonable value range of combination weight according to the subjective and objective weights, taking the interval as the constraint and the maximum discrimination of the evaluated object as the objective function, the optimization model is established, the optimal solution of the optimization model is the combination weight. The advantages of this model are mainly reflected in the following two aspects: the first advantage is this method maximizes the variance of the evaluation results of each evaluation indicator, thereby effectively highlighting the difference between each indicator. The second advantage is it can avoid the inconsistency of evaluation scores and rankings obtained by a single evaluation method. The specific steps are as below:

Step 1: Data normalization treatment.

In this paper, the evaluation indicators of China's coal supply sustainability can be divided into two categories: The first category is indicators that has a positive impact on the China's coal supply sustainability, that is, positive indicator; the other category is indicators that has a negative impact on the China's coal supply sustainability, that is, negative indicator. When the indicator is a positive index, **Formula 1** is used for normalization, otherwise, when the indicator is a negative indicator **Formula 2** is used for normalization.

$$x_{it} = \frac{v_{it} - \min(v_{it})}{\max(v_{it}) - \min(v_{it})} \tag{1}$$

$$x_{it} = \frac{\max(v_{it}) - v_{it}}{\max(v_{it}) - \min(v_{it})} \tag{2}$$

$(t = 1.2, \ldots, k; i = 1.2, \ldots m)$Where, v_{it} is the actual value of the ith indicator in year t, x_{ik} is the standardized value of the ith index in the year t.

Step 2: Determine the combination weight matrix.

Suppose that in the t year, the j-th weighting method is used to weight the i-th indicator of China's coal supply sustainability, The weight matrix A is obtained as follows:

$$A = \left[\theta_{ij}\right]_{m\times n} = \begin{bmatrix} \theta_{11}(t) & \dots & \theta_{1j}(t) & \dots & \theta_{1n}(t) \\ \cdots & \dots & \dots & \dots & \dots \\ \theta_{i1}(t) & \dots & \theta_{ij}(t) & \dots & \theta_{in}(t) \\ \dots & \dots & \dots & \dots & \dots \\ \theta_{m1}(t) & \dots & \theta_{mj}(t) & \dots & \theta_{mn}(t) \end{bmatrix} \quad (3)$$

Where,θ_{ij} is the weight of the i th indicator calculated by the j-th weighting method. (i = 1.2, . . . ,m; j = 1, 2).

Step 3: Determine the reasonable value range of combination weight.

The reasonable interval range of combination weight can be determined by matrix A. Firstly, the following three definitions are given.

Definition 1: $\forall\delta > 0$, if the combination weight θ_i of the i th indicator falls in the δ neighborhood of the subjective (objective) weight, that is, the combination weight θ_i takes into account the weight information of subjective (objective) weights. The smaller δ is, the better the combination weight is.

Definition 2: $\forall\delta > 0$, if the combination weight θ_i of the i th indicator falls in both the δ neighborhood of subjective weight and the δ neighborhood of objective weight, which indicates that the combination weight takes into account the weight information of subjective and objective weights.

Definition 3: hypothesis $\delta_i = \theta_j^+ - \theta_j^-$, then the reasonable interval of the combination weight of the i th indicator θ_i is $[\theta_i^-, \theta_i^+]$. θ_i^+ is the upper bound of the combination weight of the ith indicator, θ_j^- is the lower bound of the combination weight of the ith attribute. Among them:

$$\theta_i^+ = max\{\theta_{1i}, \theta_{2i}, \dots, \theta_{ni}\} \quad (4)$$

$$\theta_i^- = min\{\theta_{1i}, \theta_{2i}, \dots, \theta_{ni}\} \quad (5)$$

Step 4: Build a combinatorial optimization model.

Define the comprehensive evaluation result of coal supply sustainability in China is CCSSI, the standardized matrix of the i th indicator in the year t is B, then

$$B = [x_{it}]_{m\times k} = \begin{bmatrix} x_{11} & \dots & x_{1t} & \dots & x_{1k} \\ \cdots & \dots & \dots & \dots & \dots \\ x_{i1} & \dots & x_{it} & \dots & x_{ik} \\ \dots & \dots & \dots & \dots & \dots \\ x_{m1} & \dots & x_{mt} & \dots & x_{mk} \end{bmatrix}$$

$$= [X_1, X_2, \dots, X_m] \quad (6)$$

$$\text{CCSSI} = \theta X = [\theta X_1, \theta X_2, \dots, \theta X_m] \quad (7)$$

Define $X_0 = \frac{1}{m}[X_1 + X_2 +, \dots, +X_m]$, then mean value of CCSSI that is $\overline{CCSSI}$ is

$$\overline{\text{CCSSI}} = \frac{1}{m}[\theta X_1 + \theta X_2 +, \dots, +\theta X_m]$$
$$= \frac{1}{m}\theta[X_1 + X_2 +, \dots, +X_m] = \theta X_0 \quad (8)$$

Define $X_i^* = X_i - X_0$, The variance of CCSSI is $[S(t)]^2$,then

$$[S(t)]^2 = \frac{1}{m-1}\sum_{i=1}^{m}[\theta X_i - \theta X_0]^2 \quad (9)$$
$$= \frac{1}{m-1}\sum_{i=1}^{m}[\theta X_i^*]^2$$
$$= \frac{1}{m-1}\sum_{i=1}^{m}\theta X_i^*[\theta X_i^*]^T$$
$$= \frac{1}{m-1}\sum_{i=1}^{m}\theta\{X_i^*[X_i^*]^T\}[\theta]^T$$

Step 4: Solving the combinatorial optimization model.

Take the maximum of $[S(t)]^2$ as the objective function, then take the sum of combination weight of different indicators and the reasonable range of indicators as shown in **Eqs 4**, **5** as the constraint condition, we build a level difference maximization model as follows:

$$max\frac{1}{m-1}\sum_{i=1}^{m}\theta\{X_i^*[X_i^*]^T\}[\theta]^T \quad (10)$$
$$\text{s.t.}\begin{cases} \sum_{i=1}^{m}\theta_i = 1 \\ \theta_{i.}^- \le \theta_i \le \theta_{i.}^+ \end{cases}$$

The combination weight θ_i of each indicator i can be obtained by solving **Equation 10**, then we can calculate out CCSSI by **Eq. 11**

$$\text{CCSSI} = \sum_{i=1}^{m} x_{it} \times \theta_i \quad (11)$$

Data Sources

This study analyzes the China's coal supply sustainability from 2000 to 2019. The dadas for indicators as coal supply per capita, coal price, coal consumption, CO_2 emissions, SO_2 emissions, clean energy consumption, coal mining mechanization degree, annual fixed assets investment in coal industry, coking efficiency, proportion of pneumoconiosis patients in the total number of occupational diseases, total number of deaths per year due to mine accidents, mortality per million tons of China coal mine, average railway transportation distance of coke and daily average railway loading vehicles were got from China Statistics Yearbook (2000–2020), China Energy Statistical Yearbook (2000–2020), BP World energy statistical database, China coal industry yearbook (2000–2020), the Wind database and Kwah Big Data Center. However, the data for reserve production ratio, coal self sufficiency rate, coal dependence, coal Market concentration and coal strength are not publicly available, so we have to calculate these indicators on our own. The details of how we estimate them are provided in **Table 2**.

RESULTS AND DISCUSSIONS

Indicator Weights for China's Coal Supply Sustainability

After analyzing the characteristics of each indicator for CCSSI and the applicability of the comprehensive evaluation model, we

TABLE 3 | Combination weighting results by maximizing the level difference method.

Indicator	Objective weight	Rank 1	Subjective weight	Rank 2	Interval of combination weight	Combination weight	Final rank
C1	0.079	3	0.0686	5	(0.0686, 0.079)	0.079	3
C2	0.0323	16	0.0633	6	(0.0323, 0.0633)	0.051	10
C3	0.0679	5	0.077	4	(0.0679, 0.077)	0.077	4
C4	0.0238	19	0.0172	19	(0.0172, 0.0238)	0.017	18
C5	0.0376	13	0.029	16	(0.029, 0.0376)	0.029	17
C6	0.0375	14	0.033	13	(0.033, 0.0375]	0.033	15
C7	0.065	6	0.0871	3	(0.065, 0.0893)	0.065	6
C8	0.0915	2	0.0926	2	(0.0915, 0.0926)	0.082	2
C9	0.0699	4	0.0568	9	(0.0568, 0.0699)	0.070	5
C10	0.0542	9	0.0607	7	(0.0542, 0.0607)	0.0542	9
C11	0.0976	1	0.1104	1	(0.0976, 0.1104)	0.1104	1
C12	0.0278	17	0.0296	15	(0.0278, 0.0296)	0.0296	16
C13	0.0614	8	0.0482	11	(0.0482, 0.0614)	0.0614	7
C14	0.043	11	0.0405	12	(0.0405, 0.043)	0.043	12
C15	0.0641	7	0.0604	8	(0.0604, 0.0642)	0.0604	8
C16	0.045	10	0.0526	10	(0.045, 0.0526)	0.045	11
C17	0.025	18	0.0172	18	(0.0151, 0.025)	0.0151	19
C18	0.0358	15	0.0233	17	(0.0233, 0.0358)	0.0358	14
C19	0.0416	12	0.0326	14	(0.0416, 0.0429)	0.0421	13

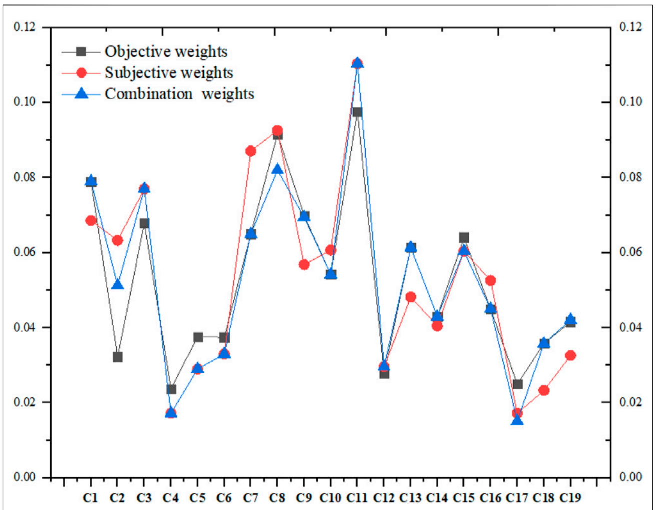

FIGURE 3 | Evolution of weight of each indicator by three methods.

utilize the data of each indicator for CCSSI from 2000 to 2019 as the sample, normalize them by **Formula 1** or **Formula 2**, and calculate the subjective and objective weights of each indicator based on the ANP method and the entropy method. We then use these weights to determine a reasonable value range for the combination weight of each indicator. Lastly, we determine the optimal combination weight of each indicator by solving the combination weighting optimization model (7). The subjective weight, objective weight, combination weight and rank of each indicator for CCSSI are shown in **Table 3**. In order to further present the effect of the combined optimization model in this paper, we made a chart of the weights for each indicator of CCSSI, as shown in **Figure 3**. **Figure 3** shows clearly that, compared with the single weighting method of the ANP method and the entropy method, the optimal combination weight have better distinguishing ability, which can better reflect the effect of each indicator on CSSI. This also verifies the rationality of the combinatorial optimization model constructed in this paper.

As shown in **Table 3**, the weight of each indicator is arranged in order: proportion of alternative energy consumption (C11), coal supply proportion in primary energy (C8), reserve production ratio (C1), coal supply per capita (C3), CO_2 emissions (C9), coal strength (C7), investment in fixed assets (C13), proportion of pneumoconiosis patients (C15), SO_2 emissions (C10), coal self-sufficiency rate (C2), deaths in mines (C16), coking efficiency (C14), coal transportation volume (C19), coal transportation distance (C18), market concentration (C6), coal mining mechanization degree (C12), coal degree of dependence (C5), coal price (C4), and mortality per million tons of China coal mine (C17). The weights represent the impact of each indicator on the CCSSI. These results are consistent with the policy objectives for the sustainable development of China's coal industry. It also fully demonstrates the rationality of the research methodology used in this study.

Of the six different dimensions, the top three were environmental sustainability (0.2707), technological sustainability (0.2444), and availability (0.2073); the bottom three were therefore health loss (0.1205), economic sustainability (0.0792), and transport sustainability (0.0779). This result is consistent with the actual coal supply situation in China. Although it is an energy resource with a high degree of pollution, coal has the highest consumption in China. The environmental sustainability of China's coal supply not only determines China's coal supply sustainability, but also has great significance for China's overall sustainable development. Therefore, environmental sustainability ranks first. China's coal technology not only determines the amount of coal supply, but it also plays a role in the environmental impact and health loss

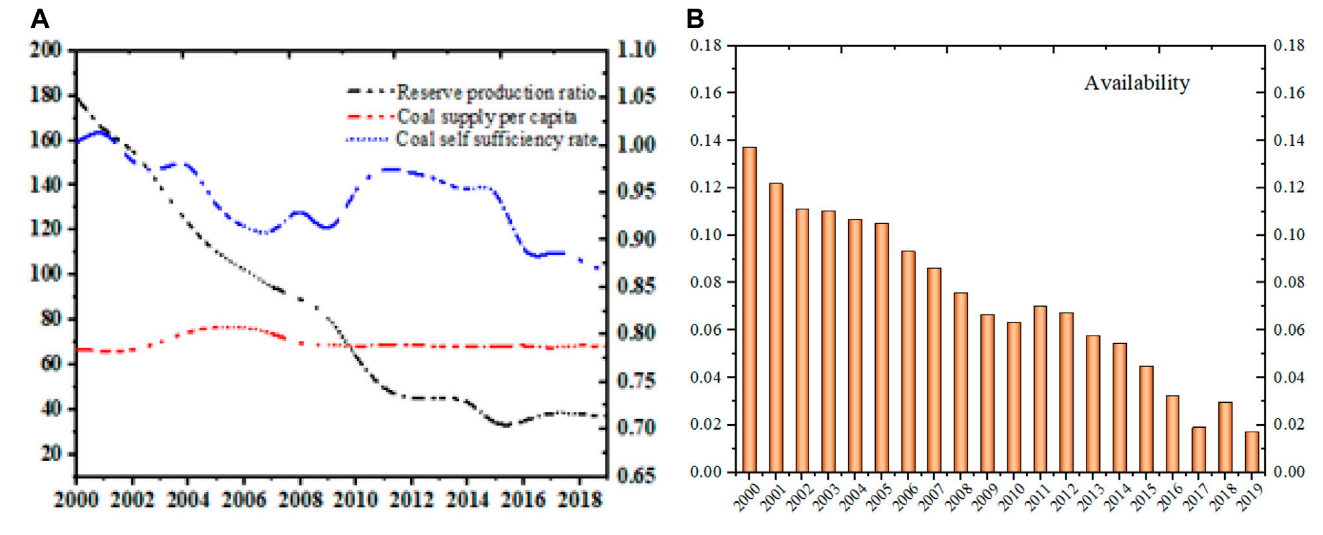

FIGURE 4 | Availability results from 2000 to 2019: **(A)** indicator value; **(B)** dimension value.

related to coal supply. Therefore, technological sustainability ranks second. In this dimension, the proportion of alternative energy consumption ranks first. This shows that if Chinese government want to fundamentally improve their coal supply sustainability, they still need to rely on renewable energy. But coal is the main energy resource in China. Therefore, the availability of coal is not only a basic requirement to ensure China's coal supply sustainability, but it is also an important indicator of China's energy supply sustainability. Therefore, the availability of coal resources ranks the third. China's coal resources rely mainly on the country's self-sufficiency. China's coal prices are becoming more and more concentrated in the market and the degree of dependence on foreign coal is low; therefore, China's coal has strong economy sustainability. Although China's coal is unevenly distributed from east to west, the coal supply has never been interrupted due to unsustainable transportation. In recent years, China's increasing coal imports have further eased the pressure of coal transportation to coastal areas in China and reduced the coal price from inland to coastal cities (Rioux et al., 2016). Therefore, compared with economic sustainability and transportation sustainability, the health loss related to China's coal supply has a greater impact on its sustainability.

Dimension Results

The results here are presented in terms of dimensions to determine the strengths and weaknesses of China's coal supply sustainability. **Figure 4** clearly shows the change characteristics of the three indicators in the coal availability dimension. We find that both reserve production ratio and the coal self-sufficiency rate indicators showed a significant downward trend during the study period. Within this period, the coal supply per capita remained virtually unchanged; except for a slight increase from 2003 to 2007, it remained at approximately 68 kg per capita. The decrease of the availability dimension from 2000 to 2010 is caused by the decreasing of reserve production ratio and coal self-sufficiency, whereas the increase of availability dimension from 2011 to 2016 is caused by the improvement of coal self-sufficiency.

Figure 5 shows the change characteristics of the three indicators in the economic sustainability dimension. During the sample interval, China's coal price was very volatile. Coal dependence showed an inverted U-shaped trend before 2012 and started increasing continuously after 2012. Market concentration dropped sharply in the sample interval, which reflects the increasing concentration of China's coal market. The economic sustainability dimension decreased from 2000 to 2019. It decreased rapidly from 2000 to 2004 mainly due to the increase of coal price and coal dependence. And after 2004, the economic sustainability dimension is around 0.03, and it declined mainly due to the sharp change of coal price.

Figure 6 shows the change characteristics of the four indicators in the environmental sustainability dimension. Except the CO_2 emissions indicator, all indicators—coal strength, coal supply, and SO_2 emissions—showed a downward trend. Among them, the coal strength indicator declined the fastest, indicating that the unit output of coal consumption per capita in China is decreasing significantly. Environmental sustainability dimension decreased from 2000 to 2005 mainly because the increase of coal strength coal consumption and SO_2 emissions. After 2005, it increased rapidly, this fully demonstrates the effectiveness of the environmental policies adopted by the Chinese government.

Figure 7 presents the change characteristics of the four indicators in the technological sustainability dimension. China's coal investment showed a rapid upward trend before 2012, after which it showed a significant V-shaped trend from 2013 to 2019. The indicators for clean energy consumption and coal mining mechanization degree increased slightly; however, the coking efficiency indicator decreased slightly in recent years. Technological sustainability dimension increased sharply from 2000 to 2019 mainly because the increase of coal mining mechanization degree coal investment.

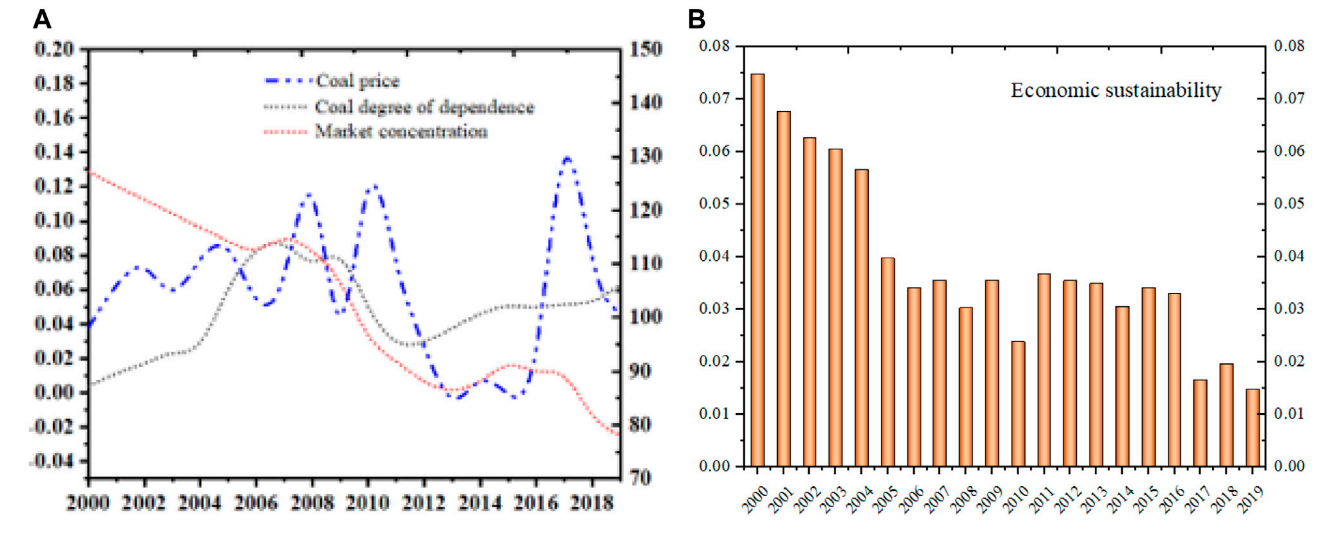

FIGURE 5 | Economic sustainability results from 2000 to 2019: (A) indicator value; (B) dimension value.

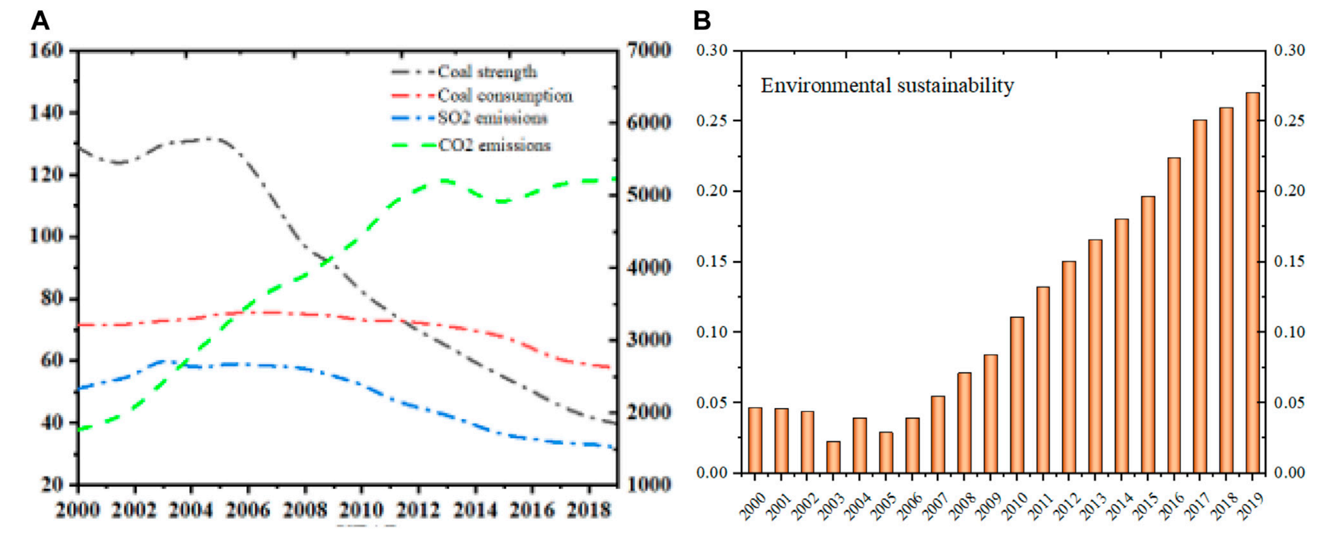

FIGURE 6 | Environmental sustainability results from 2000 to 2019: (A) indicator value; (B) dimension value.

Figure 8 shows clearly the change characteristics of the three indicators in the health and safety dimension. Within the sample interval, the deaths in mines and mortality rate per million tons dropped significantly. However, the proportion of pneumoconiosis patients increased slightly after 2010. This does not explain why the degree of absenteeism in China's coal mines is getting worse and worse, despite safety protocols. The reason for the increase in diagnosed miners is that the Chinese government increased its efforts to detect pneumoconiosis as a reason for absenteeism after 2010. Coal miners who had not been tested for pneumoconiosis before 2010 were gradually tested in these years. In addition, this is also because pneumoconiosis itself is a chronic disease with a longer period of onset. Health and security dimension is lower than 0.4 from 2000 to 2003 mainly because the increase of pneumoconiosis patients and sharp increase of deaths in mines, especially the sharp increase of deaths in mines. After 2009, with the sharp decrease of deaths in mines, health and security dimension become increased.

Figure 9 shows clearly the change characteristics of the two indicators in the transport sustainability dimension. China's coal transportation distance has been increasing from 2000 to 2019; however, the coal transportation volume declined after 2011 and then increased again. It is very interesting that the overall trends of coal transportation volume and the coal investment curve is very consistent. It reflects that China's coal transportation volume is closely related to coal industry investment. It shows clearly that the trend of transport sustainability is very similar to the trend of

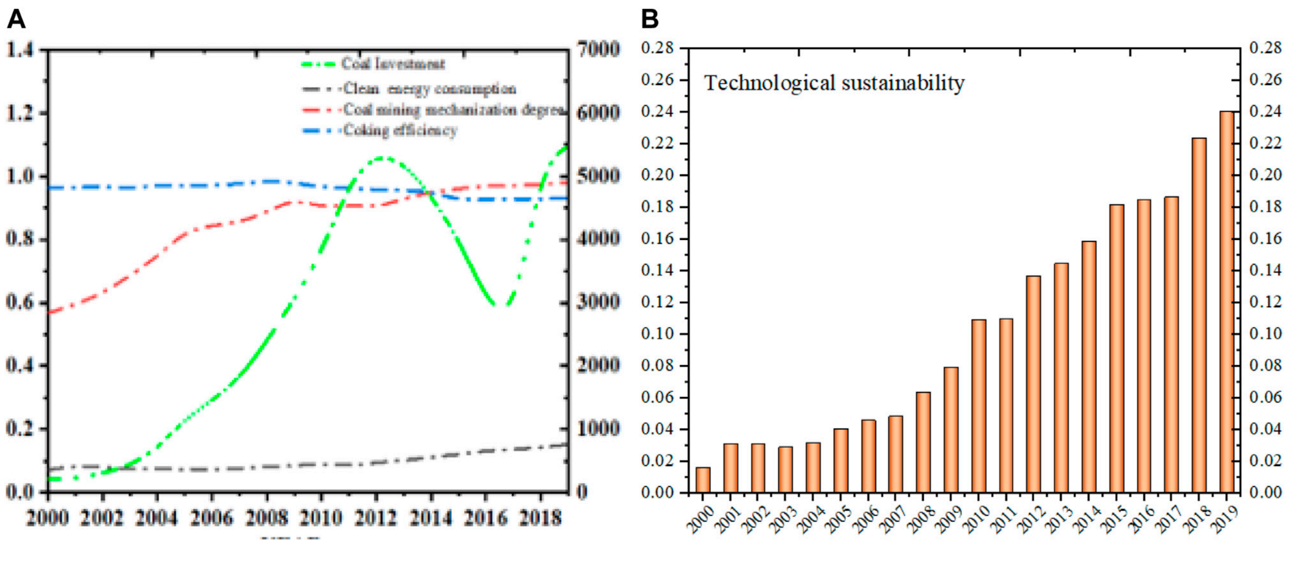

FIGURE 7 | Technological sustainability results from 2000 to 2019: **(A)** indicator value; **(B)** dimension value.

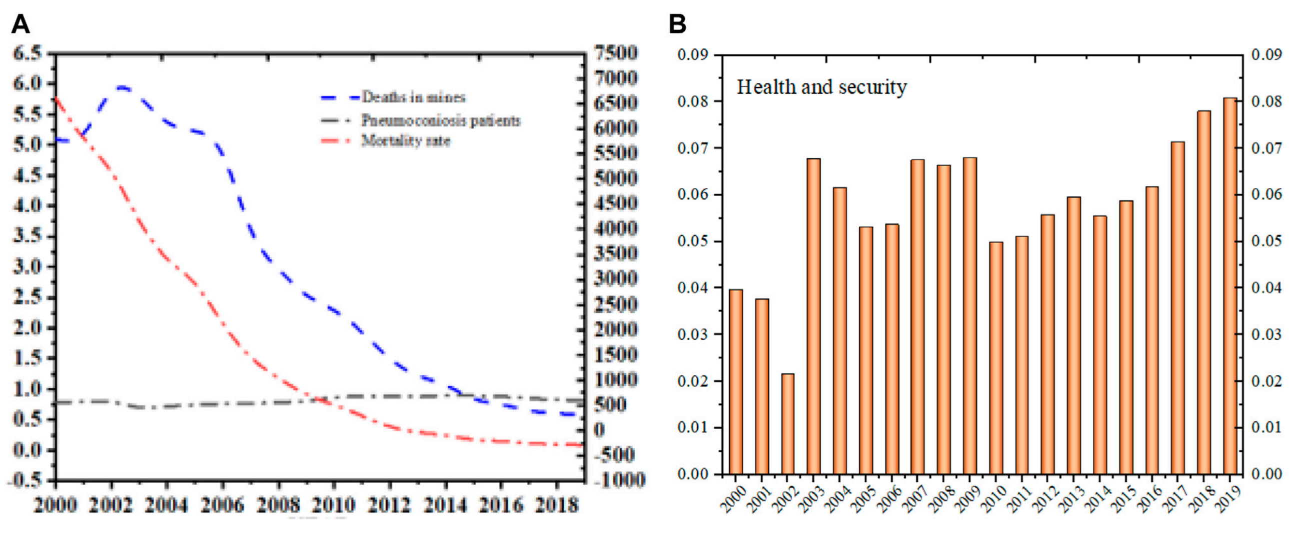

FIGURE 8 | Health and safety results from 2000 to 2019: **(A)** indicator value; **(B)** dimension value.

coal transportation volume, which fully proved that coal transportation volume is the main determinant of coal transport sustainability.

The average value of availability, economic sustainability, environmental sustainability, technological sustainability, health and security and transport sustainability dimensions between 2000 and 2019 are 0.0736, 0.0388, 0.1209, 0.1045, 0.0580 and 0.0445, respectively. The highest average dimension value is environmental sustainability, while the lowest is economic sustainability. The dimensions that increases more quickly from 2000 to 2019 are environmental sustainability and technological sustainability, whereas availability and economic sustainability dimensions are tend to decrease. Thus, the environmental sustainability and technological sustainability should be improved immediately to create a more sustainable coal supply (see **Figure 10**).

Comprehensive Evaluation Results for China's Coal Supply Sustainability

The optimal combination weight of each CCSSI indicator in **Figure 11** is substituted into **Formula 11** to obtain the CCSSI from 2000 to 2019. The evolution trend and change rate of CCSSI are shown in **Figure 12**. **Figure 12** shows that within the sample interval, China's energy supply sustainability improved significantly, from 0.3102 in 2000 to 0.7004 in 2019. However,

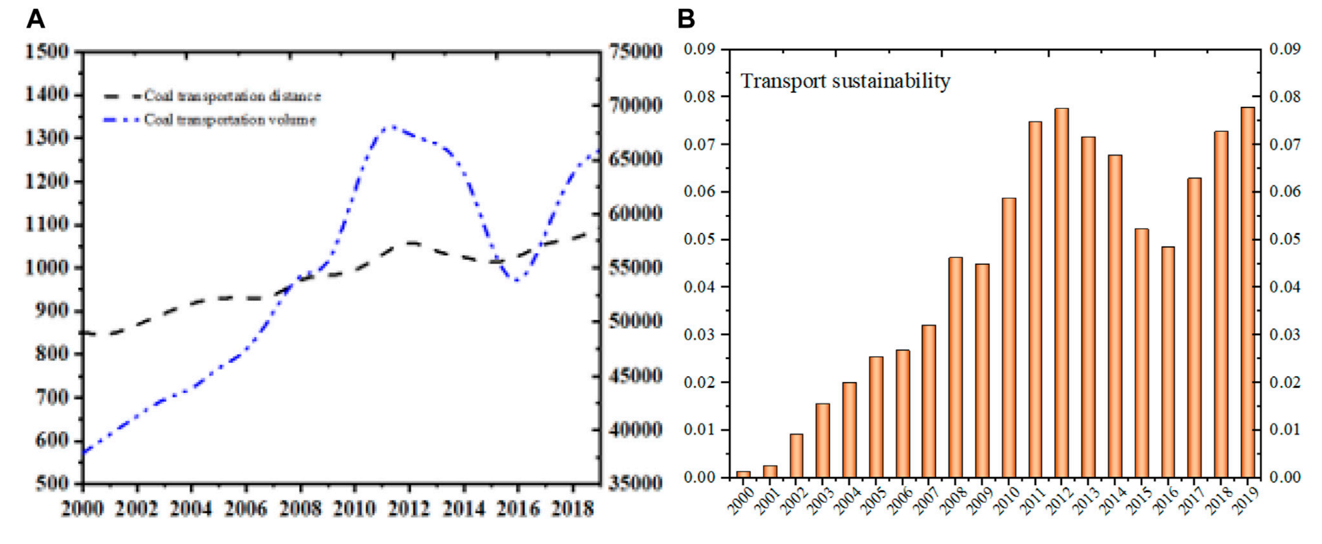

FIGURE 9 | Transport sustainability results from 2000 to 2019: **(A)** indicator value; **(B)** dimension value.

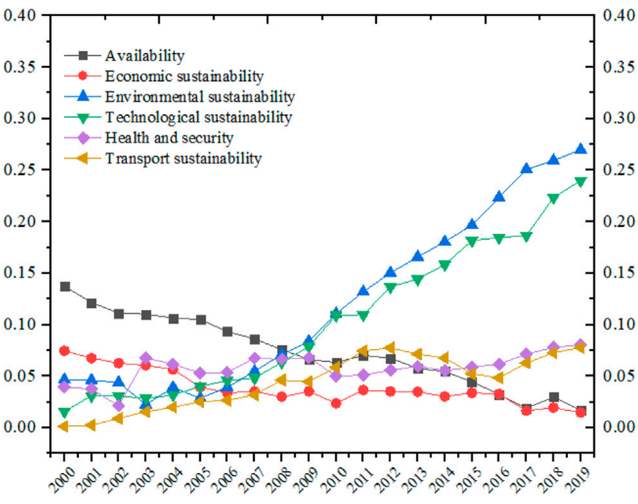

FIGURE 10 | Comparison of different dimensions values between 2000 and 2019.

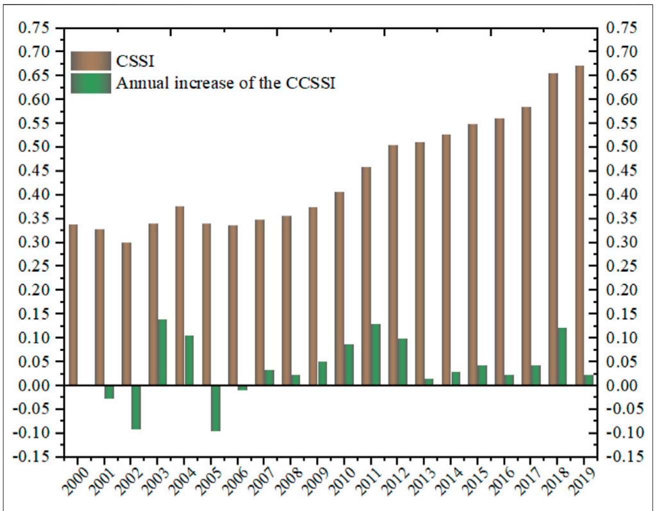

FIGURE 11 | Evolution trend of China's coal supply sustainability.

it is obvious that the overall level of China's energy supply sustainability is not high.

From 2000 to 2005, China's coal supply sustainability level fluctuated greatly. Compared with the year 2000, China's coal supply sustainability began to decline from the year 2001, the decline rate reached as high as 8.59% in the year 2002. In the year 2003, China's coal supply sustainability started increasing rapidly. In the year 2003 and the year 2004, the growth rate reached 17.26 and 12.32% respectively. However, in the year 2005, there was a decline of 7.58%. Because of the rapid development of China's economy from 2000 to 2005, the proportion of coal in primary energy consumption increased from 71.5% in 2000 to 75.4% in 2005. However, for this period, China's.

Coal technology was relatively unsophisticated and coal mine safety accidents were also very frequent. According to statistics, there were 18,514 accidents in China's coal mines from 2001 to 2005, which caused 31,064 deaths. The average annual number of coal mine safety accidents of all kinds was 3,702, and the death toll of mine accidents reached 6,213 in this period.

Since 2006, China's coal supply sustainability index has been increasing, especially during the period from 2009 to 2012 and during 2018. This is because after 2007, the Chinese government increased investment in coal mine safety, continuously improved equipment and the level of safety technology, and paid attention to safety technology training and safety education among coal mine workers. Since then, China's coal production has increased continuously, the mortality rate per million tons has gradually decreased, and the coal mine supply safety situation has obviously

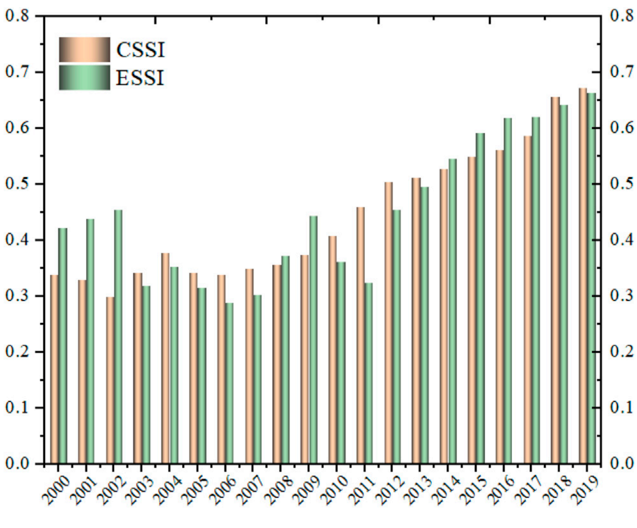

FIGURE 12 | Comparison of CSSI and ESSI

improved. From 2008, the Chinese government started paying attention to the importance to renewable energy. More than 20 related supporting policies—including supporting electricity price and investment subsidies—have been successively issued. This has effectively promoted the industrial progress of renewable energy. Considering the emission standard of air pollutants for thermal power plants, in 2011, a new version of "the emission standard of air pollutants for thermal power" was issued by the Chinese government. This regulation greatly increased the emission concentration requirements of sulphur dioxide, nitrogen oxides, smoke, and dust, some of these regulations are even stricter than the European Union standards, which greatly urging thermal power plants to carry out energy-saving and emission-reducing transformation to reduce emissions and to add waste gas treatment and disposal facilities to improve the environmental impact of coal supply. With the support of the series of policies mentioned above, the supply sustainability level of coal in China improved significantly, from 0.3849 in 2009 to 0.5293 in 2012.

After 2013, China's coal supply sustainability index increased steadily at a speed of about 0.2% per year; however, in 2018, the growth rate suddenly increased to 12.45%. This is because in this period, China's carbon emissions increased rapidly (Wang et al., 2020b). Coal, as China's main energy source, still produces a lot of environmental pollution and health losses. China's coal technology is still less developed than many developed countries, and in recent years, the import of coal has also increased significantly. In 2018, China's coal consumption fell below 60% for the first time. The significant increase of CCSSI in 2018 than 2017 shows clearly that the promotion speed for CCSSI brought by clean energy substitution is much higher than that of other coal sustainable development policies issued by China. Interestingly, the evolution trend of China's coal supply sustainability is almost consistent with the functional curve of China's energy security. This result is also consistent with China's actual coal supply situation. As the main energy source in China, the sustainable supply of coal determines China's energy security; this also reflects the important role of coal for China's energy security.

DISCUSSIONS

As referring to the Li et at (Li and Zhang, 2019) about China's energy supply sustainability (ESSI), here we get the comparison results of China's energy supply sustainability (ESSI) and China's coal supply sustainability (CSSI) as seen in **Figure 12**. From the change trend of CSSI and ESSI, ESSI is a little bit more volatile, because ESSI is influenced not only by the sustainability of China's coal supply, but also by oil, gas, renewable energy, and complex factors both at home and abroad. In **Figure 11**, it is very clear that the economic crisis of 2008, the economic crisis has reduced energy consumption in most countries around the world while maintaining large supplies, and thus CSSI and ESSI all increased (Erahman et al., 2016). This also explains the linear relationship between economic sustainability and energy supply sustainability. As refer to (Gong et al., 2021) measured the energy security levels of 30 provinces in China from 2004 to 2017 the entropy weight method, they found that the energy security level of Inner Mongolia, Shanxi, and Shaanxi ranked in the top three in China. These three provinces are very rich in coal resources in China. Once again verified the important role of coal for China's energy security. It shows that the entropy method is suitable for the study of small sample and multi-index attribute problems such as energy security and coal supply sustainability.

CONCLUSION AND POLICY IMPLICATIONS

Based on the United Nations' sustainable development agenda, focuses on the Chinese carbon neutrality goals, and according to the characteristics of coal supply in China, this paper designs the research framework of 'policy objective analysis—index system construction—model construction—empirical research' taking China's theme energy coal as the research object. On the basis of previous studies, aiming at the practical problems and difficulties in China's current coal supply process, and in particular, the health and security, and transport sustainability indicators are taken into consideration, we proposed a China's coal supply sustainability index based on six aspects: availability, economic sustainability, environmental sustainability, technological sustainability, health and security, and transport sustainability. Then fully considered advantages of ANP and EM models, we constructed a novel optimized comprehensive evaluation model with level difference maximization, and assessed the sustainability of China's coal supply over the past 20 years from 2000 to 2019.

This study found that the sustainability of China's coal supply has been greatly improved from 2000 to 2019, indicating that China's coal supply is becoming more and more sustainable. Mainly credit to the greatly improved environmental sustainability and technological sustainability. Among them, the substitution of renewable energy, the improvement of coal mechanization and the implementation of related environmental policies are the fundamental reasons. Economic efficiency has a negative effect on the sustainability of coal supply, this result is consistent with the World Energy Trilemma Index and also in line with the reality of the Chinese coal market.

Although China will continue to develop renewable energy and take more measures to reduce coal consumption in the process of achieving the carbon neutral goal, China's coal consumption may increase in the short term, especially in the next 5 years. In the long run, even if renewable energy develops vigorously, coal will play an important role in ensuring the flexibility of the power system in the future. Improving the sustainability of coal supply is of great significance to ensuring the security of China's energy supply.

According to the research results of this paper, the optimal coal supply system in China should be an advanced and intelligent supply system with zero emissions of CO_2, SO_2 and other pollutants, zero death, stable market price and sufficient supply. In the future, coal power plants have strong flexibility, which can flexibly adjust the peak, make up for the instability of renewable power such as solar power and wind power, improve the current situation of insufficient power supply in some areas in some years, and ultimately promote the adequate supply and clean supply of the power system. Therefore, in addition to continuing to promote technological innovation in the coal field, we must also vigorously promote the application of blockchain technology, big data and other technologies in the energy system to improve the efficiency of coal mining and use, and ensure that the supply of coal is available. Persistent (Weng and Huang, 2021). Moreover, there is an urgent need to increase policy flexibility, focus on building a new development pattern of domestic and international double cycles and mutual promotion, organically combine domestic development with strengthening international cooperation, and make better use of both domestic and foreign markets and resources. To promote a win-win relationship between carbon peaking and coal sustainability in the process of opening up to the outside world, so as to achieve high-quality development of the coal industry and sustainable economic and social development.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors contributed equally to this work. JZ proposed the original idea; JX modified and refined the manuscript; PL designed the research and wrote the manuscript; HY optimized the methodology and embellished the picture in this paper. MD provided most of the important data and edited the language. All authors read and approved the final manuscript.

FUNDING

This research was supported by the National Natural Science Foundation of China under grant nos. 71273206 and 72004181, by the National Social Science Foundation of China under grant nos. 18AZD005 and 20BJY076, and by the China Postdoctoral Science Foundation, grant no. 2019M663781.

ACKNOWLEDGMENTS

The authors would like to express their sincere thanks to the anonymous referees as well as the editors.

REFERENCES

Ai De, C. (2008). *Forecast and Early-Warning on Coal Supply and Demand Balance in China[D]*. China: China University of Mining and Technology.

Ali, S. H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., et al. (2017). Mineral Supply for Sustainable Development Requires Resource Governance. *Nature* 543 (7645), 367–372. doi:10.1038/nature21359

Ang, B. W., Choong, W. L., and Ng, T. S. (2015). A Framework for Evaluating Singapore's Energy Security. *Appl. Energ.* 148, 314–325. doi:10.1016/j.apenergy.2015.03.088

Botin, J. A. M. (2009). *Managing Project Feasibility and Construction: Sustainable Management of Mining Operations*. Littleton, USA: Society for Mining, Metallurgy, and Exploration, 207–260.

Breaking, I. (2002). *New Ground: Mining, Minerals and Sustainable Development (Report of the MMSD Project)[M]*. Earthscan Publications Limited.

Brown, M. A., and Sovacool, B. K. (2007). Developing an 'energy Sustainability index' to Evaluate Energy Policy. *Interdiscip. Sci. Rev.* 32 (4), 335–349. doi:10.1179/030801807x211793

Chen, F., and Wu, C. (2020). A Novel Methodology for Forecasting Gas Supply Reliability of Natural Gas Pipeline Systems. *Front. Energ.* 14 (2), 213–223. doi:10.1007/s11708-020-0672-5

Chen, S.-S., Xu, J.-H., and Fan, Y. (2015). Evaluating the Effect of Coal Mine Safety Supervision System Policy in China's Coal Mining Industry: A Two-phase Analysis. *Resour. Pol.* 46, 12–21. doi:10.1016/j.resourpol.2015.07.004

Chen, X., and Zhou, D. (2010). An Empirical Study of Market Concentration of China's Coal Industry[J]. *Contemp. Finance Econ.* (02), 80–89.

Corder, G. D., Mclellan, B. C., and Green, S. (2010). Incorporating Sustainable Development Principles into Minerals Processing Design and Operation: SUSOP. *Minerals Eng.* 23 (3), 175–181. doi:10.1016/j.mineng.2009.12.003

Cui, R. Y., Hultman, N., Cui, D., McJeon, H., Yu, S., Edwards, M. R., et al. (2021). A Plant-By-Plant Strategy for High-Ambition Coal Power Phaseout in China. *Nat. Commun.* 12 (1), 1468. doi:10.1038/s41467-021-21786-0

Duan, H., Zhou, S., Jiang, K., Bertram, C., Harmsen, M., Kriegler, E., et al. (2021). Assessing China's Efforts to Pursue the 1.5°C Warming Limit. *Science* 372, 378–385. doi:10.1126/science.aba8767

Erahman, Q. F., Purwanto, W. W., Sudibandriyo, M., and Hidayatno, A. (2016). An Assessment of Indonesia's Energy Security index and Comparison with Seventy Countries. *Energy* 111, 364–376. doi:10.1016/j.energy.2016.05.100

Fang, X., and Zhang, W. (2013). Sustainability of China's Coal Import and Adjustment of Import Country Structure -- Strategic Thinking on China Russia Coal Cooperation and Development and Utilization of Russian Far East Coal Resources [J]. *Contemp. Econ. Res.* 000 (011), 22–29.

Feng, Y., Wang, S., Sha, Y., Ding, Q., Yuan, J., and Guo, X. (2018). Coal Power Overcapacity in China: Province-Level Estimates and Policy Implications. *Resour. Conserv. Recycl.* 137, 89–100. doi:10.1016/j.resconrec.2018.05.019

Gong, X., Wang, Y., and Lin, B. (2021). Assessing Dynamic China's Energy Security: Based on Functional Data Analysis. *Energy* 217, 119324. doi:10.1016/j.energy.2020.119324

Green, E. C. (2001). *Paper–Towards a European Strategy for the Security of Energy supply[J]*. Luxembourg: Office for Official Publications of the European Communities.

Guo, J., and Wang, E. (2010). Measurement Indicator System and Comprehensive Appraisal for Coal Energy Security in China. *[J]. China Saf. Sci. J.* 11, 112–118.

Hughes, L. (2009). The Four 'R's of Energy Security. *Energy Policy* 37 (6), 2459–2461. doi:10.1016/j.enpol.2009.02.038

Iddrisu, I., and Bhattacharyya, S. C. (2015). Sustainable Energy Development Index: A Multi-Dimensional Indicator for Measuring Sustainable Energy Development. *Renew. Sust. Energ. Rev.* 50, 513–530. doi:10.1016/j.rser.2015.05.032

Jie, D., Xu, X., and Guo, F. (2021). The Future of Coal Supply in China Based on Non-fossil Energy Development and Carbon price Strategies. *Energy* 220, 119644. doi:10.1016/j.energy.2020.119644

Jing, Q., and Jiang, X. (2006). Study on Index System of Capability of Production Safety in Coal Mine Based on AHP[J]. *China Saf. Sci. J.* (09), 74–79.

Kemmler, A., and Spreng, D. (2007). Energy Indicators for Tracking Sustainability in Developing Countries. *Energy Policy* 35 (4), 2466–2480. doi:10.1016/j.enpol.2006.09.006

Kemp, D., Worden, S., and Owen, J. R. (2016). Differentiated Social Risk: Rebound Dynamics and Sustainability Performance in Mining. *Resour. Pol.* 50, 19–26. doi:10.1016/j.resourpol.2016.08.004

Kowalska, I. J. (2014). Risk Management in the Hard Coal Mining Industry: Social and Environmental Aspects of Collieries' Liquidation. *Resour. Pol.* 41, 124–134. doi:10.1016/j.resourpol.2014.05.002

Kumar, D., and Katoch, S. S. (2014). Sustainability Indicators for Run of the River (RoR) Hydropower Projects in Hydro Rich Regions of India. *Renew. Sust. Energ. Rev.* 35, 101–108. doi:10.1016/j.rser.2014.03.048

Laponche, B., and Tillerson, K. (2001). Green Paper: Towards a European Strategy for the Security of Energy Supply[J]. *Vgb Powertech* 1 (82), 27–29.

Li, N., and Chen, W. (2018). Modeling China's Interprovincial Coal Transportation under Low Carbon Transition. *Appl. Energ.* 222, 267–279. doi:10.1016/j.apenergy.2018.03.103

Li, P., and Zhang, J. (2019). Is China's Energy Supply Sustainable? New Research Model Based on the Exponential Smoothing and GM(1,1) Methods. *Energies* 12 (2), 236. doi:10.3390/en12020236

Liu, F., Lv, T., Sajid, M., and Li, X. (2018). Optimization for China's Coal Flow Based on Matching Supply and Demand Sides. *Resour. Conserv. Recycl.* 129, 345–354. doi:10.1016/j.resconrec.2016.08.013

Liu, K., and Lin, B. (2019). Research on Influencing Factors of Environmental Pollution in China: A Spatial Econometric Analysis. *J. Clean. Prod.* 206, 356–364. doi:10.1016/j.jclepro.2018.09.194

Liu, X., Guo, P., and Guo, S. (2019). Assessing the Eco-Efficiency of a Circular Economy System in China's Coal Mining Areas: Emergy and Data Envelopment Analysis. *J. Clean. Prod.* 206, 1101–1109. doi:10.1016/j.jclepro.2018.09.218

Liu, X., Liu, Z., Jiao, W., Li, X., Lin, J., and Ku, A. (2021). Impact of "ultra Low Emission" Technology of Coal-Fired Power on PM2.5 Pollution in the Jing-Jin-Ji Region. *Front. Energ.* 15 (1), 235–239. doi:10.1007/s11708-017-0518-y

Mainali, B., and Silveira, S. (2015). Using a Sustainability index to Assess Energy Technologies for Rural Electrification. *Renew. Sust. Energ. Rev.* 41, 1351–1365. doi:10.1016/j.rser.2014.09.018

Mallapaty, S. (2020). How China Could Be Carbon Neutral by Mid-century. *Nature* 586 (586), 482–483. doi:10.1038/d41586-020-02927-9

Marquez-Ballesteros, M.-J., Mora-López, L., Lloret-Gallego, P., Sumper, A., and Sidrach-de-Cardona, M. (2019). Measuring Urban Energy Sustainability and its Application to Two Spanish Cities: Malaga and Barcelona. *Sust. Cities Soc.* 45, 335–347. doi:10.1016/j.scs.2018.10.044

Martín-Gamboa, M., Iribarren, D., García-Gusano, D., and Dufour, J. (2017). A Review of Life-Cycle Approaches Coupled with Data Envelopment Analysis within Multi-Criteria Decision Analysis for Sustainability Assessment of Energy Systems. *J. Clean. Prod.* 150, 164–174. doi:10.1016/j.jclepro.2017.03.017

Meghan, L. O. S. (2013). *The Entanglement of Energy, Grand Strategy, and International security[Z]*. England: John Wiley & Sons, 1–566.

Merino-Saum, A., Baldi, M. G., Gunderson, I., and Oberle, B. (2018). Articulating Natural Resources and Sustainable Development Goals through green Economy Indicators: A Systematic Analysis. *Resour. Conserv. Recycl.* 139, 90–103. doi:10.1016/j.resconrec.2018.07.007

Mondal, M. A. H., and Denich, M. (2010). Assessment of Renewable Energy Resources Potential for Electricity Generation in Bangladesh. *Renew. Sust. Energ. Rev.* 14 (8), 2401–2413. doi:10.1016/j.rser.2010.05.006

Munasinghe, M. (1994). Protected Area Economics and Policy: Linking Conservation and Sustainable Development. *Economic and Policy Issues in Natural Habitats and Protected Areas*, 15–49.

Narula, K., and Reddy, B. S. (2016). A SES (Sustainable Energy Security) index for Developing Countries. *Energy* 94, 326–343. doi:10.1016/j.energy.2015.10.106

Oberschelp, C., Pfister, S., Raptis, C. E., and Hellweg, S. (2019). Global Emission Hotspots of Coal Power Generation. *Nat. Sustain.* 2 (2), 113–121. doi:10.1038/s41893-019-0221-6

Our Common Future (1987). Report of the World Commission on Environment and Development[J].

Pavlović, D., Banovac, E., and Vištica, N. (2018). Defining a Composite index for Measuring Natural Gas Supply Security - the Croatian Gas Market Case[J]. *Energy Policy* 114, 30–38.

Radovanović, M., Filipović, S., and Pavlović, D. (2017). Energy Security Measurement – A Sustainable Approach[J]. *Renew. Sust. Energ. Rev.* 68, 1020–1032.

Rauner, S., Bauer, N., Dirnaichner, A., Dingenen, R. V., Mutel, C., and Luderer, G. (2020). Coal-exit Health and Environmental Damage Reductions Outweigh Economic Impacts. *Nat. Clim. Chang.* 10 (4), 308–312. doi:10.1038/s41558-020-0728-x

Raza, S. S., Janajreh, I., and Ghenai, C. (2014). Sustainability index Approach as a Selection Criteria for Energy Storage System of an Intermittent Renewable Energy Source. *Appl. Energ.* 136, 909–920. doi:10.1016/j.apenergy.2014.04.080

Rioux, B., Galkin, P., Murphy, F., and Pierru, A. (2016). Economic Impacts of Debottlenecking Congestion in the Chinese Coal Supply Chain. *Energ. Econ.* 60, 387–399. doi:10.1016/j.eneco.2016.10.013

Sovacool, B. K., Mukherjee, I., Drupady, I. M., and D'Agostino, A. L. (2011). Evaluating Energy Security Performance from 1990 to 2010 for Eighteen Countries. *Energy* 36 (10), 5846–5853. doi:10.1016/j.energy.2011.08.040

Sovacool, B. K., and Walter, G. (2018). Major Hydropower States, Sustainable Development, and Energy Security: Insights from a Preliminary Cross-Comparative Assessment. *Energy* 142, 1074–1082. doi:10.1016/j.energy.2017.09.085

Stefanova, B. (2012). European Strategies for Energy Security in the Natural Gas Market. *[J]* 3 (5). doi:10.5038/1944-0472.5.3.4

sustainable Energy Development (1995). Issues and Policy[M].

Tian, S., and Zhao, P. (2015). Study on the Early-Warning Management of Daqing's Overseas Oil Drilling Project Risks—Based on Fuzzy Comprehensive Evaluation Model. *Nat. Resour. Econ. China* (1), 29–33.

Tsai, W.-T. (2010). Energy Sustainability from Analysis of Sustainable Development Indicators: A Case Study in Taiwan. *Renew. Sust. Energ. Rev.* 14 (7), 2131–2138. doi:10.1016/j.rser.2010.03.027

von der Goltz, J., and Barnwal, P. (2019). Mines: The Local Wealth and Health Effects of mineral Mining in Developing Countries. *J. Dev. Econ.* 139, 1–16. doi:10.1016/j.jdeveco.2018.05.005

Wang, C., and Zhang, Y. (2020). Implementation Pathway and Policy System of Carbon Neutrality Vision[J]. *Chin. J. Environ. Manag.* 72 (06), 60–66.

Wang, D., Nie, R., Long, R., Shi, R., and Zhao, Y. (2018). Scenario Prediction of China's Coal Production Capacity Based on System Dynamics Model. *Resour. Conserv. Recycl.* 129, 432–442. doi:10.1016/j.resconrec.2016.07.013

Wang, J.-J., Jing, Y.-Y., Zhang, C.-F., and Zhao, J.-H. (2009). Review on Multi-Criteria Decision Analysis Aid in Sustainable Energy Decision-Making. *Renew. Sust. Energ. Rev.* 13 (9), 2263–2278. doi:10.1016/j.rser.2009.06.021

Wang, J., Feng, L., Davidsson, S., and Höök, M. (2013). Chinese Coal Supply and Future Production Outlooks. *Energy* 60, 204–214. doi:10.1016/j.energy.2013.07.031

Wang, L., Cao, Q., and Zhou, L. (2018). Research on the Influencing Factors in Coal Mine Production Safety Based on the Combination of DEMATEL and ISM. *Saf. Sci.* 103, 51–61. doi:10.1016/j.ssci.2017.11.007

Wang, Q., Li, S., and Pisarenko, Z. (2020). Modeling Carbon Emission Trajectory of China, US and India. *J. Clean. Prod.* 258, 120723. doi:10.1016/j.jclepro.2020.120723

Wang, W., Jia, H., and Lin, Y. (2013). Study on Research Framework of Effective Supply Capability of Regional Coal[J]. *China Coal* (12), 12–15.

Wang, Y., Chen, H., Long, R., and Yang, M. (2020). Health Economic Loss Measurement and Risk Assessment of New Cases of Coal Worker's Pneumoconiosis in China. *Saf. Sci.* 122, 104529. doi:10.1016/j.ssci.2019.104529

Wang, Z. H., and li, X. (2013). Study on the Efficiency Evaluation of green Investment of Coal enterprise Based on Entropy Method. *[J]* (05), 28–30.

Wei, Y.-M., Chen, H., Chyong, C. K., Kang, J.-N., Liao, H., and Tang, B.-J. (2018). Economic Dispatch Savings in the Coal-Fired Power Sector: An Empirical Study of China. *Energ. Econ.* 74, 330–342. doi:10.1016/j.eneco.2018.06.017

Wei, Y. M., Han, R., Wang, C., Yu, B., Liang, Q. M., Yuan, X. C., et al. (2020). Self-preservation Strategy for Approaching Global Warming Targets in the post-Paris Agreement Era. *Nat. Commun.* 11 (1), 1624. doi:10.1038/s41467-020-15453-z

Weng, S., and Huang, Z. (2021). Building a Modern Energy System in the Yangtze River Delta. *Strateg. Study CAE* 23 (01), 42–51.

Wirl, F. (1995). The Exploitation of Fossil Fuels under the Threat of Global Warming and Carbon Taxes: A Dynamic Game Approach. *Environ. Resource Econ.* 5 (4), 333–352. doi:10.1007/bf00691573

Wu, H., Hao, Y., and Weng, J.-H. (2019). How Does Energy Consumption Affect China's Urbanization? New Evidence from Dynamic Threshold Panel Models. *Energy Policy* 127, 24–38. doi:10.1016/j.enpol.2018.11.057

Wyman, O. (2013). *World Energy Trilemma 2013 Energy Sustainability index*. London: UK: World Energy Council.

Xu, X., and Wang, W. (2021). Vulnerability Assessment and Management Strategies of the Regional Coal Market Supply in China. *[J].China Coal.* 44 (09), 5–10.

Xu, Z., Chau, S. N., Chen, X., Zhang, J., Li, Y., Dietz, T., et al. (2020). Assessing Progress towards Sustainable Development over Space and Time. *Nature* 577 (7788), 74–78. doi:10.1038/s41586-019-1846-3

Yan, Y., Sun, L., Peng, Z., Qi, H., Liu, L., and Sun, R. (2021). Effects of Pyrolyzed Semi-char Blend Ratio on Coal Combustion and Pollution Emission in a 0.35 MW Pulverized Coal-Fired Furnace. *Front. Energ.* 15 (1), 78–90. doi:10.1007/s11708-020-0678-z

Yang, R. G., and Fan, Y. (2005). System Dynamics Analytic Model for Coal Supply and Investment[J]. *J. Appl. Stat. Manage.* (05), 6–12.

Yang, Y., Zeng, M., Xue, S., Wang, J., and Li, Y. (2018). Unifying the "Dual-Track" Pricing Mechanism for Coal in China: Policy Description, Influences, and Suggestions for Government and Generation Enterprises. *Resour. Conserv. Recycl.* 129, 402–415. doi:10.1016/j.resconrec.2016.04.004

Yuan, J., Li, P., Wang, Y., Liu, Q., Shen, X., Zhang, K., et al. (2016). Coal Power Overcapacity and Investment Bubble in China during 2015-2020. *Energy Policy* 97 (10), 136–144. doi:10.1016/j.enpol.2016.07.009

Zhang, C., Su, B., Zhou, K., and Sun, Y. (2020). A Multi-Dimensional Analysis on Microeconomic Factors of China's Industrial Energy Intensity (2000-2017). *Energy Policy* 147, 111836. doi:10.1016/j.enpol.2020.111836

Zhang, Y., Nie, R., Shi, R., and Zhang, M. (2018). Measuring the Capacity Utilization of the Coal Sector and its Decoupling with Economic Growth in China's Supply-Side Reform. *Resour. Conserv. Recycl.* 129, 314–325. doi:10.1016/j.resconrec.2016.09.022

Zhao, D., Li, C., Wang, Q., and Yuan, J. (2020). Comprehensive Evaluation of National Electric Power Development Based on Cloud Model and Entropy Method and TOPSIS: A Case Study in 11 Countries. *J. Clean. Prod.* 277, 123190. doi:10.1016/j.jclepro.2020.123190

Zhu, L., Gao, Z., and Cheng, X. (2021). An Assessment of Surrogate Fuel Using Bayesian Multiple Kernel Learning Model in Sight of Sooting Tendency[J]. *Front. Energ.*

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 17 December 2021
doi: 10.3389/fenrg.2021.777244

Multidimensional Assessment and Alleviation of Global Energy Poverty Aligned With UN SDG 7

Xiahui Che[1]*, *Minxing Jiang*[2] *and Cheng Fan*[1]

[1]School of Management Science and Engineering, Nanjing University of Information Science and Technology, Nanjing, China,
[2]Business School, Nanjing University of Information Science and Technology, Nanjing, China

There are increasing concerns that energy poverty across nations is weakening the global efforts toward achieving Sustainable Development Goals (SDGs). A systematic assessment of energy poverty is, therefore, essential to track the spatiotemporal pattern of SDG 7 and monitor the global efforts in alleviating energy poverty. This article develops the first Multidimensional Energy Poverty Assessment Index (MEAI), incorporating energy availability, affordability, and efficiency applicable to quantify the spatiotemporal dynamics of energy poverty development at global, regional, and national scales. Our analyses indicate that the overall MEAI and indices in all dimensions decreased from 2001 to 2016 at a global level with energy affordability experiencing the highest decline. The MEAI at the national level declines within the same period, showing significant regional heterogeneity in terms of the sub-index. Energy efficiency in developed and less-developed regions is characterized by high carbon emissions and low energy modernization, respectively. The energy availability indices are lower in developed nations and in nations with abundant energy resources. Overall, our results highlight a sudden increase in MEAI for Central America in 2014 and a gradual decline in MEAI for East Asia during 2014–2016. A call for regional actions is critically needed to solve energy poverty from different facets.

Keywords: energy poverty, multidimensional energy poverty assessment index (MEAI), energy availability, energy affordability, energy efficiency

OPEN ACCESS

Edited by:
Yong-cong Yang,
Guangdong University of Foreign Studies, China

Reviewed by:
Di Zhou,
Guangdong University of Foreign Studies, China
Dong-xiao Yang,
Hunan University of Technology and Business, China

***Correspondence:**
Xiahui Che
chexiahui@yeah.net

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *15 September 2021*
Accepted: *27 September 2021*
Published: *17 December 2021*

Citation:
Che X, Jiang M and Fan C (2021) Multidimensional Assessment and Alleviation of Global Energy Poverty Aligned With UN SDG 7. Front. Energy Res. 9:777244. doi: 10.3389/fenrg.2021.777244

INTRODUCTION

Energy poverty has received growing attention worldwide in both academic communities and political agendas in recent years. The United Nation's Sustainable Development Goal 7 (SDG 7) refers specifically to energy poverty and aims to achieve universal access to affordable, reliable, sustainable, and modern energy services by 2030. However, there is no internationally consistent definition of energy poverty. It is usually considered a situation where households are unable to adequately meet their energy needs at an affordable cost (Dobbins et al., 2019),thus thwarting efforts to achieve Sustainable Development Goals (SDGs). A lack of access to modern energy causes severe health problems, including cardiovascular, cerebrovascular, and respiratory disorders (SDG 3: Good Health and Well-Being), blunts future generation's opportunity to reach satisfactory lifestyles (SDG 10: Reduced Inequalities), results in global deforestation and climate change (SDG 13: Climate Action), and affects many of the SDGs (Chapman et al., 2019). To fight energy poverty with sound policies and measures, a systematic and comprehensive assessment of energy poverty is of necessity for human sustainability.

TABLE 1 | Indicators selected for each of the dimensions.

Dimensions	Indicators	Attribute
Energy availability(0.3492)	Household energy consumption per capita (0.3375)	–
	Household electricity consumption per capita (0.3430)	–
	Proportion of population with access to electricity (0.3195)	–
Energy affordability(0.3278)	GDP per capita (0.3416)	–
	Household disposable income per capita (0.3710)	–
	Cellphone ownership per 100 people (0.2874)	–
Energy efficiency(0.3230)	Proportion of population with access to clean fuels and technologies for cooking (0.1914)	–
	Ratio of biomass and waste consumption on total final household energy consumption (0.2052)	+
	Household CO_2 emissions per capita (0.2051)	+
	Ratio of non-solid commodity energy on household commodity energy (0.1903)	–
	Proportion of non-thermal electricity generation on electricity generation (0.2080)	–

Note: the numbers within parentheses were weights derived from the large-scale survey.

Energy poverty is considered a multidimensional concept, including socioeconomic challenges, environment climate concerns, and so on. Multidimensional energy poverty measurement attempts to capture various dimensions and results of energy poverty and has become the prevailing method of assessing energy poverty. Jayasinghe et al. (2021) examine the incidence, intensity, inequality, and determinants of energy poverty in Sri Lanka by constructing the Multidimensional Energy Poverty Index (MEPI). Gafa and Egbendewe (2021) proposed a new multidimensional measure to evaluate the levels and determinants of energy poverty in rural West Africa. Halkos and Gkampoura (2021) examined energy poverty for 28 selected European countries, using a composite measurement. We found that previous studies are limited to a particular country or region, and rarely studies are found to assess global energy poverty by using multidimensional energy poverty measurement. The study by Che et al. (2021) is an attempt to assess global energy poverty with an integrated approach. However, the score for a sample country is relative closeness that is better suited to national ranking and the calculation process of this integrated approach is complicated.

Hence, based on the study by Che et al. (2021), we construct a Multidimensional Energy Poverty Assessment Index (MEAI) that not only reflects the reality of energy poverty but also is relatively simple to calculate. The MEAI takes into a set of multiple dimensions to represent the overall performance toward alleviating energy poverty. It is an aggregate index with fixed weights for sub-dimensions/indicators by their importance. With such a universal index, it makes the comparison of energy poverty possible at the national level (Xu et al., 2020).

METHODOLOGY

Indicator Selection and Data Sources

To get a full picture of energy poverty at national, regional, and global levels, the MEAI is designed and composed of three dimensions: energy availability, energy affordability, and energy efficiency, as shown in **Table 1**. Households lack access to modern energy due to unreliable energy supply, inadequate energy infrastructure, and tenure status or structural fabric of the building (Bouzarovski and Petrova, 2015). Low incomes keep households from affording basic levels of energy needed to attain a socially and materially necessitated level of energy services (Buzar, 2007). In addition, the inefficient use of an appliance contributes to indoor air pollution, and the combustion process of solid energy exacerbates climate change (Casillas and Kammen, 2010; Liu et al., 2016).

For each dimension, we chose as many corresponding indicators as deemed feasible from previous studies, based on data availability at the national, regional, and global levels and temporal scales. 1) Energy availability refers to a lack of access to modern energy. Household energy consumption per capita was used to measure the energy consumption. For household energy consumption, electricity is found superior to other energies because it is more efficient and could serve all energy-end uses. Therefore, household electricity consumption per capita was used to describe the access to modern clean fuels. Adequate energy supply is a precondition to access energy services. As a result, the proportion of population with access to electricity was selected as an indicator for the reliability of energy supply. 2) Energy affordability means that the energy cost is too high for householders to pay. According to the energy ladder hypothesis, GDP per capita and household disposable income per capita were used to measure the burden of energy costs. The number of household appliances reflected a household's ability to pay for modern energy and efficient equipment. Communication equipment played a key role in social life, and cellphone ownership per 100 people, therefore, was taken into account. 3) Energy efficiency considers the quality of household energy consumption from low-carbon development and modernization of energy consumption structure. The proportion of population with access to clean fuels and technologies for cooking and ratio of biomass and waste consumption on total final household energy consumption was used to explain the modernization of energy consumption structures. Household CO_2 emissions per capita, ratio of non-solid commodity energy to household commodity energy, and the proportion of non-thermal power generation on electricity generation were used to evaluate low-carbon development.

Data for "household energy consumption" were obtained from the following authoritative sources: the World Energy Balances, the Energy Balances of OECD Countries, and the Energy Balances of Non-OECD Countries. Data for "household CO_2

emissions" were from the CO_2 Emissions from Fuel Combustion. Data for "proportion of population with access to electricity," "gross domestic product" (GDP)," "household final consumption expenditure," "cellphone ownership per 100 people," "proportion of population with access to clean fuels and technologies for cooking," "proportion of non-thermal electricity generation on electricity generation," and "national population" were from the World Bank Open Data. GDP and "household final consumption expenditure" were adjusted with purchasing power parity (PPP) dollars in 2011 to remove the effect of exchange rate volatility and inflation.

Normalization of Indicator Values

The indicator values for each dimension were normalized in order to ensure comparability across dimensions. Traditional normalized approaches used annual values for the mean and standard deviation of each indicator as the criterion of normalization, which varied over time. The normalized indicator values were incomparable across time scales, and the MEAI only reflected the spatial distribution of energy poverty. However, the fixed base difference method chose the values of benchmark year indicators as the unified criterion of the annual values for 2001–2016 for the selected indicator metrics of each dimension, which objectively reflected the spatiotemporal dynamics of progress toward alleviating energy poverty at the global, regional, and national levels.

We converted negative indicators into positive indicators by using the equation$x_{ij}^{'} = -x_{ij}$and then followed the fixed base difference method to normalize the global, regional, and national data arrays for each dimension indicator. The following formula was used to normalize dimension indicator values toward meeting a dimension target at the global, regional, and national levels:

$$X_{ij}^{l} = \frac{V_{ij}^{t} - V_{ij,min}^{t_0}}{V_{ij,max}^{t_0} - V_{ij,min}^{t_0}} \times 100, \quad (1)$$

where V_{ij}^{t} was the original data value of each dimension indicator at time t, $V_{ij,max}^{t_0}/V_{ij,min}^{t_0}$represented the maximum/minimum original data values at time t_0(the benchmark year) for the worst/best performance, and $X_{ij}^{l}$was the normalized individual value for a given dimension indicator. A lower normalized dimension index indicated better performance toward alleviating the dimension. All normalized values greater than 100 meant that the indicators at time t were significantly worse than those at time t_0, and all normalized values less than 0 meant that the indicators at time t were significantly better than those at time t_0. We normalized the data across global, regional, and national levels simultaneously so that the dimension indices were comparable across regions and nations.

Weight of Indicator

The weights of indicators had a significant impact on the MEAI. Our study period was 16 years. The indicator weights were differentiated annually by using the objective weighting approaches, which were not suitable to conduct dynamic research. Hence, we weighted all dimensions and indicators within each dimension, respectively, by using a large-scale survey. Corresponding scores were based on the Likert scale, where (4,5]—very important; (3,4]—important; (2,3]—fair; (1,2]—unimportant; and (0,1]—very unimportant.

The survey began in August 2019 and lasted for 2 months. Thousand questionnaires were sent out by E-mail all over the world, and 581 valid questionnaires were collected. In the valid sample, the respondents were from China, the United States, the United Kingdom, and other countries, respectively. Authoritative experts, such as Yin Jinyue (KTH Royal Institute of Technology) and Wang Zhaohua (Beijing Institute of Technology), accounted for 4.0%; teachers and researchers from internationally renowned universities, such as the Chinese Academy of Sciences and the National University of Singapore, accounted for 51.1%; and Master's and doctoral students accounted for 32.5%. Most of the respondents were familiar with energy poverty and could score the indicators objectively. Hence, the weights of the indicators were convincing.

According to the theory of random error, the extreme scores had negative impacts on the reliability of the results. The Pauta Criterion (3δ) was used to remove extreme scores in order to minimize the potential effects of skewed data distribution on the weights of indicators. According to the actual calculation results, K was defined as 2.

$$\mu_k + 2\sigma_k > P_k > \mu_k - 2\sigma_k, \quad (2)$$

where$P_k$was the score of indicator k and $\mu_k$and$\sigma_k$were the mean value and standard deviation, respectively. The weight was based on the proportion of the average score of each dimension/indicator after the extreme scores were removed.

Calculation of the Multidimensional Energy Poverty Assessment Index and Individual Dimension Index Over Time

We calculated the MEAI at the global, regional, and national levels by using arithmetic means. The MEAI was an aggregate index that consisted of individual indices for all three dimensions and represented global, regional, or national overall progress in alleviating all dimensions over time. The individual dimension index was yielded by multiplying the indicator values within each dimension with the assigned weights.

$$X_i = \sum_{j=1}^{n_i} \omega_{ij} X_{ij}, \quad (3)$$

where$X_i$was the individual dimension index, $X_{ij}$and ω_{ij}were the values of indicator and the weight within each dimension, and $n_i$was the total number of indicators within each dimension.

We aggregated all three dimensions into one global/regional/national MEAI for each year from 2001 to 2016, which was defined as follows:

$$Z = \sum_{i=1}^{3} \omega_i X_i, \quad (4)$$

where Z was what the study called the MEAI ,and$\omega_i$was the weight of each dimension.

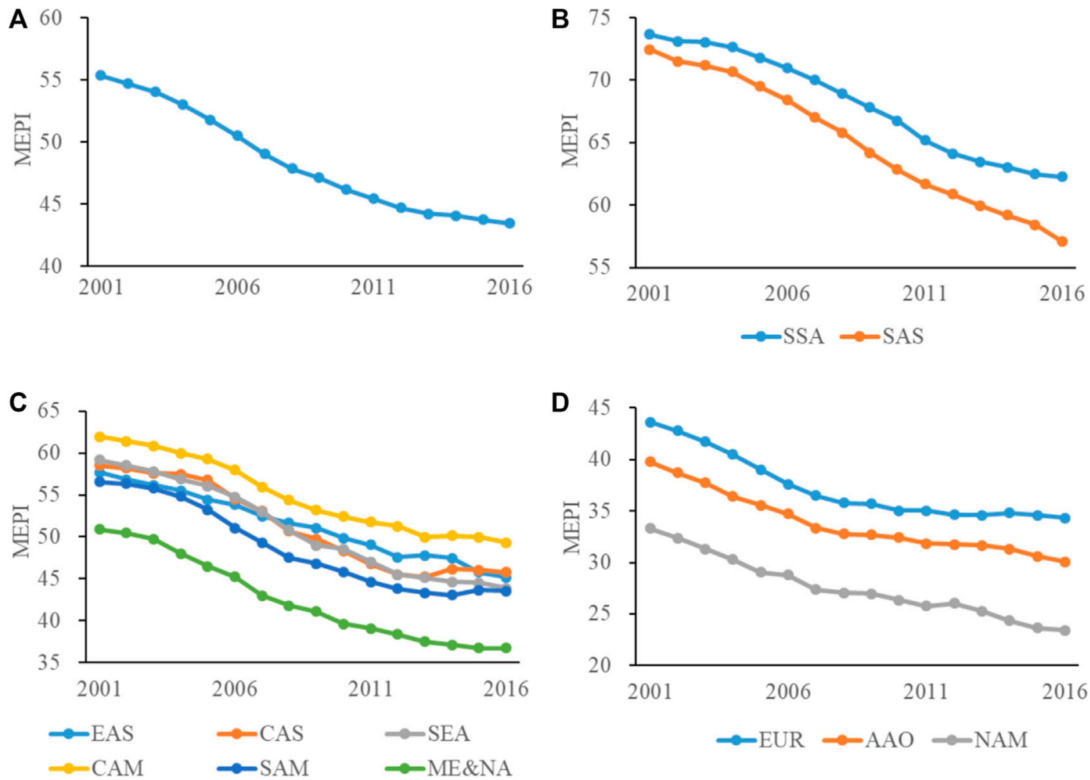

FIGURE 1 | Change in the MEAI from 2001 to 2016. **(A)** At the global level. **(B–D)** At the regional level. North America is the abbreviation for NAM, Central America for CAM, South America for SAM, Middle East and North Africa for ME&NA, sub-Saharan Africa for SSA, Europe for EUR, Central Asia for CAS, East Asia for EAS, Southeast Asia for SEA, South Asia for SAS, and Australia and Oceania for AAO.

RESULTS AND DISCUSSIONS

Characteristics of Global Energy Poverty

We compiled annual time series data relevant to energy poverty from 2001 to 2016 for 125 countries. In total, 11 indicators were used in this assessment. These indicators allow us to calculate the three dimensions of energy poverty (including energy availability, energy affordability, and energy efficiency) and the MEAI at global, regional, and national levels. **Figure 1** shows that the MEAI at the global level decreased gradually over time, which was mainly attributed to the improvement of the energy affordability. The global MEAI decreased by approximately 27.4% from 55.3 in 2001 to 43.4 in 2016. Specifically, we found a clear distinction before and after the year 2008. The average annual decrease rate of the global MEAI after 2008 was 1.13% compared to that of 1.71% before 2008. This reveals that although global energy poverty was alleviated gradually, the financial crisis in 2008 may have had a permanent and negative impact on energy poverty alleviation. This may be because that the crisis increases unemployment and reduces household disposable income.

Figure 1 also presents the changes in the MEAI from 2001 to 2016 at the regional level. The mean value of the MEAI at the regional level declined by 22.3% between 2001 and 2016. In 2001, the MEAI ranged from 33.3 to 73.7 with a mean value of 55.2. The mean value decreased to 42.9 from 2016. East Asia's MEAI experienced a continuous decline with that of China as the largest contributor in this region. China reached full electrification in 2015, which has a significant effect in reducing the MEAI in East Asia. It is worth noticing that the MEAI in Central America suddenly increased by 2.08% from 45.2 in 2013 to 46.2 in 2014, respectively, suggesting that substantial changes in alleviating energy poverty occurred across different regions.

The mean value of the MEAI for all 125 nations is 48.5, as we can see from **Figure 2**. The national average MEAI of 66 countries is higher than the mean (48.5), accounting for 52.8% of our sample (**Figure 2**). The world is still suffering from energy poverty and, over time, all nations decreased their MEAI from 2001 to 2016 with significant spatial heterogeneity, ranging from 15.1 in Norway to 77.9 in Congo (*10*).

Figure 3 illustrates the changes in dimension indices: energy availability, energy affordability, and energy efficiency. At the global level, all dimension indices decreased over time. Energy availability and energy affordability were the key drivers for the MEAI. The three dimensions, in order of the greatest to least decline, were energy affordability, energy availability, and energy efficiency, and the decline in energy affordability was substantially higher than the others. At the regional level, the changes in energy availability from 2001 to 2016 were greater

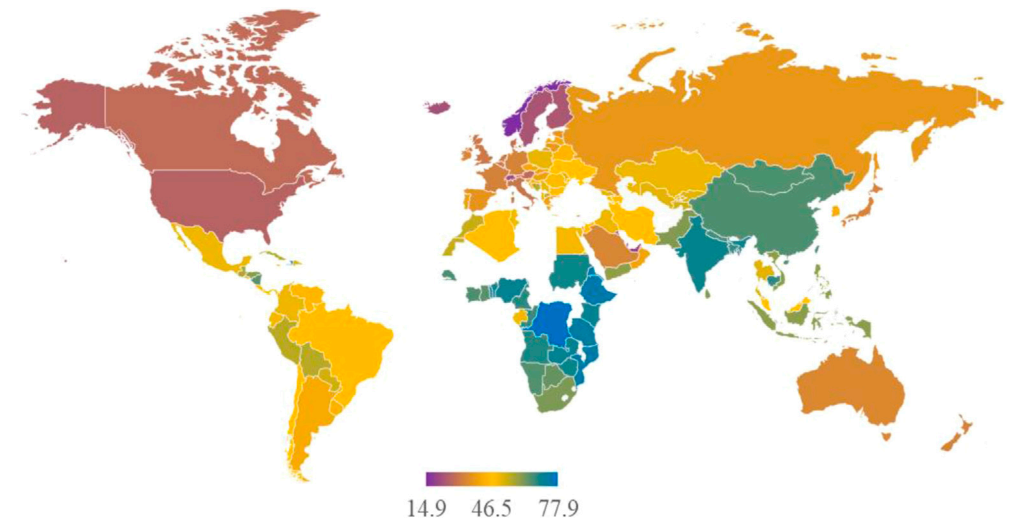

FIGURE 2 | Average MEAI between 2001 and 2016 for 125 global nations.

than zero for North America, Europe, and Australia and Oceania, and the change in energy efficiency was also greater than zero for Central Asia, implying a deterioration in energy availability and energy efficiency in these regions. The most obvious indicator responsible for such deterioration in North America, Europe, and Australia and Oceania is "household energy consumption per capita" (Sovacool and Brown, 2012; Thomson and Snell, 2013). Generally, the changes in dimension indices at the national level showed similar dynamics as those at the global and regional levels.

Mechanisms for Energy Poverty

The spatiotemporal patterns of the MEAI are the combined outcome of a number of factors, including domestic energy conditions, income level, and policy implementation. In the following section, we provide key insights on the three dimensions of the MEAI at global, regional, and national levels.

Energy availability is defined by the International Energy Agency as a lack of access to modern energy. A lower value for the energy availability index shows its contribution to the alleviation of energy poverty. At the national level, 32 of the top 40 nations, in order of the least to greatest increase for energy availability, belong to developed nations. The remaining eight nations were high-/upper-/ middle–income nations with abundant natural resources such as Kuwait, Bahrain, the United Arab Emirates, Qatar, Russia, Iran, Saudi Arabia, and Brunei. The bottom 40 nations were low-/lower- middle-income nations in Central America, South Asia, and sub-Saharan Africa. The top 40 nations have established perfect infrastructures of energy service to improve household's energy consumption levels and have gained an overall access to modern energy (Bednar and Reames, 2020). In contrary, the bottom 40 nations lack the access to adequate amounts of modern energy and rely mainly on traditional cooking fuels due to unfavorable conditions, including high energy prices, energy shortages, and inadequate energy infrastructure (Mendoza et al., 2019). At the regional level, the improvement on "household electricity consumption per capita" and "household energy consumption per capita" will have significant and positive impacts on reducing the energy availability index (see the **Figure 4**).

The energy affordability index shows to what extent households cannot afford basic levels of energy needed to attain a socially and materially necessitated level of energy services (González-Eguino, 2015). A higher value of energy affordability indicates increased difficulty in affording basic energy needs. The average index of energy affordability among nations between 2001 and 2016 ranged from −1.4 in Kuwait to 97.8 in Congo, with large variations across nations. One of the indicators for energy affordability is "cellphone ownership per 100 people," which reflects the situation of modern energy consumption and household appliance utilization (Nussbaumer et al., 2012). It has a significant positive influence on reducing the index of energy affordability, as households tend to spend more money on the modern energy consumption and efficient household appliance utilization with the increase in income. We find the change in the index values for "cellphone ownership per 100 people" among regions from 2001 to 2016 ranging from a 1.79 % decrease (Australia and Oceania) to a 93.1% decrease (sub-Saharan Africa), which plays a significant role in energy affordability improvement compared to the survey conducted in 2001 (**Figure 4**).

A higher energy efficiency level has a positive effect on reducing the final energy consumption, whereas a lower energy efficiency level poses challenges to alleviate energy poverty for all nations (Bonatz et al., 2019). In this study, energy efficiency is divided into two categories: low-carbon development and energy modernization. Low-carbon development measured by "household CO_2 emissions per capita" represent low-carbon development, "ratio of non-solid commodity energy on household commodity energy," and "proportion of non-thermal electricity generation on electricity generation." The three indicators account for over 60% of the index values of energy efficiency in North America, Europe, and Australia and Oceania. This implies that the energy efficiency issue in

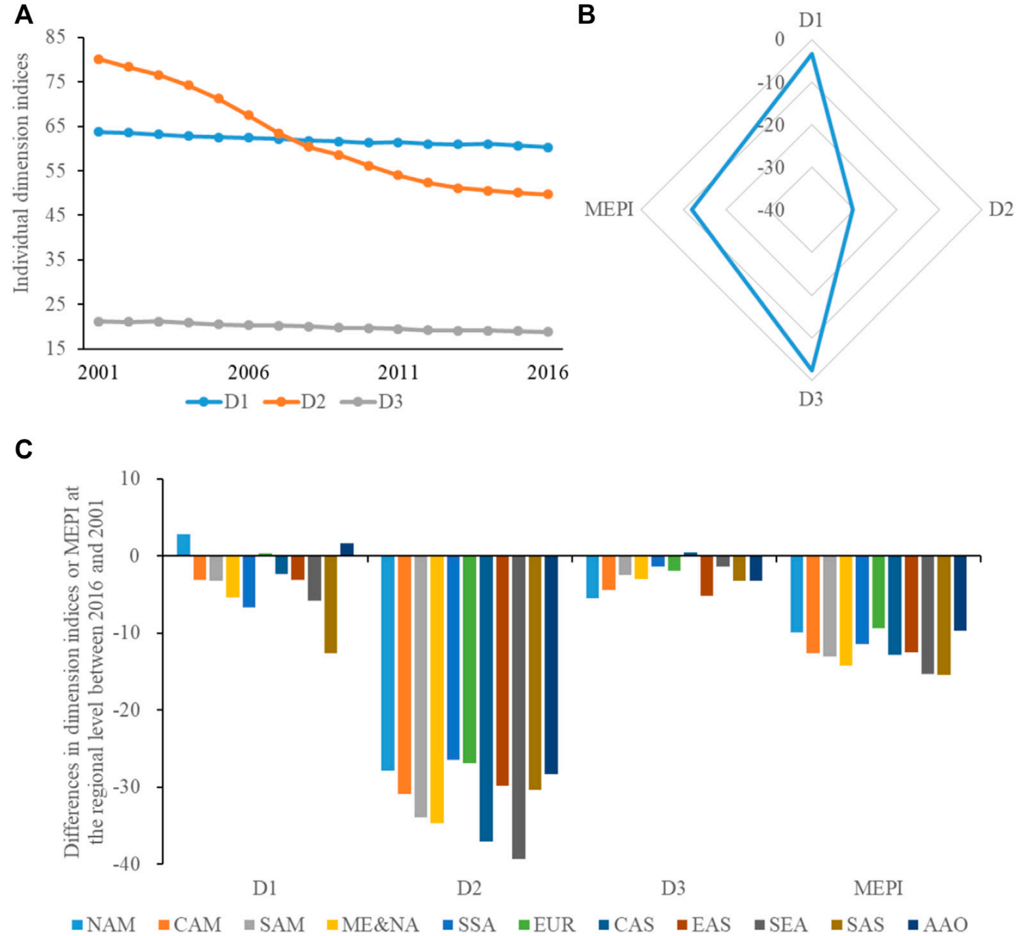

FIGURE 3 | Change in dimension indices or the MEAI. **(A)** Changes in dimension indices from 2001 to 2016 at the global level. **(B)** Differences in dimension indices between 2016 and 2001 at the global level. **(C)** Differences in dimension indices and the MEAI between 2016 and 2001 at the regional level. D1 is the abbreviation for energy availability, D2 for energy affordability, and D3 for energy efficiency. A positive value indicates an increase in the index from 2001 to 2016, whereas a negative value indicates a decrease in the index from 2001 to 2016.

the three regions is related more to carbon emissions than modernization (see **Figure 4**). The three regions are dominated by developed nations. Although these nations have reached an overall access to energy services, they still heavily depend on traditional fossil fuels to meet household energy consumption demand and lack access to adequate amounts of modern energy. In contrary, two indicators including "proportion of population with access to clean fuels and technologies for cooking" and "ratio of biomass and waste consumption on total final household energy consumption," contribute to more than 55% of the energy efficiency index value in Central America, South America, Middle East, North Africa, sub-Saharan Africa, Southeast Asia, and South Asia. Therefore, energy efficiency in these six regions concerns more on modernization (**Figure 4**). A large number of less-developed nations are clustered in the six regions, for which it is the priority to meet household basic energy requirements without considering the energy consumption structure. In East Asia, two categories of indicators, low-carbon development and energy modernization, play equal roles in constituting the energy efficiency index, implying that both carbon emissions and energy modernization are equally important for this region (**Figure 4**). This is because most nations (except Korea, Republic of China, and Japan) in East Asia are less-developed nations, and households mainly rely on energy-intensive and inefficient appliances to meet their basic energy requirements, which have a negative effect on energy modernization. Meanwhile, coal is abundant in this region, and thus final energy consumption is dominated by coal. Reducing the carbon emissions is a great challenge in this region, which is affecting the overall MEAI.

Although our results show that energy poverty has been alleviated to a large extent, evidenced by the reduction in the MEAI at global, regional, and national levels in general, the major driver for such improvement is attributed to energy affordability as the results of fast economic growth and international cooperation. The dimensional sub-index provides additional information for further action. From the perspective of energy availability, energy shortage and inadequate energy infrastructure hold back improvements on global energy consumption (Sovacool, 2012). The expansion of renewable energy technologies and the related distribution options, such as small-scale

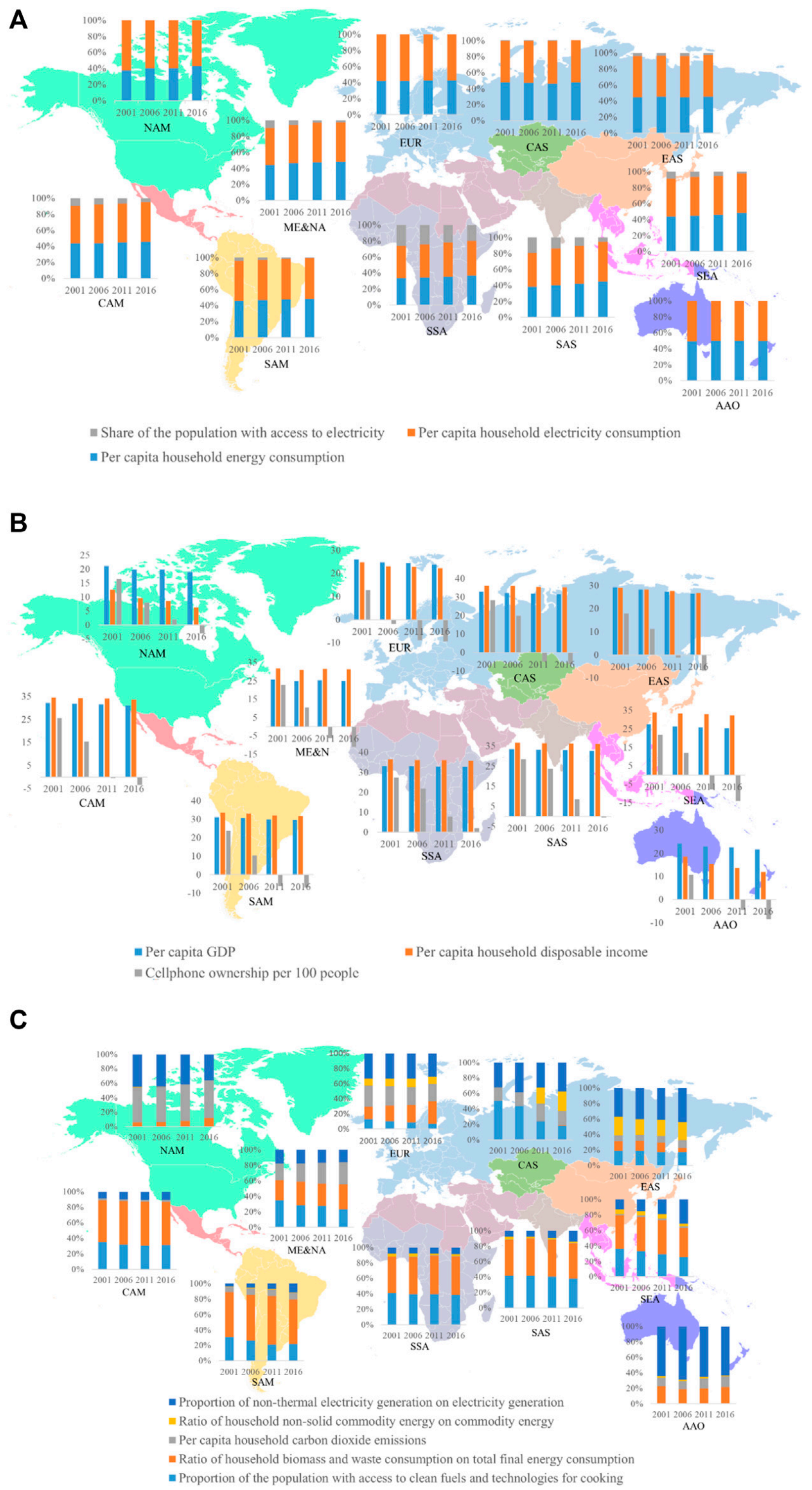

FIGURE 4 | Structure of dimension indices at the regional level in 2001, 2006, 2011, and 2016. **(A)** D1 (energy availability). **(B)** D2 (energy affordability). **(C)** D3 (energy efficiency).

photovoltaics, diesel generators, and improved cooking stoves, provide a chance to improve the access to modern energy for rural households (Yan et al., 2019). From an energy-efficient perspective, high-carbon emissions, and low-energy modernization have made energy poverty difficult to alleviate (Cameron et al., 2016). Burning solid fuels such as dung, firewood, and coal in traditional stoves for heating and cooking

TABLE 2 | Sensitivity of national ranks in 2001 in weights of indicators.

Nation	S0	S1	S2	S3	Nation	S0	S1	S2	S3	Nation	S0	S1	S2	S3
AGO	106	106	106	104	FIN	8	8	8	8	NGA	115	114	115	118
ALB	61	59	59	63	FRA	17	17	18	17	NIC	105	105	105	105
ARE	2	2	2	2	GAB	73	72	74	74	NLD	15	15	16	16
ARG	44	44	44	43	GBR	18	18	17	20	NOR	1	1	1	1
ARM	57	57	57	56	GEO	81	81	81	81	NPL	108	108	108	107
AUS	27	27	28	29	GHA	103	103	103	103	NZL	23	23	23	22
AUT	14	14	13	14	GRC	33	33	33	33	OMN	71	73	71	68
AZE	50	50	50	49	GTM	90	90	90	90	PAK	91	91	92	91
BEL	11	11	11	11	HND	93	93	93	93	PAN	77	77	77	76
BEN	118	118	118	116	HRV	39	39	39	39	PER	88	88	88	89
BGD	111	110	111	109	HTI	116	116	116	115	PHL	92	92	91	92
BGR	70	70	69	73	HUN	35	35	35	35	POL	76	76	75	79
BHR	20	20	20	19	IDN	94	94	94	94	PRT	31	31	31	31
BIH	83	83	83	85	IND	121	121	121	124	PRY	80	80	79	80
BLR	46	46	46	46	IRL	24	24	24	25	QAT	10	10	10	9
BOL	85	85	85	84	IRN	49	49	51	48	ROU	64	63	64	69
BRA	54	54	54	55	IRQ	66	65	66	60	RUS	40	40	40	41
BRN	25	25	25	24	ISL	5	5	5	5	SAU	59	66	63	58
BWA	95	96	95	95	ISR	26	26	26	27	SDN	109	109	109	108
CAN	12	13	14	12	ITA	16	16	15	15	SEN	99	99	99	98
CHE	6	6	6	6	JAM	63	62	61	65	SGP	19	19	19	18
CHL	48	48	48	50	JOR	45	45	45	45	SLV	82	82	82	82
CHN	107	107	107	117	JPN	21	21	22	21	SRB	74	74	73	78
CIV	101	101	101	100	KAZ	79	79	80	77	SVK	38	38	38	36
CMR	100	100	100	101	KEN	119	119	119	119	SVN	32	32	32	32
COD	125	125	125	125	KGZ	75	75	76	72	SWE	7	7	7	7
COG	114	115	114	112	KHM	113	113	113	111	TGO	120	120	120	120
COL	72	71	72	71	KOR	37	37	37	37	THA	84	84	84	83
CRI	53	53	53	52	KWT	3	3	3	3	TJK	78	78	78	75
CUB	67	67	68	66	LKA	96	95	96	96	TUN	69	69	70	70
CYP	30	30	30	30	LTU	42	42	42	42	TZA	122	122	122	121
CZE	36	36	36	38	LUX	4	4	4	4	UKR	60	60	62	64
DEU	22	22	21	23	LVA	43	43	43	44	URY	47	47	47	47
DNK	13	12	12	13	MAR	87	87	87	87	USA	9	9	9	10
DOM	62	61	60	62	MDA	65	64	65	61	UZB	56	56	56	57
DZA	55	55	55	54	MEX	52	52	52	53	VEN	41	41	41	40
ECU	68	68	67	67	MKD	86	86	86	88	VNM	98	98	98	102
EGY	58	58	58	59	MLT	29	29	29	26	YEM	89	89	89	86
ERI	117	117	117	114	MNG	104	104	104	106	ZAF	97	97	97	97
ESP	28	28	27	28	MOZ	124	124	124	123	ZMB	110	111	110	110
EST	34	34	34	34	MYS	51	51	49	51	ZWE	112	112	112	113
ETH	123	123	123	122	NAM	102	102	102	99	102				

Note: S0 is the abbreviation for original rankings, S1 for Scenario 1, S2 for Scenario 2, and S3 for Scenario 3. The codes for countries refer to the World Bank Database.

contributes to global deforestation and climate change. Improving energy efficiency helps to enforce sustainable energy development, speed up the exploration of efficient household appliances, and mitigate climate change. National policymakers could consider strategies to improve energy efficiency in sub-Saharan African and South Asian nations in order to narrow the energy poverty gap between developed regions and less-developed regions.

Sensitivity analysis

We considered three scenarios to assess the sensitivity of national ranks to changes in weights of indicators in 2001. Equal weights were assigned to relative indicators, respectively, (Nussbaumer et al., 2012) and the other weights were kept constant. Altogether three scenarios were presented in the study: Scenario 1 (the equal weights of indicators within energy availability), Scenario 2 (the equal weights of indicators within energy affordability), and Scenario 3 (the equal weights of indicators within energy efficiency). We recalculated the national ranks in 2001 in three scenarios, as shown in **Table 2**. The ranks of 11 countries changed in Scenario 1, the ranks of 29 countries changed in Scenario 2, and the ranks of 77 countries changed in Scenario 3. The results show that national ranks were relatively sensitive to changes in weights of indicators, and it is important to note that the weights to indicators should be cautiously assigned.

CONCLUSION

The empirical results indicate that the overall MEAI and indices in all dimensions decreased from 2001 to 2016 at a global level with energy affordability experiencing the highest decline. The MEAI at the national level declines within the same period, showing significant regional heterogeneity in terms of the sub-index. Energy efficiency in developed and less-developed regions is characterized by high-carbon emissions and low-energy modernization, respectively. The energy availability indices are lower in developed nations and in nations with abundant energy resources. Overall, our results highlight a sudden increase in the MEAI for Central America in 2014 and a gradual decline in MEAI for East Asia during 2014–2016.

Data availability is an important criterion for selecting the dimension indicators. The lack of available data hinders researchers exploring the spatiotemporal dynamics of progress toward alleviating energy poverty. This article constructed a unique micro-level dataset from national statistical departments and international databases, providing a solid basis for developing a set of standard indicators to better evaluate the progress toward energy poverty across space and time. Policymakers continuously track and monitor energy poverty by a periodical updating of the data.

This article developed a systematic and comprehensive evaluation method of SDG 7 at global, regional, and national levels. The method outlined in our article enables us to track the spatiotemporal pattern of SDG 7 and monitor national efforts toward energy poverty alleviation. It will not only help to guide policy development and implementation but also provide reference for the next action. One direction for further research is to include qualitative indicators obtained through a participatory survey method, to reflect household's subjective feelings on energy poverty. An investigation of non-economic factors, such as educational level, cultural preferences, and dietary habits on household's energy alternatives may be helpful to reveal the complex mechanisms and consequences of energy poverty alleviation. In addition, investigations on the trade-offs and synergies between SDG 7 and the other SDGs will enrich our path toward sustainability.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

XC conducted all data compilation, processing, and calculations and wrote the first draft.

ACKNOWLEDGMENTS

Our heartfelt thanks should be given to the National Natural Science Foundation of China (71903099), the General Foundation of Philosophy and Social Science Research in Colleges and Universities in Jiangsu Province (2019SJA0165), and the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (19KJB610019) for funding supports.

REFERENCES

Bednar, D. J., and Reames, T. G. (2020). Recognition of and Response to Energy Poverty in the United States. *Nat. Energ.* 5 (6), 432–439. doi:10.1038/s41560-020-0582-0

Bonatz, N., Guo, R., Wu, W., and Liu, L. (2019). A Comparative Study of the Interlinkages between Energy Poverty and Low Carbon Development in China and Germany by Developing an Energy Poverty index. *Energy and Buildings* 183, 817–831. doi:10.1016/j.enbuild.2018.09.042

Bouzarovski, S., and Petrova, S. (2015). A Global Perspective on Domestic Energy Deprivation: Overcoming the Energy Poverty-Fuel Poverty Binary. *Energ. Res. Soc. Sci.* 10, 31–40. doi:10.1016/j.erss.2015.06.007

Buzar, S. (2007). The 'hidden' Geographies of Energy Poverty in post-socialism: Between Institutions and Households. *Geoforum* 38 (2), 224–240. doi:10.1016/j.geoforum.2006.02.007

Cameron, C., Pachauri, S., Rao, N. D., McCollum, D., Rogelj, J., and Riahi, K. (2016). Policy Trade-Offs between Climate Mitigation and Clean cook-stove Access in South Asia. *Nat. Energ.* 1 (1), 1–5. doi:10.1038/nenergy.2015.10

Casillas, C. E., and Kammen, D. M. (2010). The Energy-Poverty-Climate Nexus. *Science* 330 (6008), 1181–1182. doi:10.1126/science.1197412

Chapman, A., Fujii, H., and Managi, S. (2019). Multinational Life Satisfaction, Perceived Inequality and Energy Affordability. *Nat. Sustain.* 2 (6), 508–514. doi:10.1038/s41893-019-0303-5

Che, X., Zhu, B., and Wang, P. (2021). Assessing Global Energy Poverty: an Integrated Approach. *Energy Policy* 149, 112099. doi:10.1016/j.enpol.2020.112099

Dobbins, A., Fuso Nerini, F., Deane, P., and Pye, S. (2019). Strengthening the EU Response to Energy Poverty. *Nat. Energ.* 4 (1), 2–5. doi:10.1038/s41560-018-0316-8

Gafa, D. W., and Egbendewe, A. Y. G. (2021). Energy Poverty in Rural West Africa and its Determinants: Evidence from Senegal and Togo. *Energy Policy* 156, 112476. doi:10.1016/j.enpol.2021.112476

González-Eguino, M. (2015). Energy Poverty: An Overview. *Renew. Sustain. Energ. Rev.* 47, 377–385. doi:10.1016/j.rser.2015.03.013

Halkos, G. E., and Gkampoura, E.-C. (2021). Evaluating the Effect of Economic Crisis on Energy Poverty in Europe. *Renew. Sust. Energ. Rev.* 144, 110981. doi:10.1016/j.rser.2021.110981

Jayasinghe, M., Selvanathan, E. A., and Selvanathan, S. (2021). Energy Poverty in Sri Lanka. *Energ. Econ.* 101, 105450. doi:10.1016/j.eneco.2021.105450

Liu, J., Mauzerall, D. L., Chen, Q., Zhang, Q., Song, Y., Peng, W., et al. (2016). Air Pollutant Emissions from Chinese Households: A Major and Underappreciated Ambient Pollution Source. *Proc. Natl. Acad. Sci. USA* 113 (28), 7756–7761. doi:10.1073/pnas.1604537113

Mendoza, C. B., Jr, Cayonte, D. D. D., Leabres, M. S., and Manaligod, L. R. A. (2019). Understanding Multidimensional Energy Poverty in the Philippines. *Energy Policy* 133, 110886. doi:10.1016/j.enpol.2019.110886

Nussbaumer, P., Bazilian, M., and Modi, V. (2012). Measuring Energy Poverty: Focusing on what Matters. *Renew. Sust. Energ. Rev.* 16 (1), 231–243. doi:10.1016/j.rser.2011.07.150

Sovacool, B. K., and Brown, M. A. (2010). Competing Dimensions of Energy Security: an International Perspective. *Annu. Rev. Environ. Resour.* 35, 77–108. doi:10.1146/annurev-environ-042509-143035

Sovacool, B. K. (2012). Deploying Off-Grid Technology to Eradicate Energy Poverty. *Science* 338 (6103), 47–48. doi:10.1126/science.1222307

Thomson, H., and Snell, C. (2013). Quantifying the Prevalence of Fuel Poverty across the European Union. *Energy Policy* 52, 563–572. doi:10.1016/j.enpol.2012.10.009

Xu, Z., Chau, S. N., Chen, X., Zhang, J., Li, Y., Dietz, T., et al. (2020). Assessing Progress towards Sustainable Development over Space and Time. *Nature* 577 (7788), 74–78. doi:10.1038/s41586-021-03479-2

Yan, J., Yang, Y., Elia Campana, P., and He, J. (2019). City-level Analysis of Subsidy-free Solar Photovoltaic Electricity price, Profits and Grid Parity in China. *Nat. Energ.* 4 (8), 709–717. doi:10.1038/s41560-019-0441-z

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 20 December 2021
doi: 10.3389/fenrg.2021.792199

The Effect of Urban Spatial Form on Energy Efficiency: A Cross-Sectional Study in China

Zi-gui Chen[1], Ling-jun Kong[2], Min Wang[3,4], Hang-kai Liu[2]*, Da-kai Xiao[2]* and We-ping Wu[2]**

[1]*Design & Art Institute, Hunan University of Technology and Business, Changsha, China,* [2]*School of Economy & Trade, Hunan University of Technology and Business, Changsha, China,* [3]*School of Information Engineering, Lanzhou University of Finance and Economics, Lanzhou, China,* [4]*School of Business, Central South University of Forestry and Technology, Changsha, China*

OPEN ACCESS

Edited by:
Yong-cong Yang,
Guangdong University of Foreign Studies, China

Reviewed by:
Kexing Wu,
Shanghai Lixin University of Accounting and Finance, China
Huihui Wang,
Cleveland State University, United States

***Correspondence:**
Min Wang
henman@163.com
Hang-kai Liu
lhk200018570552616@163.com
Da-kai Xiao
xdk123321@163.com
We-ping Wu
wuweiping.2007@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *09 October 2021*
Accepted: *04 November 2021*
Published: *20 December 2021*

Citation:
Chen Z-g, Kong L-j, Wang M, Liu H-k, Xiao D-k and Wu W-p (2021) The Effect of Urban Spatial Form on Energy Efficiency: A Cross-Sectional Study in China.
Front. Energy Res. 9:792199.
doi: 10.3389/fenrg.2021.792199

Rational planning and optimization of urban spatial form to achieve the goal of energy efficient utilization and carbon emission reduction is one of the important ways to improve energy efficiency. We deconstruct urban spatial form into centrality, aggregation and complexity, and analyze net effect and its heterogeneity of urban spatial form on energy efficiency with OLS, quantile regression model as well as grouped regression model. The results show that the effects of urban spatial centrality and complexity on energy efficiency are nonlinear. For the vast majority of cities, strengthening urban spatial centrality will significantly improve energy efficiency, but the growth rate will gradually decrease. The impact effect of urban complexity on energy efficiency has the characteristics of U-shaped trend with an inflection point value of 0.429. And for the three-quarters of urban samples, enhancing urban spatial complexity will reduce energy efficiency. The positive effect of urban spatial aggregation on energy efficiency is only significant in cities with high quantile for energy efficiency. In terms of urban heterogeneity, the positive effects of spatial centrality and aggregation on energy efficiency are more obvious in megacities with a permanent population of more than 5 million, and the negative effect of spatial complexity on energy efficiency is more obvious in small and medium-sized cities. Whether it is promotion or inhibition, the urban samples with high energy efficiency are more affected by the change of urban spatial form. Optimizing the urban spatial form is one of the important ways to improve the energy efficiency, and the policy setting should give full consideration to the urban heterogeneity and classified policies.

Keywords: urban spatial form, energy efficiency, centrality, aggregation, complexity, China

INTRODUCTION

Resource depletion and ecological environment problems caused by excessive energy consumption have become one of the major challenges of human development in the 21st century. Improving energy efficiency is the key to achieve the goals of energy conservation, emission reduction and green development (Chen et al., 2018). Looking back on the development process of major countries in the world, as the lifeline of national economic development, energy plays a self-evident role as the driving force for a country or region's economic growth. At the same time, the dependence of the world economy on energy has not decreased markedly, but has deepened (Zhang et al., 2020). In China, energy has supported the process of industrialization and urbanization to a certain extent, and has become a vital factor of production for economic growth. According to the data released by BP

World Energy Statistical Yearbook, China is still the largest energy consumer in the world. In 2018, China's total energy consumption has reached 3.273 billion tons of oil equivalents, accounting for 23.6% of the world, and its contribution to the growth of total primary energy consumption has reached 34%, far exceeding that of other countries in the world. On the supply side, energy consumption has shifted from self-sufficiency to import, and the proportion of import has increased year by year. Since 2018, China has become the world's largest oil and gas importer, and its dependence on foreign crude oil and natural gas has reached a new high in recent 50 years (Rong et al., 2016). The huge energy consumption makes China's carbon emissions jump to the first in the world, accounting for 28.9% of the global total.

Consistent with the growth trend of energy consumption, China has experienced a large-scale and rapid urbanization process since the reform and opening up. Over the past 40 years, more than 650 million rural residents have moved to cities to live and work. By the end of 2020, China's urbanization rate has reached 63.89%. According to Wu et al. (2020), by 2035, China's urbanization rate will reach 75–80%, adding nearly 400 million urban residents. The expanded cities have rapidly obtained factors of production such as labor and energy, and achieved rapid development. At the same time, they have also expanded the scale of production and life, increased fossil energy consumption, and exacerbated the problem of regional and structural energy shortage. As the center of human social and economic activities, urban areas now account for 85% of the total national energy consumption and more than 70% of the national carbon emissions. In addition, the decentralization and complexity of urban spatial form, as well as the spatial mismatch between industry and resource elements in the city, inhibit the efficient and intensive utilization of energy resources to a certain extent. Therefore, how to achieve the goals of energy efficient utilization and carbon emission reduction through reasonable planning, optimization and adjustment of urban spatial form provides a new path for China to deal with the energy crisis and improve energy efficiency under the "double carbon" strategic goal.

This study is structured as follows. *Literature Review and Hypothesis* Section summarizes the existing research progress and theory hypothesis. *Material and Methods* Section presents the identification method of urban spatial form and energy efficiency, and the econometric model specification of the theoretical hypothesis test. In *Result* section, the net effect and its heterogeneity of urban spatial form on energy efficiency are systematically analyzed. *Conclusion* Section draws conclusions and policy implications.

LITERATURE REVIEW AND HYPOTHESIS

The research on urban spatial form originated from the urban form and land use research center founded by British scholars March and Martin in the 1950s. They believe that urban spatial form is a variety of spatial structures and traffic corridors composed of basic spatial geometric elements. After entering the 21st century, with the reorganization of the world economic pattern and global economic integration, the urban spatial form has further developed in the direction of regionalization and information networking, and its internal mechanism has become more complex (Tanushri and Sarika, 2021). The evolution of urban spatial form is showing unprecedented new mechanisms and characteristics, and has become an important field of urban geography and economic research (Li et al., 2021; (Xiong and Duan, 2020). This is because the urban spatial form can not only comprehensively reflect the social and economic activities of the city in different periods, but also change with the changes of urban economic activities and social culture, showing a dynamic interaction process. At this stage, there are various measurement indicators of urban spatial form, mainly focusing on the geometric characteristics of urban space and the economic and social indicators related to spatial form, which can be roughly divided into three types: urban spatial aggregation, urban spatial complexity and urban spatial centrality. Among them, the indicators to measure urban spatial aggregation include cluster degree (Shu and Lam, 2011), similar adjacency rate (Falahatkar et al., 2020), aggregation index (Fang et al., 2015), compactness index (Liu et al., 2012), maximum patch compactness index (Makido et al., 2012), etc; Indicators to measure urban spatial complexity include landscape shape index (Bereitschaft and Debbage, 2013; Liu et al., 2015), edge density (Ma et al., 2013), average perimeter area ratio (Ou et al., 2013), etc; The largest patch area (Chen et al., 2011; Jia et al., 2019) is the index to measure the urban spatial centrality.

The effect of urban spatial form on energy efficiency has always been the focus of academic attention. However, from the existing research, few literatures systematically explore the net impact of urban spatial form on energy efficiency and its mechanism from multiple dimensions. It mainly investigates the impact of a certain dimension index of urban spatial form on urban energy efficiency (Zhong et al., 2020; Esfandi et al., 2022). First, some researchers have investigated the impact of urban spatial aggregation on energy efficiency, and believe that the higher the aggregation, the higher the energy efficiency (Ewing and Rong., 2008). This is because high aggregation degree means that urban spatial form shows high population density, high building density and relatively high industrial concentration, which are more conducive to improving energy intensive utilization efficiency (Steemers, 2003; Wang et al., 2020). Moreover, the centralized residential space and industrial distribution form help to save the energy consumption of transportation, commuting and product transportation (Hankey and Marshall, 2010; Ma et al., 2015; Quan and Li, 2021). Second, the centralization of urban spatial structure will also have a positive impact on energy efficiency, because the higher the urban centrality, the more conducive to saving overall energy consumption and realizing intensive utilization (Chen et al., 2011; Mangan et al., 2020). Third, the complexity of urban spatial form represents the geometric complexity of urban patch form. Moreover, cities with higher complexity usually have higher energy consumption and lower energy efficiency. This conclusion was obtained by Falahatkar et al. (2010) based on the sample data of Iran and Makido et al. (2012) Based on the empirical analysis of Japanese sample data. Therefore, this paper proposes proposition 1.

Proposition 1. Aggregation, centrality and complexity of urban spatial form will have an impact on energy efficiency. And urban spatial aggregation and centrality are positively correlated with energy efficiency, while urban spatial complexity is negatively correlated with energy efficiency.

In addition, the impact of urban spatial form on energy efficiency is not invariable (Mangan et al., 2020). On the one hand, with the change of urban spatial form, the urban internal population and industrial spatial structure will be dynamically adjusted, and the corresponding energy consumption scale and structure will also be adjusted accordingly (Zeng et al., 2021; Wu et al., 2021a). It can be seen that the effect of urban spatial form on energy efficiency is not necessarily completely linear, but may show nonlinear characteristics. On the other hand, urban space is not completely homogeneous. The heterogeneity of different cities in geographical characteristics, economic development and technological innovation (Peng et al., 2021) makes the impact of urban spatial form on the scale and structure of energy consumption significantly different among different cities (Yu, 2021; Zhang and Gao, 2021). Therefore, this paper proposes the second and third theoretical hypothesis.

Proposition 2. The aggregation, centrality and complexity of urban spatial form may have a nonlinear impact on energy efficiency.

Proposition 3. The marginal effect of aggregation, centrality and complexity of urban spatial form on energy efficiency will show urban heterogeneity characteristics.

MATERIAL AND METHODS

Data

This paper performs an empirical analysis based on cross-sectional data from 282 cities of China in 2017. The cross-sectional data in 2017 is selected as the analysis data set because the original data of urban spatial form variable indicators calculated in this paper comes from the basic remote sensing data source published by Gong et al. (2019), and the latest year of the data source is 2017. In urban spatial form recognition, the most important thing is to obtain the spatial structure data of urban built-up areas, and the urban impervious surface is the main path to extract urban built-up areas (Liu et al., 2021; Gong et al., 2019). The basic remote sensing data source of urban spatial morphology released by Gong et al. (2019) comprehensively considers MODIS and night light data, and effectively separates the impervious surface between urban and rural areas. In order to obtain the spatial form data set of 282 cities in China, we first derived the impervious surface data in 2017, then segmented and extracted the impervious surface grid map by using the segmented city vector map, and then obtained the impervious surface distribution map of 282 cities. At the same time, the landscape index calculation software FRAGSTATS is used to calculate the index data including patch, area, shape, edge and so on. Finally, in view of the dimensional difference of urban spatial form variable index data, in order to eliminate this influence, we also use the extreme value standardization method to normalize all variable indexes.

The independent variable of this study is energy efficiency, which is also calculated through relevant input and output indicators. Among them, the data of some input index variable, such as the number of employees, total investment in fixed assets, and R&D expenditure, are derived from *the China Economic and Social Big Data Research Platform of the China National Knowledge Infrastructure* (CNKI). The input index of energy consumption refers to the total energy consumption of various types, including coal, oil, natural gas, primary power and other energy consumption. The variable index is obtained by converting the common energy consumption into standard coal and summing it up. The data of output index variable, such as GDP, gross value of industrial output, industrial SO_2 emissions, industrial wastewater discharge, are derived from the *Economy Prediction System* (EPS). The missing data of some variable indicators are supplemented by *China Urban Statistical Yearbook* and various urban statistical yearbooks.

Identification Methods

Urban Spatial Form

Scientific, reasonable and accurate identification of urban spatial form is the key to ensure the reliability of research results. Based on the existing related research, this paper describes the urban spatial form from the three dimensions of centrality, aggregation and complexity. In order to avoid the tendency and multi-collinearity of the index set, only one characterization index is reserved for each dimension of urban spatial form recognition.

(1) Centrality

Galster et al. (2001) defined the centrality of urban spatial form as the degree to which urban residential or non residential areas are close to the central business district, which can also be expressed as the degree to which urban spatial form is characterized by a single core development model. This paper uses the maximum patch index to measure the centrality of urban spatial form. Among them, the largest patch index is the proportion of the largest patch area in the total urban landscape area, and the largest proportion indicates that the higher the city centrality. The calculation formula is as follow:

$$Centrality = \frac{\max_{j=1}^{n} a_{ij}}{\sum_{i=1}^{m} a_i\,(1/10000)} \times 100 \tag{1}$$

Where $Centrality$ represents the centrality of the urban spatial form, and the result of $Centrality$ is multiplied by 100 to convert to a percentage; $\max_{j=1}^{n} a_{ij}$ is the area of the largest urban patch; m is the number of patch types, n is the number of patches of a class; a_{ij} is the area of patch ij, and $\sum_{i=1}^{m} a_i\,(1/10000)$ is the total landscape area.

(2) Aggregation

Aggregation refers to the degree of agglomeration or separation of patch types in space. Generally speaking, the landscape organized by many discrete small patches in a landscape has a low degree of aggregation; When a landscape is composed of several large patches or the patches of the same category are fully connected, the degree of aggregation is higher. As the core concept of urban sustainable development, the quantitative index of aggregation degree is an effective method to evaluate the aggregation distribution of urban spatial structure. Aggregation development makes urban economic development and function distribution more compact, and effectively shortens the spatial distance between urban patches. The calculation formula is as follows:

$$Aggregation = \left[\frac{G_i - P_i}{P_i}\right] \quad if \quad G_i < P_i < 0.5 \quad else$$
$$Aggregation = \left[\frac{G_i - P_i}{1 - P_i}\right] \tag{2}$$
$$Given \quad G_i = \frac{g_{ii}}{\sum_{k=1}^{m} g_{ik} - \min e_i}$$

Where P_i is the proportion of the landscape occupied by patch type i, and G_i is the proportion of the landscape occupied by like adjacencies between pixels of patch type i; $\min e_i$ is the minimum perimeter of a patch type i for a maximally aggregated patch type; g_{ii} is the number of like adjacencies between pixels of class i, and g_{ik} is the number of adjacencies between pixels of class i and class k.

(3) Complexity

The complexity of urban spatial form mainly refers to the irregularity of patch shape. In landscape ecology, shape index is closely related to edge effect. Therefore, scholars often characterize the complexity of landscape patches based on the area and perimeter of patches. Generally speaking, the urban landscape with highly complex and irregular boundaries will increase the straight-line distance and commuting time between different patches in the city. This paper uses the landscape shape index to describe the regularity of urban spatial form, and uses the perimeter area ratio of urban patches to measure the landscape shape index. The calculation formula is as follow:

$$Complexity = \frac{0.25\sum_{k=1}^{m} e_{ik}^{*}}{\sqrt{\sum_{i=1}^{n} a_i\,(1/10000)}} \tag{3}$$

Where e_{ik} is the total edge length of class i in the landscape, and $\sum_{i=1}^{m} a_i\,(1/10000)$ is the total landscape area.

Energy Efficiency

There are many indicators and methods for measuring energy efficiency in academia, such as parametric and nonparametric estimation methods. Considering that the super-SBM model not only overcomes the limitations of the traditional SBM model, but also has relatively high accuracy of measurement results (Li et al., 2021), this paper establishes a super-SBM model of non angular, non radial and considering undesirable output to measure energy efficiency with reference to the practice of Wu et al., 2021b. The model is constructed as follows:

$$\rho = \min \frac{1 - \frac{1}{N} S_m^x / x_{ki}^{'t}}{1 + \frac{T}{M+1}\left(\sum_{m=1}^{M} S_m^y / y_{km}^{'t} + \sum_{i=1}^{I} S_i^b / b_{ki}^{'t}\right)} \; s.t.$$
$$\sum_{t=1}^{T}\sum_{k=1}^{K} Z_k^t X_{kn}^t + S_n^x = x_{kn}^{'t} \quad (n = 1, \cdots, N)$$
$$\sum_{t=1}^{T}\sum_{k=1}^{K} Z_k^t x_{km}^t + S_m^y = y_{km}^{'t} \quad (m = 1, \cdots, M) \tag{4}$$
$$\sum_{t=1}^{T}\sum_{k=1}^{K} Z_k^t b_{ki}^t + S_i^b = b_{ki}^{'t}$$
$$(i = 1, \cdots, I) Z_k^t \geq 0, S_n^x \geq 0, S_m^y \geq 0, S_i^b \geq 0 \,(k = 1, \cdots, K)$$

In **Eq. 1**, ρ is energy efficiency values that need to be measured, which is greater than or equal to 0. Among them, $ind\_control$ indicates that there is room for energy efficiency improvement; a is the number of input indicators; P_0 is the number of desirable output indicators; and a is the number of undesirable output indicators. The expression P_1 represents the input (output) value of the $\ln(wage_{ijt}) = \alpha + \beta_1 ex\_poverty_{jt} + \gamma_1 ind\_control_{ijt} + \gamma_2 fam\_control_{jt} + \varepsilon_{ijt}$ decision-making unit in period $\ln(wage_{ijt}) = \alpha + \beta_2 in\_poverty_{jt} + \gamma_1 ind\_control_{ijt} + \gamma_2 fam\_control_{jt} + \varepsilon_{ijt}$; and i represents the slack variable of input (output). If the slack variable is larger than 0, it indicates that the input of factors is not fully used. The variable j represents the weight of the decision-making unit; t means the return on scale of the model is constant, $\ln(wage)$ means the model has variable returns to scale.

For a more comprehensive understanding of energy efficiency in China, a multidimensional analytical framework has been created for energy efficiency identification. The framework characterized has two dimensions (i.e., the inputs and outputs), as shown in **Table 1**. Number of employees (per 10 thousand people), total investment in fixed assets (per 10 thousand RMB), Energy consumption (kgce/100 million tons), and R&D expenditure (per 10 thousand RMB) are selected as indicators of inputs. GDP (per 100 million RMB), and gross value of industrial output (per 100 million RMB) are selected as an index of desirable output indicators. And industrial SO_2 emissions (per ton), industrial wastewater discharge (per 10 thousand t) are selected as an index of undesirable output indicators.

Model Specification

The impact of urban spatial form on energy efficiency has been supported by theoretical research. Moreover, as the three types of representations of urban spatial form, there are obvious differences in the effects and mechanisms of centrality, aggregation, and complexity on urban energy efficiency. In order to further verify the response of urban energy efficiency to the centrality, aggregation, and complexity of spatial form, this paper constructs the following three groups of basic regression models:

$$energy\_eff_i = \alpha + \beta Centrality_i + \gamma control_i + \varepsilon_i \tag{5}$$

TABLE 1 | Input and output variables for energy efficiency identification.

	Inputs	Outputs
Energy efficiency	①Number of employees ②Total investment in fixed assets ③Energy consumption ④R&D expenditure	①GDP (+) ②Gross value of industrial output (+) ③Industrial SO_2 emissions (—) ④Industrial wastewater discharge (—)

Note*: "+" represents the desirable output indicator, "- " represents an indicator of undesirable output.*

$$energy\_eff_i = \alpha + \beta Aggregation_i + \gamma control_i + \varepsilon_i \quad (6)$$

$$energy\_eff_i = \alpha + \beta Complexity_i + \gamma control_i + \varepsilon_i \quad (7)$$

Where, the dependent variable $energy\_eff_i$ represents the energy efficiency of city *i*; The independent variables are centrality, aggregation, and complexity of urban spatial form, and β is the net effect of urban spatial form on energy efficiency; *control* is the control variables, including social, economic, and institutional factors. The social factors controlled in this paper include population density (*density*), urbanization rate (*urbanization*); the economic factors include per capita GDP (*rjgdp*), industrial structure index (*structure*); and the institutional factors include government expenditure level (*expenditure*), innovation ability (*innovation*). The population density is the number of permanent residents per unit of urban construction area; The urbanization rate is the ratio of the number of urban permanent residents to the total population; The industrial structure index is measured by the proportion of the output value of the primary and tertiary industries; Urban innovation capability is measured by the number of urban invention patents authorized. In order to obtain more stable research results, the article also takes natural logarithms for variables such as population density, per capita GDP, government expenditure level and innovation ability.

In addition, certain literatures show that the centrality, aggregation, and complexity of urban spatial form may have a nonlinear relationship with energy efficiency. In order to verify this inference, the basic regression model is optimized, and the nonlinear performance of influence effect is investigated by adding the quadratic term of independent variable. The model settings are as follows:

$$energy\_eff_i = \alpha + \beta Centrality_i + \delta Centrality_i \times Centrality_i + \gamma control_i + \varepsilon_i \quad (8)$$

$$energy\_eff_i = \alpha + \beta Aggregation_i + \delta Aggregation_i \times Aggregation_i + \gamma control_i + \varepsilon_i \quad (9)$$

$$energy\_eff_i = \alpha + \beta Complexity_i + \delta Complexity_i \times Complexity_i + \gamma control_i + \varepsilon_i \quad (10)$$

After introducing the quadratic term of the independent variable, the influence coefficient of urban spatial form on energy efficiency is adjusted as follows:

$$\frac{\partial energy\_eff_i}{\partial Centrality_i} = \beta + 2\delta \times Centrality_i \quad (11)$$

$$\frac{\partial energy\_eff_i}{\partial Aggregation_i} = \beta + 2\delta \times Aggregation_i \quad (12)$$

$$\frac{\partial energy\_eff_i}{\partial Complexity_i} = \beta + 2\delta \times Complexity_i \quad (13)$$

RESULT

Baseline Regression

Table 2 represents the baseline estimates for the net effect of urban spatial form on energy efficiency. Among them, regression **Equations 1–3** only investigate the linear effects of urban spatial centrality, aggregation, and complexity on energy efficiency; In regression **Equations 4–6**, the quadratic variables of urban spatial centrality, aggregation and complexity are introduced respectively to further investigate the nonlinear effects of urban spatial centrality, aggregation and complexity on energy efficiency. From the estimation results of **Equations 1–3**, the urban spatial centrality has a significant positive effect on energy efficiency, and the marginal effect is 1.48, which means that every unit increase in the urban spatial centrality will effectively improve energy efficiency by 1.48 units. The complexity of urban spatial form has a significant negative effect on energy efficiency, and its marginal influence coefficient is 0.61, indicating that every increase of urban spatial complexity will lead to a decrease of urban energy efficiency by 0.61 units. The estimation coefficient of urban spatial aggregation is positive but not significant, indicating that urban spatial aggregation has no significant impact on energy efficiency. In other words, from the perspective of overall average effect, it is impossible to clearly distinguish the net impact of urban aggregation on energy efficiency. In summary, it can be seen that part of the proposition 1 has been proved.

In regression **Eq. 4**, the estimated coefficient of the urban spatial centrality is significantly positive, and the quadratic term estimation coefficient is significantly negative, indicating that the effect of urban spatial centrality on energy efficiency shows the inverted U trend characteristic. Further, the inflection point value of this impact effect is 0.3449, and only 5 cities are greater than the inflection point value, namely Shanghai, Shenzhen, Xiamen, Foshan, and Zhongshan. Therefore, it can be considered that for the vast majority of cities, increasing the centralization is conducive to improving energy efficiency. That is to say, for the vast majority of urban samples whose centrality is not high enough, enhancing the area proportion of the largest urban patch essentially strengthens the urban single center structure

TABLE 2 | Baseline regression estimation results.

	Dependent variable: *energy_eff*					
	(1)	(2)	(3)	(4)	(5)	(6)
Centrality	1.4841*** (0.2306			0.8433** (0.4221		
Centrality Centrality*				-1.2227** (0.6647)		
Aggregation		0.1657 (0.1114)			0.6437 (0.4449)	
Aggregation Aggregation*					-0.4393 (0.3959)	
Complexity			-0.6058*** (0.1170)			-0.9617*** (0.3177)
Complexity Complexity*						1.1208*** (0.3705)
ln(density)	0.0713*** (0.0252)	0.0455* (0.0271)	0.0537** (0.0271)	0.0695*** (0.0252)	0.0462* (0.0271)	0.0485** (0.0268)
urbanization	0.2276 (0.1584)	0.2750* (0.1574)	0.2508* (0.1577)	0.1071 (0.1586)	0.2593* (0.1580)	0.1561 (0.1585)
ln(rjgdp)	0.0342 (0.0354)	0.0307 (0.0377)	0.0322 (0.0380)	0.0360 (0.0353)	0.0333 (0.0378)	0.0367 (0.0375)
structure	0.0036** (0.0017)	0.0036** (0.0018)	0.0035* (0.0019)	0.0037** (0.0017)	0.0036* (0.0019)	0.0030* (0.0017)
ln(expenditure)	0.1544*** (0.0392)	0.1191*** (0.0414)	0.1098*** (0.0436)	0.1687*** (0.0400)	0.1211*** (0.0414)	0.1285*** (0.0434)
ln(innovation)	0.0687*** (0.0164)	0.0610*** (0.0175)	0.0589*** (0.0178)	0.0613*** (0.0170)	0.0592*** (0.0176)	0.0530*** (0.0176)
F Stats	20.550***	13.130***	12.770***	18.400***	11.650***	12.650***
R^2	0.2442	0.2512	0.2460	0.3503	0.2546	0.2705
Obs	282	282	282	282	282	282

Note: *** p < *0.01,* ** p < *0.05,* * p < *0.1, robust standard errors in parentheses (the same below).*

mode, which is conducive to the intensive consumption and efficient utilization of energy resources. However, strengthening the centrality of cities such as Shanghai, Shenzhen, Xiamen, Foshan, and Zhongshan is not conducive to the improvement of energy efficiency, which may be related to the heavy reliance of the above cities on the single center structure mode. Therefore, the appropriate development of the multi center structure mode is more conducive to the improvement of urban energy efficiency.

In **Equation 6**, the estimation coefficient of urban spatial complexity is significantly negative and the estimation coefficient of quadratic term is significantly positive, which means that the impact effect of urban complexity on energy efficiency has the characteristics of U-shaped trend. Further calculation shows that the inflection point value of urban complexity is 0.4290, and three-quarters of urban samples are located on the left side of the inflection point value, and one-quarter of urban samples are located on the right side of the inflection point value. This shows that for most cities, increasing the complexity of urban spatial form will reduce their energy efficiency. This is because the more complex the shape and edge of urban space, the more dispersed the energy consumption within the city, which is not conducive to the intensive utilization of energy resources. In **Equation 5**, the estimation coefficients of urban spatial aggregation and its quadratic term variable are not significant, indicating that from the overall average effect, aggregation has no significant impact on urban energy efficiency. In short, for the vast majority of cities, appropriately improving urban centrality or reducing urban complexity is conducive to enhancing urban energy efficiency. Therefore, the part of the theoretical proposition 2 is proved.

From the estimation results of control variables, the variables such as urban population density, urbanization, industrial structure index, government expenditure level, and innovation ability have consistent estimation results in each regression equation, and the regression coefficients are significantly positive, indicating that the higher the urban population density, urbanization, government expenditure level and urban innovation ability, the more conducive it is to promote the intensive consumption and efficient use of urban energy. In addition, the industrial structure biased towards the primary and tertiary industries is conducive to the improvement of urban energy efficiency. Finally, from the significance test results of the model, F statistical values of each estimation equation are 20.55, 13.13, 12.77, 18.40, 11.65 and 12.65 respectively, which are significant at the 1% level, indicating that the econometric model is well set.

Heterogeneity Analysis

Quantile Regression Estimation

Traditional regression estimation studies the relationship between conditional expectations between independent variables and dependent variables. The quantile regression studies the relationship between the conditional quantiles of independent variables and dependent variables, so it can further identify the heterogeneous effects of urban spatial form on energy efficiency at different quantiles. Furthermore, according to the statistical data, there are significant differences in energy efficiency between different cities, which means that cities with different energy efficiency may be affected differently by urban spatial form. In order to verify this inference, we use quantile regression model (QR) to further investigate the differentiated effect of urban spatial form on the energy efficiency at different quantiles.

Table 3 reports the response of energy efficiency to urban spatial form at the 25th, 50th and 75th quantile. Firstly, from the centrality estimation results, the estimation coefficients of urban centrality variables are significantly positive in all quantile regression models, and the estimation coefficients of quadratic term are significantly negative, indicating that the net effect of urban centrality on energy efficiency shows an inverted U-shaped trend of first rising and then falling. Moreover, the net effect of centrality on energy efficiency gradually strengthens with increasing quantiles, meaning that cities with higher energy

TABLE 3 | Quantile regression estimation results.

	Dependent variable: *energy_eff*								
	25 points			**50 points**			**75 points**		
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
Centrality	0.3745**			-0.7134***			1.7828**		
	(0.1884)			(0.1712)			(0.8342)		
*Centrality**	-2.5848***			-2.1215***			-2.9480**		
Centrality	(0.4773)			(0.5945)			(1.3806)		
Aggregation		0.1980			0.7222**			1.3255*	
		(0.2516)			(0.3280)			(0.7962)	
*Aggregation**		-0.1836			-0.5687*			-0.9612*	
Aggregation		(0.2238)			(0.2908)			(0.6008)	
Complexity			-0.7134***			-1.0982***			-1.7159***
			(0.1712)			(0.2094)			(0.5900)
*Complexity**			0.7713***			1.3055***			2.0880***
Complexity			(0.1996)			(0.2442)			(0.6878)
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES
Pseudo R^2	0.2710	0.2401	0.2596	0.2772	0.2414	0.2676	0.2726	0.2196	0.2314
Obs.	282	282	282	282	282	282	282	282	282

Note: *** p < *0.01,* ** p < *0.05,* * p < *0.1, robust standard errors in parentheses.*

TABLE 4 | Urban heterogeneity analysis results.

	Dependent variable: *energy_eff*								
	Megacities			**Large cities**			**SMCs**		
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
Centrality	2.0874**			1.7847***			3.4185		
	(1.002)			(0.5455)			(2.2778)		
*Centrality**	-3.5119*			-0.4849**			18.0134		
Centrality	(1.9107)			(0.2117)			(11.7900)		
Aggregation		1.2961*			0.2787			0.7387	
		(0.7314)			(0.6775)			(0.6873)	
*Aggregation**		-0.8533*			-0.1106			-0.6959	
Aggregation		(0.4735)			(0.6058)			(0.6116)	
Complexity			-3.2037			-0.6829			-1.8601***
			(2.2808)			(0.4457)			(0.6165)
*Complexity**			3.8515			0.8375			2.0828***
Complexity			(2.3440)			(0.5316)			(0.7904)
Control	YES	YES	YES	YES	YES	YES	YES	YES	YES
F Stats	6.650**	7.760**	6.650**	12.170***	3.310**	0.4164	4.750***	4.580***	5.897***
R^2	0.3852	0.3978	0.3852	0.4207	0.1650	3,364	0.2517	0.2447	0.2943
Obs.	16	16	16	143	143	143	122	122	122

Note: *** p < *0.01,* ** p < *0.05,* * p < *0.1, robust standard errors in parentheses.*

efficiency benefit more from the centralization of urban spatial structure. Secondly, the estimated coefficients of urban aggregation variables and their quadratic terms are only significant in the 50 and 75 quantile regression models, and showed inverted U trend features. This shows that for urban samples with high energy efficiency, the net effect of aggregation on energy efficiency will also show an inverted U trend characteristic of rising first and then decreasing. Moreover, cities with relatively high energy efficiency can more benefit from urban spatial aggregation. Thirdly, the estimated coefficients of urban complexity variables are significantly negative in all quantile regression models, and their quadratic terms are significantly positive, meaning that the net effect of urban complexity on energy efficiency exhibited a U-shaped trend characteristic of falling first before rising. Moreover, for urban samples with high energy efficiency, urban complexity has the most obvious inhibitory effect on energy efficiency. Taken together, urban samples with high energy efficiency are more prominently affected by urban spatial morphology changes, whether by facilitation or inhibition.

Urban Heterogeneity Analysis

According to the research of Wu et al. (2020), megacities, large cities, and small and medium-sized cities show certain heterogeneity in spatial structure and economic development level, which means that the impact of urban spatial form on energy efficiency will be different in different levels of cities. Therefore, this paper classifies cities according to the size of permanent population in the municipal area, and divides cities with a permanent population of more than 5 million into megacities, cities with a permanent population of more than 1 million and less than 5 million into large cities, and cities with a permanent population of less than 1 million into small and medium-sized cities (SMCs). **Table 4** reports the grouping estimation results of different types of urban samples.

From the estimates of urban centrality, its primary-term and quadratic-term regression coefficients are only significant in the megacities and large city samples, but not in SMCs. In addition, the net effect of centrality on the energy efficiency of megacities and big cities shows the inverted U type trend of rising first before decreasing, and it will gradually increase with the expansion of urban scale. For urban aggregation, its net effect on urban energy efficiency is only significant in megacities, and also presents a characteristic of inverted U trend of rising first and then decreasing. From the estimates of urban complexity, the net effect on energy efficiency is only significant in small and medium-sized city samples. Moreover, the inhibitory effect of complexity on urban energy efficiency will gradually slow down with increasing complexity. In general, the effects of urban aggregation, centrality, and complexity on energy efficiency show obvious heterogeneity in urban scale heterogeneity, which means that optimizing energy efficiency from the urban spatial form needs to consider urban heterogeneity and adopt classified policies. In conclusion, the theoretical proposition 3 is proved.

CONCLUSION

This study deconstructed urban spatial form into centrality, aggregation and complexity, and analyzed net effect and its heterogeneity of urban spatial form on energy efficiency with OLS, quantile regression model as well as grouped regression model. The following main conclusions were reached: First, the effect of urban centrality on energy efficiency shows an inverted U-shaped trend with an inflection point value of 0.34, and 98.23% of the city samples are on the left of the inflection point, meaning that strengthening urban centralization for the vast majority of cities helps improve energy efficiency. Second, the effect of urban spatial complexity on energy efficiency shows a U-shaped trend of first decreasing and then increasing, and about three-quarters of urban samples are located on the left side of the inflection point. It can be seen that with the rise of urban spatial complexity, the urban energy efficiency tends to decline, but the decreasing rate gradually decreases. Third, from the perspective of the overall average effect, the net effect of urban aggregation on energy efficiency is not significant. However, in the sample of high quantile for energy efficiency, the net effect of urban spatial aggregation on energy efficiency is significantly positive, but the growth rate tends to decrease. Fourth, whether it is promotion or inhibition, the urban samples with high energy efficiency are more affected by the change of urban spatial form. Fifth, the effect of urban spatial form on energy efficiency shows obvious urban heterogeneity. Specifically, the positive effect of spatial centrality and aggregation on urban energy efficiency is more obvious in megacities, and the negative effect of spatial complexity on urban energy efficiency is more obvious in SMCs. In short, the significant impact of different types of urban spatial forms on energy efficiency provides new ideas for the path selection and optimization of urban energy efficiency improvement, which is to push force from the urban spatial form. That's to say, optimizing the urban spatial form is one of the important ways to improve the energy efficiency. But the policy setting should give full consideration to the urban heterogeneity and classified policies.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

Z-gC: Conceptualization, Writing - original draft, Methodology L-jK: Data curation, Software MW: Methodology, Writing - review & editing H-kL: Data curation, Supervision D-kX: Software, Conceptualization.

FUNDING

This research is supported by the National Natural Science Foundation of China (Grant No. 71903056), MOE (Ministry of Education in China) Project of Humanities and Social Sciences (Grant No. 19YJC790154), Natural Science Foundation of Hunan Province in China (Grant No. 2020JJ5104), Project of Hunan Social Science Achievement Appraisal Committee (Grant No. XSP21YBZ094), Scientific Research Project of Hunan Education Department in China (Grant No. 19C1038), Research and Innovation Project for Graduate Students in Hunan Province (Grant No. CX20211,126), and Innovation and Entrepreneurship Training Program for College Students in Hunan Province (Grant No. S202010554045).

REFERENCES

Bereitschaft, B., and Debbage, K. (2013). Urban Form, Air Pollution, and CO_2Emissions in Large U.S. Metropolitan Areas. *The Prof. Geographer* 65 (4), 612–635. doi:10.1080/00330124.2013.799991

Chen, X., Yi, N., Zhang, L., and Li, D. (2018). Does Institutional Pressure foster Corporate green Innovation? Evidence from China's Top 100 Companies. *J. Clean. Prod.* 188 (7), 304–311. doi:10.1016/j.jclepro.2018.03.257

Chen, Y., Li, X., Zheng, Y., Guan, Y., and Liu, X. (2011). Estimating the Relationship between Urban Forms and Energy Consumption: A Case

Study in the Pearl River Delta, 2005-2008. *Landscape Urban Plann.* 102 (1), 33–42. doi:10.1016/j.landurbplan.2011.03.007
Esfandi, S., Rahmdel, L., Nourian, F., and Sharifi, A. (2022). The Role of Urban Spatial Structure in Energy Resilience: An Integrated Assessment Framework Using a Hybrid Factor Analysis and Analytic Network Process Model. *Sustain. Cities Soc.* 76, 103458. doi:10.1016/j.scs.2021.103458
Ewing, R., and Rong, F. (2008). The Impact of Urban Form on U.S. Residential Energy Use. *Housing Policy Debate* 19 (1), 1–30. doi:10.1080/10511482.2008.9521624
Falahatkar, S., Rezaei, F., and Afzali, A. (2020). Towards Low Carbon Cities: Spatio-Temporal Dynamics of Urban Form and Carbon Dioxide Emissions. *Remote Sensing Appl. Soc. Environ.* 18, 100317. doi:10.1016/j.rsase.2020.100317
Fang, C., Wang, S., and Li, G. (2015). Changing Urban Forms and Carbon Dioxide Emissions in China: A Case Study of 30 Provincial Capital Cities. *Appl. Energ.* 158, 519–531. doi:10.1016/j.apenergy.2015.08.095
Galster, G., Hanson, R., Ratcliffe, M. R., Wolman, H., Coleman, S., and Freihage, J. (2001). Wrestling Sprawl to the Ground: Defining and Measuring an Elusive Concept. *Housing Policy Debate* 12 (4), 681–717. doi:10.1080/10511482.2001.9521426
Gong, P., Li, X., and Zhang, W. (2019). 40-Year (1978–2017) Human Settlement Changes in China Reflected by Impervious Surfaces From Satellite Remote Sensing. *Sci. Bull.* 64 (11), 756–763.
Hankey, S., and Marshall, J. D. (2010). Impacts of Urban Form on Future US Passenger-Vehicle Greenhouse Gas Emissions. *Energy Policy* 38 (9), 4880–4887. doi:10.1016/j.enpol.2009.07.005
Jia, Y., Tang, L., Xu, M., and Yang, X. (2019). Landscape Pattern Indices for Evaluating Urban Spatial Morphology - A Case Study of Chinese Cities. *Ecol. Indicators* 99, 27–37. doi:10.1016/j.ecolind.2018.12.007
Li, H., Chen, Z., and Guo, Q. (2021). The Evolution and Approaches of Information Analysis Service of University Libraries in China. *Sci. Tech. Libraries* 40 (1), 52–64. doi:10.1080/0194262x.2020.1830921
Liu, J., Jiao, L., Zhang, B., Xu, G., Yang, L., Dong, T., et al. (2021). New Indices to Capture the Evolution Characteristics of Urban Expansion Structure and Form. *Ecol. Indicators* 122 (4), 107302. doi:10.1016/j.ecolind.2020.107302
Liu, X., Hu, G., Ai, B., Li, X., and Shi, Q. (2015). A Normalized Urban Areas Composite index (NUACI) Based on Combination of DMSP-OLS and MODIS for Mapping Impervious Surface Area. *Remote Sensing* 7 (12), 17168–17189. doi:10.3390/rs71215863
Liu, Y., Song, Y., and Arp, H. P. (2012). Examination of the Relationship between Urban Form and Urban Eco-Efficiency in China. *Habitat Int.* 36 (1), 171–177. doi:10.1016/j.habitatint.2011.08.001
Ma, J., Liu, Z., and Chai, Y. (2015). The Impact of Urban Form on CO2 Emission from Work and Non-work Trips: The Case of Beijing, China. *Habitat Int.* 47, 1–10. doi:10.1016/j.habitatint.2014.12.007
Ma, M., Hietala, R., Kuussaari, M., and Helenius, J. (2013). Impacts of Edge Density of Field Patches on Plant Species Richness and Community Turnover Among Margin Habitats in Agricultural Landscapes. *Ecol. indicators* 31, 25–34. doi:10.1016/j.ecolind.2012.07.012
Makido, Y., Dhakal, S., and Yamagata, Y. (2012). Relationship between Urban Form and CO2 Emissions: Evidence from Fifty Japanese Cities. *Urban Clim.* 2, 55–67. doi:10.1016/j.uclim.2012.10.006
Mangan, S. D., Oral, G. K., Kocagil, I. E., and Sozen, I. (2020). The Impact of Urban Form on Building Energy and Cost Efficiency in Temperate-Humid Zones. *J. Building Eng.* 33, 101626. doi:10.1016/j.jobe.2020.101626
Ou, J., Liu, X., Li, X., and Chen, Y. (2013). Quantifying the Relationship between Urban Forms and Carbon Emissions Using Panel Data Analysis. *Landscape Ecol.* 28 (10), 1889–1907. doi:10.1007/s10980-013-9943-4
Peng, Y., Feng, T., and Timmermans, H. J. P. (2021). Heterogeneity in Outdoor comfort Assessment in Urban Public Spaces. *Sci. Total Environ.* 790, 147941. doi:10.1016/j.scitotenv.2021.147941
Quan, S. J., and Li, C. (2021). Urban Form and Building Energy Use: A Systematic Review of Measures, Mechanisms, and Methodologies. *Renew. Sustain. Energ. Rev.* 139, 110662. doi:10.1016/j.rser.2020.110662
Rong, H., Zhang, H., Xiao, S., Li, C., and Hu, C. (2016). Optimizing Energy Consumption for Data Centers. *Renew. Sustain. Energ. Rev.* 58, 674–691. doi:10.1016/j.rser.2015.12.283
Shu, Y., and Lam, N. S. N. (2011). Spatial Disaggregation of Carbon Dioxide Emissions from Road Traffic Based on Multiple Linear Regression Model. *Atmos. Environ.* 45 (3), 634–640. doi:10.1016/j.atmosenv.2010.10.037
Steemers, K. (2003). Energy and the City: Density, Buildings and Transport. *Energy and Buildings* 35 (1), 3–14. doi:10.1016/s0378-7788(02)00075-0
Tanushri, K., and Sarika, B. (2021). Investigating Application of Compact Urban Form in central Indian Cities. *Land Use Policy* 23, 105694. doi:10.1016/j.landusepol.2021.105694
Wang, S., Yu, D., Kwan, M.-P., Zheng, L., Miao, H., and Li, Y. (2020). The Impacts of Road Network Density on Motor Vehicle Travel: an Empirical Study of Chinese Cities Based on Network Theory. *Transportation Res. A: Pol. Pract.* 132, 144–156. doi:10.1016/j.tra.2019.11.012
Wu, W.-p., Zhu, Y.-f., Zeng, W.-k., Wang, M., Yang, D.-x., and Chen, W.-f. (2021b). Green Efficiency of Water Resources in Northwest China: Spatial-Temporal Heterogeneity and Convergence Trends. *J. Clean. Prod.* 320, 128651. doi:10.1016/j.jclepro.2021.128651
Wu, W. P., Chen, Z. G., and Yang, D. X. (2020). Do internal Migrants Crowd Out Employment Opportunities for Urban Locals in China?—Reexamining under the Skill Stratification. *Physica A: Stat. Mech. its Appl.* 537 (1), 1–16. doi:10.1016/j.physa.2019.122580
Wu, W. P., Zeng, W. K., Gong, S. W., and Chen, Z. G. (2021a). Does Energy Poverty Reduce Rural Labor Wages? Evidence from China's Rural Household Survey. *Front. Energ. Res.* 9, 1–8. doi:10.3389/fenrg.2021.670026
Xiong, X., and Duan, Y. J. (2020). Analysis on the Spatial Differences of Shared Development Level and its Causes in Urban Agglomerations in the Middle Reaches of the Yangtze River. *Commercial Sci. Res.* 27 (1), 120–128.
Yu, B. (2021). Urban Spatial Structure and Total-Factor Energy Efficiency in Chinese Provinces. *Ecol. Indicators* 126, 107662. doi:10.1016/j.ecolind.2021.107662
Zeng, S., Su, B., Zhang, M., Gao, Y., Liu, J., Luo, S., et al. (2021). Analysis and Forecast of China's Energy Consumption Structure. *Energy Policy* 159, 112630. doi:10.1016/j.enpol.2021.112630
Zhang, H., Cai, G., and Yang, D. (2020). The Impact of Oil price Shocks on Clean Energy Stocks: Fresh Evidence from Multi-Scale Perspective. *Energy* 196, 117099. doi:10.1016/j.energy.2020.117099
Zhang, M., and Gao, Z. (2021). Effect of Urban Form on Microclimate and Energy Loads: Case Study of Generic Residential District Prototypes in Nanjing, China. *Sustain. Cities Soc.* 70 (16), 102930. doi:10.1016/j.scs.2021.102930
Zhong, Z., Peng, B., Xu, L., Andrews, A., and Elahi, E. (2020). Analysis of Regional Energy Economic Efficiency and its Influencing Factors: A Case Study of Yangtze River Urban Agglomeration. *Sustainable Energ. Tech. Assessments* 41, 100784. doi:10.1016/j.seta.2020.100784

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, orclaim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 26 January 2022
doi: 10.3389/fenrg.2021.709582

Check for updates

Ecological Efficiency Evaluation and Spatiotemporal Characteristics Analysis of the Linkage Development of the Logistics Industry and Manufacturing Industry

Wen-Long Zheng[1], *Jian-Wei Wang*[2], *Xin Hua Mao*[2]* *and Jin-Feng Li*[1,3]

[1]School of Economics and Management, Chang'an University, Xi'an, China, [2]College of Transportation Engineering, Chang'an University, Xi'an, China, [3]School of Logistics and Electronic Commerce, Henan University of Animal Husbandry Economics, Zhengzhou, China

OPEN ACCESS

Edited by:
You-hua Chen,
South China Agricultural University, China

Reviewed by:
Jibiao Zhou,
Tongji University, China
Ehsan Elahi,
Shandong University of Technology, China

****Correspondence:***
Xin Hua Mao
maoxinhua@chd.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *14 May 2021*
Accepted: *31 December 2021*
Published: *26 January 2022*

Citation:
Zheng W-L, Wang J-W, Mao XH and Li J-F (2022) Ecological Efficiency Evaluation and Spatiotemporal Characteristics Analysis of the Linkage Development of the Logistics Industry and Manufacturing Industry. Front. Energy Res. 9:709582. doi: 10.3389/fenrg.2021.709582

The logistics and manufacturing industries are basic industries that support social development. First, this study classifies the carbon emissions from the logistics industry and pollution emissions from the manufacturing industry as undesirable outputs and evaluates the ecological efficiency of the logistics and manufacturing industries in the Yangtze River Delta from 2006 to 2016 by using the unexpected slacks-based measure (SBM) model. Second, the study analyzes the spatial differences in industrial correlation efficiency by using the exploratory spatial data analysis method. Third, the spatial econometric model is used to analyze the driving factors of the linkage ecological efficiency between logistics industry and manufacturing industry. Finally, the neural network model is used to predict the linkage ecological efficiency. The results show that the ecological efficiency of the manufacturing industry has steadily improved. The ecological efficiency of the logistics industry presents the rising trend in fluctuation. The level of the linkage development between the logistics and manufacturing industries is high. The results of the spatial heterogeneity analysis show that the spatial differentiation of high–high agglomeration and low–low agglomeration is obvious. The spatial agglomeration characteristics are relatively stable, and the spatial diffusion effect is strong. In space, the linkage ecological efficiency shows a trend of development from multiple agglomeration areas to one agglomeration area. The results of driving factor analysis show that foreign direct investment (FDI), government intervention (GI), and human capital (HP) have positive effects on linkage ecological efficiency, while industrial structure (IS), environmental regulation (ER), and energy intensity (EI) have negative effects on linkage ecological efficiency. The results of the linkage development trend analysis show that the linkage ecological efficiency of the two industries will tend to be stable in the future.

Keywords: ecological efficiency, logistics industry, manufacturing industry, spatiotemporal characteristics, spatial econometric model

INTRODUCTION

At present, with the rapid development of the social economy, China's logistics demand is increasing rapidly, and the scale of logistics is expanding rapidly. How to continuously improve the quality of the logistics industry while reducing energy consumption and carbon dioxide emissions is an urgent problem to be considered. Similarly, while China's manufacturing industry has made great achievements, it has also encountered various environmental problems in the process of industrialization similar to developed countries in recent centuries. The extensive economic growth mode of high input and high energy consumption leads to the problems of low resource utilization efficiency and the aggravation of environmental pollution (De Koster, 2003).

The logistics and manufacturing industries have a naturally close relationship; they influence each other and develop interactively (W.L. Zheng et al., 2020). The linkage degree of the logistics and manufacturing industries determines the development level of the "two industries" and the comprehensive competitiveness of the regional economy. In recent years, the development trend of linkage and integration between China's logistics and manufacturing industries has increased, but the degree of integration is not high enough, the scope is not wide enough, and the degree is not deep enough, which does not meet the general requirements of promoting the formation of a strong domestic market, building a modern economic system, and adapting to the new pattern of "double cycle" development (Notice, 2020).

China's economy has entered the stage of high-quality development, and the cultivation of industrial clusters with international competitiveness has become a new power source to achieve high-quality economic development. In 2018, the integrated development of the Yangtze River Delta became a national strategy. The Yangtze River Delta is an important gathering area for China's advanced manufacturing industry. Through informatization, networking, and the integration effect of modern logistics, the logistics cost of manufacturing enterprises can be effectively reduced, and more resources can be concentrated to develop the core competitiveness of the manufacturing industry. Therefore, it is of great practical significance to study the development of the linkage between the logistics and manufacturing industries to promote the transformation and upgradability of the manufacturing industry in the Yangtze River Delta region, to achieve the goal of "made in China 2025" and to realize the high-quality development of the regional economy.

Since the concept of ecological benefit was first proposed by Schartger and Sturm (1990), in recent years, many scholars have studied ecological efficiency (Zhou et al., 2015) (Watanabe and Tanaka, 2007:; Wang et al., 2010). The two directions related to this study are logistics industry's efficiency and manufacturing industry's efficiency.

1) In terms of ecological efficiency of the logistics industry:

Long et al. (2020) used carbon dioxide emissions as undesirable outputs to evaluate logistics ecological efficiency. Zhang (2019) used the SBM undesirable model to measure the efficiency of China's logistics industry under low-carbon constraints, and the panel Tobit model was used to empirically analyze its influencing factors. The results show that the overall efficiency of China's logistics industry is at the upper middle level, with obvious regional differences.

2) In terms of ecological efficiency of the manufacturing industry:

Zhang et al. (2019) constructed a three-stage efficiency measurement model of advanced manufacturing green technology innovation by using non-mandatory range adjustment and stochastic frontier functions and measured its green technology innovation efficiency based on the manufacturing panel data. The results show that the overall efficiency of green technology innovation in the national advanced manufacturing industry is still low, and the capital intensity and industry profit rate have a significantly positive effect on the efficiency of green technology innovation in the advanced manufacturing industry (Han et al. 2014). Using the directional distance function, the ecological efficiency level of the manufacturing industry is calculated under the condition of considering the energy input and undesirable outputs. The research shows that the ecological efficiency of China's manufacturing industry is on the rise, but it is significantly lower than that without considering resource input and negative environmental output. The ecological efficiency level of the manufacturing industry shows obvious industry heterogeneity.

Recently, various studies have focused on the production sector for estimation of resources and climatic and institutional barriers in land use (Elahi et al., 2021a; Elahi et al., 2021b; Elahi et al., 2019a; Elahi et al., 2019b; Elahi et al., 2019c: Elahi et al., 2019d; Elahi et al., 2018). Some studies for instance (Peng et al., 2020a; Peng et al., 2020b; Peng et al, 2019; Peng et al, 2019; Peng et al., 2018; Huang et al., 2020; Wang et al., 2019) have focused on ecological security, ecological footprint, ecological carrying capacity, and ecological environmental vulnerability. However, ecological efficiency evaluation and the spatiotemporal characteristics analysis of the linkage development of the logistics industry and the manufacturing industry have not been explored yet. Therefore, the current article aims to determine the ecological efficiency of the linkage development of the logistics industry and the manufacturing industry considering environmental effects as well as the spatial model (spatial heterogeneity, spatial agglomeration, and driver analysis) and trend dynamic evolution of the linkage development efficiency of the two industries.

The rest of this article is organized as follows: The second part introduces relevant models. The third part explains the indicators and unexpected data. The fourth part presents the empirical analysis. Finally, this article summarizes the conclusions and discusses relevant suggestions.

Model Introduction

Slacks-Based Measure Model of Industrial Linkage Ecological Efficiency

In actual social production, when people's material demand is solved, it also produces various kinds of side effect products, such as wastewater, waste residue, waste gas, and other pollutants. This article defines these indicators as undesirable outputs. People want to avoid this kind of undesirable outputs as much as possible; therefore, undesirable outputs are gradually becoming a concern for relevant scholars. Because there are undesirable outputs in environmental performance evaluation, we cannot simply use traditional DEA for performance evaluation, and we must consider new methods to evaluate environmental performance. Scholars call this kind of system performance, which simultaneously considers input, expected output, and undesirable outputs of environmental factors, an environmental performance, and the corresponding evaluation is called an environmental performance evaluation (Zhou et al., 2008; Sueyoshi et al., 2016). Therefore, Tone proposed a new SBM model in 2003 (Tone, 2003), that is, the unexpected SBM model. The new SBM model has actually made some extensions on DEA, which precisely highlights the progressiveness of the SBM model. The reason is that this model does not need to set the target of the optimal behavior of the production unit and preset the production function. In addition, the novelty of the model is that the results are more accurate because the radial and angular models are used to calculate the production units less than the relaxation variables without considering the relaxation variables. The calculation results (environmental efficiency) of this study are calculated by using Max DEA Ultra 7.10 software (used to measure the efficiency of the logistics industry, manufacturing industry, and the linkage efficiency between the two industries). Therefore, the efficiency (logistics efficiency, manufacturing efficiency, and linkage development efficiency) mentioned in this article is ecological efficiency, which is not repeated later.

Data envelopment analysis (DEA) is a systematic analysis method developed by famous American operational research scientists A. Charnes, W. W. Cooper, and E. Rhodes in 1978 based on the concept of "relative effectiveness" to study the relative effectiveness of multiple-input and multiple-output decision-making units (Chames et al., 1978). Because energy, environment, and output need to be included in the model, the model needs to include both expected and unexpected outputs. Tone (2001) proposed a non-radial and non-angular efficiency measurement method based on relaxation variables—slacks-based measure (SBM) model. Different from the traditional CCR or BCC model, the SBM model directly adds the relaxation vector to the objective function, so the economic interpretation of the SBM model is to maximize the actual profit, not just the benefit proportion. At the same time, Tone (2002) proposed a super efficiency SBM model on this basis to solve the problem of distinguishing and sorting when the efficiency values of multiple decision-making units are all 1. Compared with other DEA models, this super SBM model considering undesired output has the following three advantages: ① taking undesired output units into account; ② the relaxation problem of input–output variables has been effectively solved; and ③ it solves the problem of distinguishing and sorting when multiple decision-making units are effective at the same time. Therefore, this study selects the super-efficiency SBM model considering unexpected output, which can more comprehensively reflect the concept of environmental efficiency of regional logistics efficiency measurement, including the technical structure relationship between an unexpected output and the factor input. The formula is as follows:

$$\rho = \min \frac{1 - (1/m)\sum_{i=1}^{m} (w_i^-/x_{ik})}{1 + 1/(r_1 + r_2)\left(\sum_{s=1}^{r_1} (w_s^d/y_{sk}^d + \sum_{q=1}^{r_2} (w_q^u/y_{qk}^u\right)}, \tag{1}$$

$$\text{s.t.} \begin{cases} x_{ik} = \sum_{j=1}^{n} x_{ij}\lambda_j + w_i^- \\ y_{sk}^d = \sum_{j=1}^{n} y_{sj}^d \lambda_j - w_s^d \ 1, \ldots, m, \\ y_{qk}^u = \sum_{j=1}^{n} y_{qj}^u \lambda_j + w_q^u \end{cases} \tag{2}$$

$$\lambda_j > 0, j = 1, \ldots, n, \tag{2a}$$

$$w_i^- \geq 0, i = 1, \ldots, m, \tag{2b}$$

$$w_s^d \geq 0, s = 1, \ldots, r_1, \tag{2c}$$

$$w_q^u \geq 0, q = 1, \ldots, r_2. \tag{2d}$$

In **Equation 2**, variables w^-, w^d, and w^u represent input relaxation variables, expected output relaxation variables, and unexpected output relaxation variables, respectively. λ represents the weight vector. The numerator and denominator in the objective function, respectively, represent the average reducible ratio and the average expandable ratio of the actual input and output of the production decision unit relative to the production foreword, that is, the input inefficiency and output inefficiency. The objective function strictly decreases with respect to w^-, w^d, and w^u. The change interval of objective function value ρ is (0,1). When ρ = 1, w^-, w^d, and w^u are equal to 0, the decision-making unit is effective in comprehensive technical efficiency, pure technical efficiency, and scale efficiency; when ρ < 1, or, w^-, w^d, and w^u are not equal to 0, the decision-making unit is invalid in comprehensive technical efficiency, pure technical efficiency, or scale efficiency, and there is room for input–output improvement.

Spatial Diffusion Effect Model

Global Spatial Correlation

Global spatial correlation is used to analyze the spatial association and spatial difference of the research object and to determine whether there is spatial diffusion. It is generally measured by the global Moran index (Moran, 1953).

$$I = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}(x_i - \bar{x})\left(x_j - \bar{x}\right)}{s^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}}, \tag{3}$$

where I is the Moran index, and $s^2 = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \bar{Y})^2$, $\bar{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i$; where X_i and X_j are the linkage efficiency values of the logistics industry and manufacturing industry of cities i and j, respectively. According to the calculation results of Moran's I statistics, the normal distribution hypothesis can be used for testing. Finally, the significance level of spatial autocorrelation is tested by using the standardized statistic Z as follows:

$$Z(d) = \frac{moran's I - E(I)}{\sqrt{VAR(I)}}. \tag{4}$$

According to the spatial distribution, the expected value of standardized Moran's I was calculated as follows:

$$E(I) = -\frac{1}{n-1}. \tag{5}$$

The variance of normal distribution is as follows:

$$VAR(I) = \frac{n^2 w_1 + n w_2 + 3w_0^2}{w_0^2 (n^2 - 1)} - E^2(I), \tag{6}$$

where E(I) is the expectation of autocorrelation of observation variables and VAR (I) is the variance. W_I and W_J refer to the sum of columns I and J in the spatial weight matrix, respectively, indicating the proximity of spatial positions I and J. When I and J are adjacent, $W_{ij} = 1$, and vice versa. The value range of the Moran index is (−1,1). When I > 0, it means that there is a positive correlation in each region; when I = 0, it means that there is no spatial correlation in each region; and when I < 0, it indicates that there is a negative correlation in each city (completed by ArcGIS 10.2, used to analyze the diffusion characteristics of logistics industrial efficiency, manufacturing industrial efficiency, and linkage efficiency of the two industries).

Local Spatial Autocorrelation

Local spatial autocorrelation is the local expression of the Moran index, which is the test form of the agglomeration and dispersion effect of the local area. It reflects the correlation degree between the attribute value of a region and the attribute value of the adjacent region.

$$I_i = \frac{(x_i - \bar{x})}{s^2} \sum_{j=1}^{n} w_{ij}\left(x_j - \bar{x}\right), \tag{7}$$

where I_i is the local Moran index of area I and other parameters are the same as above.

If I_i is greater than 0, it means that the local area and the surrounding area present similar spatial agglomeration (high or low agglomeration). If I_i is less than 0, it shows different spatial agglomeration (high–low or low–high agglomeration). The cluster of regions can be directly analyzed by the Moran scatter diagram, and the local Moran index is still tested by Z statistic.

Spatial Econometric Model

Common spatial measurement models include the spatial lag model (SLM), spatial error model (SEM), and spatial Durbin model (SDM) (Elhorst, 2014; Liu et al., 2017). When spatial correlation exists in the error terms of the model, then using the SEM it can be expressed as follows:

$$Z = X_\alpha + \delta W_\mu + \varepsilon, \varepsilon \in N\left(0, \delta^2\right), \tag{8}$$

where Z indicates explained variables and is the vector of (n×1); X indicates explanatory variables, α indicates the regression coefficient, and is the vector of (k×1); μ indicates the random error vector; δ is the coefficient of spatial correlation between regression residuals; W indicates the spatial weight matrix (n×n); and ε indicates distributed random terms independently. If the model has significant dependence between explained variables and would affect its results, then using the SLM model, which can be expressed as follows:

$$Z = \rho WY + X_\alpha + \varepsilon, \varepsilon \in N\left(0, \delta^2\right), \tag{9}$$

where ρ indicates the coefficient of endogenous interaction effects (WY), with its size representing the degree of spatial diffusion and spatial dependence. A significant value shows that definite spatial dependence exists in explained variables. If the model considers both the endogenous interaction effect of the error term and the endogenous interaction effect of explained variables, then using SDM, which can be expressed as follows:

$$Z = \rho WY + X_\alpha + WX\theta + \varepsilon, \varepsilon \in N\left(0, \delta^2\right), \tag{10}$$

where θ is the spillover coefficient and others are the same with the SLM model.

Trend Prediction Model

The linkage development of the logistics and manufacturing industries has the characteristics of stage and dynamics. It is difficult to indicate its complexity to predict its development with general linear or non-linear models. Artificial neural networks have been successfully applied in many fields due to their unique information processing ability. A generalized regression neural network (GRNN) is a kind of radial basis function network that has strong a non-linear mapping ability, flexible network structure, high fault tolerance, and robustness. It has strong advantages over the RBF network in the approximation ability and learning speed, and the network converges. When the sample size is large, the prediction effect is good.

The theoretical basis of the GRNN is a non-linear regression analysis, which is composed of four layers in structure: an input layer, a mode layer, an addition layer, and an output layer. The number of neurons in the input layer is equal to the dimension of the input vector in the learning sample, the number of neurons in the mode layer is equal to the number of the learning sample, and the number of neurons in the output layer is equal to the dimension of the output vector in the learning sample (Matlab Chinese Forum, 2010; Zhang et al., 2020; Zheng et al., 2018).

$$R_i(x) = \exp\left[-(x - x_i)^T (x - x_i) \big/ 2\sigma^2\right], i = 1, \ldots, n, \tag{11}$$

$$S_D = \sum_{i=1}^{n} R_i(x), S_{Nj} = \sum_{i=1}^{n} y_{ij} R_i(x), j = 1, 2, \ldots, k, y_j = S_{Nj} \big/ S_D, \tag{12}$$

where x is the input variable, x_i is the learning sample corresponding to the *i*th neuron, y_{ij} is the connection weight between the pattern layer and the summation layer, and y_j is the output result corresponding to the *j*th neuron in the output layer

TABLE 1 | Index system of manufacturing industry ecological efficiency.

Evaluation system	Index type	Name of index	Unit
Manufacturing system	Input indicators	The number of employees on the job in the manufacturing industry	Ten thousand people
		Total assets of industrial enterprises above designated size	100 million
	Output indicators	Industrial added value	100 million
		Main business income of industrial enterprises above designated size	100 million
	Undesirable outputs	Industrial wastewater	Tons
		Industrial waste gas	Billion standard cubic meters
		Industrial solid waste	Tons

TABLE 2 | Index system of logistics industry ecological efficiency.

Evaluation system	Index type	Name of index	Unit
Logistics system	Input indicators	Number of employees in the logistics industry	Ten thousand people
		Fixed capital investment	100 million
		Energy consumption	Ten thousand tons of standard coal
	Output indicators	Highway freight volume	Tons
		GDP of logistics industry	100 million
		Cargo turnover	Million ton-km
	Undesirable outputs	Carbon emissions from transportation	tons

(the calculation process is programmed and completed by MATLAB 2012, which is used to predict the efficiency of the logistics and manufacturing industries and the efficiency of linkage between the two industries).

Indicators and Undesirable Outputs Data

Selection of Indicators

With reference to very weak research on the linkage efficiency of these two industries, combined with some selection principles (significance, practicability, data availability, and isotropy) of the indicator system, manufacturing and logistics industry, linkage development, and efficiency evaluation, the index system is constructed from the perspective of input and output (Ji et al., 2018; Liang, 2015; Chen et al., 2020). The data used in this study are obtained mainly from the China Statistical Yearbook, the statistical yearbooks of the provinces, the National Bureau of Statistics, the China Industrial Statistical Yearbook, the China Environmental Statistical Yearbook, the China Energy Statistical Yearbook, and the school library. Due to the availability of data, the transportation industry and warehousing, postal, and telecommunications industrial data are generally used as logistics industrial data (since China has not yet established a relatively complete statistical system for the logistics industry and the statistical caliber of the logistics industry in each country is not the same, the model and index selection in this study are only applicable to a single country or region with unified logistics industrial data statistics). The specific selection indicators are as follows.

The linkage efficiency of logistics industry and manufacturing industry is the comparative relationship between input and output or between cost and income in the process of business activities of the whole system formed by logistics industry and manufacturing industry. Therefore, the ecological efficiency of the linkage between the manufacturing industry and the logistics industry means that the ecological efficiency of the logistics industry and the manufacturing industry are input factors to each other, which has an impact on the system. Therefore, referring to the research methods of Wang, 2017, on the basis of **Table 1** and **Table 2**, and after considering the impact of both sides on each other, the index system as shown in **Table 3** is constructed (Wang, 2017). To sum up, and consider the driving factor on this basis, so as to form the variable of spatial economic model as shown in **Table 4**.

Undesirable Outputs Data

1) Concept of Desirable Outputs and Undesirable Outputs

In the production process of general economic system, we always hope that the smaller the input is, the better the output is. That is to say, we can produce as many outputs as possible with the smallest input, and the relative efficiency of production unit is also higher. The core idea of traditional DEA model in dealing with input–output in efficiency evaluation is also based on this. The output mentioned here is the expected output, which is the main purpose of economic production, and refers to the output with benefit. However, the production process will inevitably produce some negative effects on economic development, and people do not want to produce output. The output mentioned here is undesirable outputs, that is, the output that people do not expect. It is a subsidiary product of economic production, which means the output that is not beneficial or even harmful. For example, the paper products industry, while producing, emits industrial wastewater, waste gas, waste, and other pollutants. The paper or paper products here are called expected output; industrial wastewater, waste gas, waste, and other pollutants are called undesirable outputs. Considering environmental variables and paying attention to undesirable outputs will

TABLE 3 | Ecological efficiency index of the linkage between logistics industry and manufacturing industry.

Evaluation system	Index type	Name of index	Unit
System of logistics industry and manufacturing industry linkage efficiency	Input indicators	Number of employees in the logistics industry	Ten thousand people
		Fixed capital investment	100 million
		Energy consumption	Ten thousand tons of standard coal
		Number of employees on the job in the manufacturing industry	Ten thousand people
		Total assets of industrial enterprises above designated size	100 million
	Output indicators	Highway freight volume	Tons
		GDP of logistics industry	100 million
		Cargo turnover	Million ton-km
		Industrial added value	100 million
		Main business income of industrial enterprises above designated size	100 million
	Undesirable outputs	Carbon emissions from transportation	tons
		Main business income of industrial enterprises above designated size	100 million
		Industrial wastewater	Tons
		Industrial waste gas	Billion standard cubic meters
		Industrial solid waste	Tons

TABLE 4 | Variable description for spatial econometric model.

Variable	Description	Unit
Logistics eco-efficiency (LE)	Logistics ecological efficiency (the results are obtained by the SBM model and **Table 1**)	Ratio
Manufacturing eco-efficiency (ME)	Manufacturing eco-efficiency (the results are obtained by the SBM model and **Table 2**)	Ratio
Manufacturing and logistics linkage eco-efficiency (MLLE)	Linkage eco-efficiency (the results are obtained by the SBM model and **Table 3**)	Ratio
Industrial structure (IS)	The added value of the secondary industry as the proportion of the regional GDP	%
Government intervention (GI)	The proportion of public finance expenditure to regional GDP	%
Foreign direct investment (FDI)	Total import and export trade as a percentage of GDP	%
Energy intensity (EI)	The ratio of the logistics total energy consumption of the total turnover of freight	Ratio
Human capital (HC)	The average number of years of education in each city	Thousand
Environmental regulation (ER)	The ratio of total investment in industrial pollutants to GDP	Ratio

have important theoretical and practical significance for transforming the mode of economic development, strengthening environmental protection, promoting sustainable development, and establishing a saving and efficient industry.

2) Undesirable Outputs Data of Logistics Industry

Refer to Yuan et al. (2016), Zhang et al., 2017, Zheng et al. (2018) and other relevant scholars' research on China's transportation carbon emissions. In this study, the logistics industry unexpected output data are obtained from the transportation carbon emissions data. Due to the availability of the data, the undesirable outputs of the manufacturing industry is derived from China's Urban Statistical Yearbook, and the logistics industry's undesirable outputs is selected from transportation carbon emissions (that is, the undesirable outputs of logistics industry in **Table 1**, **2**, and **3**). The specific calculation method is as follows.

To ensure the accuracy of calculations of carbon emissions in the transportation industry in each province, this analysis uses 21 kinds of energy sources, including raw coal, cleaned coal, other washed coal, briquette, coke, coke oven gas, other gas, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, refinery dry gas, natural gas, and electric power as statistical objects, which are different from those in the past. The carbon emission amount (D) of the transportation industry is calculated as shown in the following formula.

$$D = \sum A_i \times B_i \times C_i \times N_i \times \frac{44}{12}, \tag{13}$$

where D is carbon emissions from energy consumed by the transportation industry; A_i is fuel consumption; B_i is the conversion standard coal coefficient of fuel i; C_i is a carbon emission coefficient of fuel i; and N_i is the oxidation rate of fuel i. B_i comes from the conversion coefficient of the "General Principle of Comprehensive Energy Consumption Calculation"

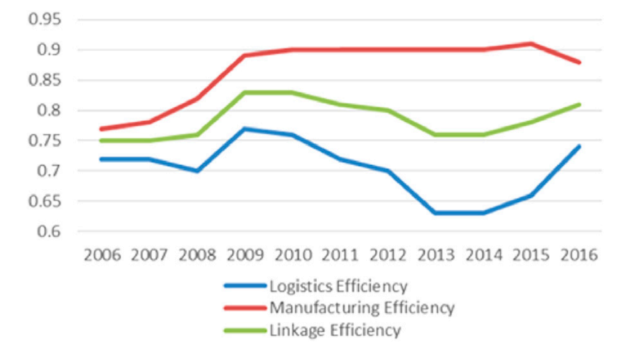

FIGURE 1 | Efficiency changing trend of the logistics industry, manufacturing industry, and manufacturing and logistics linkage efficiency.

(GB/T 2589-2008); and C_i is derived from the default value of the IPCC carbon emission calculation guidelines.

3) Undesirable Outputs Data of Manufacturing Industry

Due to the availability of data, combined with domestic and foreign scholars' research (Watanabe and Tanaka, 2007; Han et al., 2014), two indicators of wastewater and solid waste are finally determined as the undesirable outputs of manufacturing industry. The data of undesirable outputs of manufacturing industry are from《China Environmental Statistical Yearbook》.

Empirical Analysis

Evaluate the Overall Efficiency Value

The calculation results of the efficiency of the logistics industry, manufacturing industry, and two industrial linkages are shown in **Figure 1**. 1) From 2006 to 2016, the efficiency of the manufacturing industry in the Yangtze River Delta was stable. From 2006 to 2008, it increased slightly; from 2009 to 2012, it decreased slightly; from 2012 to 2014, it began to rise steadily and reached the highest value in 2014; and from 2014 to 2016, it decreased first and then increased, with slight fluctuation. 2) From 2006 to 2016, the efficiency of the logistics industry in the Yangtze River Delta increased slightly. It increased slightly from 2006 to 2011 and decreased significantly from 2011 to 2016. After efficiency reached the highest value in 2014, it rapidly decreased to the lowest value in 2016. When the manufacturing and logistics industries are both effective in the DEA, they can achieve linkage development. 3) The deviation of the efficiency curve between the manufacturing and logistics industries shows that the study area failed to achieve linkage development considering undesirable outputs, but the main industries that failed to achieve linkage development were not the same. Among them, the low efficiency of the manufacturing industry in 2009–2013 failed to achieve linkage development, and the low efficiency of the logistics industry in 2014–2016 failed to achieve linkage development.

Empirical Analysis of Spatial Diffusion Effect

1) Empirical Analysis of Global Spatial Autocorrelation

Utilizing ArcGIS 10.2 software, the data of the logistics and manufacturing industries in 25 cities in the Yangtze River Delta from 2006 to 2016 are calculated, and Moran's I value and its standardized Z value are obtained (see **Table 5**). The results show that the index of the logistics and manufacturing industries of 25 cities in the Yangtze River Delta is positively correlated. The Z value for each year is positive, and the p-value is less than α (0.05), which indicates that the spatial autocorrelation is significant. This indicates that the regions with similar development levels (high or low) of the logistics and manufacturing industries in the Yangtze River Delta are concentrated in space; that is, the cities with higher linkage levels of the two industries have higher linkage levels of the two industries in their peripheral cities, and vice versa. From 2006 to 2016, the Moran index of the logistics and manufacturing industry in the Yangtze River Delta showed a trend of first rising and then declining, but the Z value of the linkage efficiency of the two industries was greater than 5, indicating that the spatial distribution of the logistics and manufacturing industries in the Yangtze River Delta during this period showed a globally significant similar level of agglomeration characteristics.

2) Empirical Analysis of Local Spatial Autocorrelation

In order to reflect the spatial structure changes of logistics industry and manufacturing industry in the Yangtze River Delta region from 2006 to 2016, according to the local spatial autocorrelation analysis method, this study selects the linkage efficiency of logistics industry and manufacturing industry in 2006, 2008, and 2016 as the research data and analyzes the spatial characteristics and changes of the linkage efficiency between each city and adjacent cities in the Yangtze River Delta region. The results (**Table 6**) show that there is an obvious spatial distribution pattern of logistics and manufacturing industry in the Yangtze River Delta.

According to the results of Lisa, each city is divided into four quadrants according to its nature. As shown in **Table 6**, this study selects several representative cities for analysis.

The first quadrant is the HH agglomeration type of logistics and manufacturing linkage ecological efficiency. The cities in this

TABLE 5 | Global autocorrelation analysis of linkage efficiency between logistics industry and manufacturing industry in the Yangtze River Delta.

Name	Year	Moran's index	Z score	p-value	Agglomeration
Linkage efficiency of logistics industry and manufacturing industry	2006	0.5457	5.2465	0.01	Yes
	2008	0.5867	6.5684	0.01	Yes
	2016	0.5921	6.9635	0.02	Yes

TABLE 6 | Results of the Lisa analysis on the linkage efficiency of logistics industry and manufacturing industry in the Yangtze River Delta in 2006, 2008, and 2016.

Feature	2006	2008	2016
High–high (HH)	Nanjing and Shanghai	Nanjing and Shanghai	Nanjing, Shanghai, and Hangzhou
High–low (HL)	Wenzhou	Wenzhou	Wenzhou
Low–high (LH)	Jiaxing and Taizhou	Jiaxing and Taizhou	Jiaxing
Low–low (LL)	Lishui and Suqian	Lishui and Suqian	Lishui and Suqian

quadrant have relatively large local Moran values, and the local Moran values of the surrounding cities are also relatively large. That is to say, the logistics and manufacturing linkage efficiency of this city is relatively high, and it has a significant positive impact on the logistics and manufacturing linkage efficiency of neighboring cities. The high-value area of industry linkage efficiency is surrounded by the same high-value area, and the diffusion effect is obvious. It can be seen that the high agglomeration areas of logistics and manufacturing linkage efficiency in the Yangtze River Delta are mainly concentrated in Shanghai, Hangzhou, and Nanjing. By comparing 2006 and 2016, it can be found that in 2006, they were mainly distributed in Shanghai, the provincial capital and municipality directly under the central government; in 2016, Wuxi, Suzhou, Changzhou, and other surrounding cities were added. The linkage efficiency of the two industries in these cities represents a development trend from multiple agglomeration areas to one agglomeration area in the space, which indicates that the linkage of logistics industry and manufacturing industry in the research area has entered a relatively centralized development stage (Li et al., 2020).

The second quadrant is the LH agglomeration type. The local Moran value of cities in this quadrant is relatively small, and the local Moran value of surrounding cities is relatively large, that is, the cities with low linkage efficiency of logistics and manufacturing industry are surrounded by high-value cities. It can be seen that the low and high efficiency agglomeration areas of logistics and manufacturing in the Yangtze River Delta are mainly concentrated in Jiaxing, Taizhou, and other cities. By comparing 2006 and 2016, it can be found that in 2006, they were mainly distributed in Jiaxing, a city close to Shanghai, and Taizhou, a city close to the Suzhou Wuxi Changzhou economic zone. By 2016, they were reduced to only Jiaxing, and the surrounding areas of Jiaxing were developed by Shanghai, Hangzhou, Ningbo, and other cities. It is surrounded by the city.

The third quadrant is LL agglomeration type. The local Moran value of cities in this quadrant is relatively small, and the local Moran value of surrounding cities is also relatively small. That is to say, the linkage efficiency of logistics and manufacturing in this city is low, and it has a significant negative impact on the linkage efficiency of logistics and manufacturing in neighboring cities The low value area of industry linkage efficiency is surrounded by the same low value area. It can be seen that the low efficiency of the linkage between logistics industry and manufacturing industry in the Yangtze River Delta is mainly concentrated in the northern and southern mountainous areas, such as Suqian, Lishui, Quzhou, and other cities. By comparing 2006 and 2016, we can find that the low and low concentration areas are all the cities in northern Jiangsu and southern Zhejiang. The linkage efficiency of the two industries in these cities presents a negative externality agglomeration in space, and these cities will easily cause a vicious circle between cities and form a marginal area through the spatial spillover effect (Hackius and Petersen, 2020; Kant and Pal, 2017; Zhang et al., 2018; Chen et al., 2020; Li et al., 2018).

The fourth quadrant is the HL agglomeration type. The cities in this quadrant have relatively large local Moran values, and the local Moran values of the surrounding cities are relatively small, that is, the logistics and manufacturing linkage efficiency of the city is higher, and the local Moran values of the surrounding cities are relatively low, that is, the cities with high logistics and manufacturing linkage efficiency are ignored Surrounded by low value cities, it has spatial spillover effect on the surrounding cities. It can be seen from **Table 6** that the agglomeration areas of logistics and manufacturing linkage efficiency in the Yangtze River Delta are mainly concentrated in Wenzhou and other cities. By comparing 2006 and 2016, it can be found that these cities are concentrated in southern Jiangsu. There are too many low value cities around, which indicates that Wenzhou, as a big city around, has limited power to drive the efficiency of the two industries linkage (Chen et al., 2020; Wang et al., 2015; Choi et al., 2016; Shi et al., 2016).

To sum up, the spatial agglomeration attribute of logistics and manufacturing linkage efficiency in the Yangtze River Delta is relatively stable, and the spatial diffusion effect is strong. In recent years, the rise of Suzhou, Wuxi, and Changzhou makes the Yangtze River Delta form a development trend from multiple agglomeration areas to relatively concentrated agglomeration areas. Jiaxing and Taizhou are the typical cities in the low–high agglomeration type. These cities are in the transition zone of Shanghai, Nanjing, and Hangzhou megalopolis; surrounded by these developed these low-low cluster type cities are the transition zone of the study area megalopolis used for factor flow. Lishui and Suqian are typical cities in low–low cluster type. The development level of logistics industry in these cities is backward, the foundation of manufacturing industry is poor, and the linkage efficiency of the two industries in the surrounding areas is also low, which is easy to form marginal areas. The typical city in high–low agglomeration type is Wenzhou, where the export-oriented economy is developed, and the manufacturing industry has a good foundation, resulting in the spatial spillover effect (Jiang et al., 2018; He et al., 2020; John., 2018).

Empirical Analysis of Spatial Econometrics

According to the previous analysis, the spatial autocorrelation test of linkage efficiency of logistics industry and manufacturing industry indicates that it exists as a spatial agglomeration. To find a proper spatial econometric model, this study use (robust) Lagrange multipliers (LM) test, the likelihood ratio (LR) test, the Wald test, and Hausman test (**Table 7**).

TABLE 7 | Estimation results without spatial interactive effects.

	Mixed OLS estimator	Spatial fixed effect	Temporal fixed effect	Temporal and spatial double fixed effect
LM_lag	3.98**	37.81***	8.84	11.61*
R_LM_lag	2.34	14.32***	14.3	2.26*
LM_error	3.12**	29.63***	6.23	3.84*
R_LM_error	1.48	12.14	1.98	1.77
Wald_spatial_lag	—	15.506**	18.632**	—
LR_spatial_lag	—	13.454**	17.563**	—
Wald_spatial_error	—	18.647**	19.457***	—
LR_spatial_error	—	18.345**	17.864**	—
Hausman test			39.497,15,0.001	
LR spatial fixed effects			614.303,30,0.000	
LR time fixed effects			289.531,12,0.000	

*Note: The data are from the model regression, and the results are sorted out by the author, *, **, and ***, respectively, indicating the significance level of 0.1, 0.05, and 0.01.*

TABLE 8 | Estimation and test results based on the spatial Durbin model (SDM) for the driving factor.

	Spatial Durbin model (SDM) for the driving factor			
	Coefficient	Direct	Indirect	Total
LnIS	−0.051** (−1.904)	−0.019*** (−0.154)	−0.056 (−0.322)	−0.075*** (−0.323)
LnFDI	0.046*** (5.172)	0.116 (0.564)	0.057 (0.261)	0.173 (0.844)
LnER	−0.031*** (−2.943)	−0.027** (−0.278)	−0.005 (−0.685)	−0.032 (−0.844)
LnGI	0.046*** (5.172)	0.046*** (1.214)	0.337*** (0.475)	0.383*** (0.527)
LnEI	−0.009*** (−2.543)	−0.028*** (−1.141)	−0.124*** (−0.439)	−0.152*** (−0.549)
LnHC	0.032*** (2.743)	0.193*** (1.233)	0.421*** (1.242)	0.614*** (1.267)
W*LnIS	−0.006 (−0.324)	—	—	—
W*LnFDI	0.098**(1.889)	—	—	—
W*LnER	0.097*** (9.979)	—	—	—
W*LnGI	−0.002*** (−2.834)	—	—	—
W*LnEI	0.065*** (4.645)	—	—	—
W*LnHC	−0.001** (−1.086)	—	—	—
W*LnLE	0.019*** (1.998	—	—	—
W*LnME	0.034*** (1.443)	—	—	—
W*LnMLLE	0.325*** (4.033)	—	—	—

****significance level at 1%. **significance level at 5%. *significance level at 10%.*

LM test results show that the spatial lag effect is more significant than the spatial error effect. Therefore, it is more suitable to use the spatial Durbin model.

It is noteworthy that the coefficients of the SDM model do not directly reflect the marginal effects of the corresponding explanatory variables on the dependent variable (LeSage and Pace, 2010), so it needs to verify spatial effects from the total effect, the direct effect, and indirect effect (**Table8**).

The regression results are shown in **Table 8**; the industrial structure (IS) has a negative impact on the linkage ecological efficiency; it fully shows that the increase in the proportion of China's logistics industry and manufacturing industry has a negative effect on ecological efficiency. With the acceleration of industrialization, the secondary industry drives economic growth will not change in a short period of time.

Foreign direct investment is the invisible driving force of the logistics industry and manufacturing industry development. Foreign direct investment increases 1%, linkage ecological efficiency will increase 0.116%, the hypothesis of "polluting heaven" is not established. This is mainly because in the process of logistics and manufacturing transformation, China gives priority to the development of green logistics and advocates green production. Relevant documents have been formulated and very strict measures have been taken for pollution prevention and ecological protection. In addition, we should pay more attention to the introduction of high-quality foreign investment and strengthen the examination and approval of foreign investment. The spillover effect of high-quality foreign capital is conducive to improving the linkage ecological efficiency of logistics industry and manufacturing industry in the Yangtze River Delta.

Environmental regulation has a negative impact on the improvement of logistics ecological efficiency, the higher the intensity of environmental regulation, the lower the logistics ecological efficiency. The inefficiency of environmental regulation is caused by the decentralized governance structure and the performance appraisal mechanism. This leads to the "race-to-the-bottom" competition of local governments in the process of enacting and implementing environmental regulations. Because environmental pollution is external and can be transmitted between regions, even if strict environmental regulations are

TABLE 9 | Network training error test of the efficiency of two industries linkage development in the Yangtze River Delta from 2006 to 2016.

Region	Yangtze River Delta								
Index	LE			ME			MLLE		
Result	SV	AV	Me	SV	AV	Me	SV	AV	Me
2006	0.721	0.713	−0.008	0.776	0.780	0.004	0.755	0.758	0.003
2007	0.724	0.728	0.004	0.784	0.788	0.004	0.753	0.750	−0.003
2008	0.703	0.710	0.007	0.823	0.828	0.005	0.762	0.756	−0.006
2009	0.775	0.773	−0.002	0.894	0.890	−0.004	0.833	0.839	0.006
2010	0.762	0.770	0.008	0.903	0.897	−0.006	0.834	0.842	0.008
2011	0.724	0.731	0.007	0.904	0.907	0.003	0.812	0.806	−0.006
2012	0.705	0.712	0.007	0.904	0.907	0.003	0.803	0.796	−0.007
2013	0.632	0.639	0.007	0.903	0.907	0.004	0.762	0.755	−0.007
2014	0.632	0.635	0.003	0.902	0.908	0.006	0.763	0.758	−0.005
2015	0.663	0.672	0.009	0.911	0.914	0.003	0.784	0.7855	0.002
2016	0.746	0.737	−0.009	0.881	0.885	0.004	0.815	0.807	−0.008

TABLE 10 | Development trend forecast of the efficiency of the linkage development of the two industries in the Yangtze River Delta from 2017 to 2025.

Region	Yangtze River Delta		
Year	LE	ME	MLLE
2017	0.73	0.89	0.81
2018	0.72	0.90	0.81
2019	0.71	0.91	0.81
2020	0.70	0.91	0.81
2021	0.68	0.92	0.80
2022	0.67	0.93	0.80
2023	0.66	0.94	0.80
2024	0.65	0.95	0.80
2025	0.66	0.95	0.81

implemented in this region, it will not necessarily reduce the damage caused by environmental pollution.

The government intervention direct coefficient is 0.046, indicating that the current government intervention has a positive impact on the linkage ecological efficiency. The problems existing in the linkage development of logistics industry and manufacturing industry are that the degree of marketization is not enough, the direct information asymmetry of the two industries, and the willingness of active cooperation is still not high. Therefore, government intervention can play a positive role in standardizing the market order, coordinating the operation of logistics and manufacturing industries, continuously guiding the two industries to actively cooperate, and improving the linkage efficiency of the two industries.

The energy intensity direct coefficient is 0.028, indicating that the energy intensity has a significant negative effect on the improvement of logistics ecological efficiency. The greater the energy intensity, the stronger will be the dependence of logistics industry and manufacturing industry on energy and also the greater the energy consumption. At the same time, the proportion of clean energy used in China's logistics industry is small. Therefore, high energy consumption and high carbon emission restrict the efficient and sustainable development of logistics industry.

Human capital direct coefficient is 0.193, indicating that the human capital has a positive impact on linkage ecological efficiency. The indirect coefficient of human capital is 0.421, indicating that human capital has a positive spillover effect. The result shows that the higher the education level of the labor force in a certain city, the more propitious it is to promote the progress of linkage ecological efficiency in neighboring city. This is related to the development stage of logistics and manufacturing in the Yangtze River Delta. At present, the Yangtze River Delta is the most active region in China's economic development and the leading region of high-tech development. The logistics industry and manufacturing industry have gradually crossed the primary stage driven by material capital and labor input, and entered the growth stage driven by human capital and core technology.

Empirical Analysis of Trend Prediction

According to the index system analyzed and the ecological efficiency results (logistics industrial efficiency, manufacturing industrial efficiency, and two industries' linkage efficiency) calculated by the SBM model in the previous study, three input indexes of the logistics industry and two input indexes of the manufacturing industry are selected as network input, and the logistics industrial efficiency (LE), manufacturing industrial efficiency (ME), and two industrial linkage efficiencies (MLLE) are utilized as network output to establish the GRNN network. In view of the small amount of data and to improve the accuracy of the prediction, K-Fold cross-validation is used for data cross-validation, the GRNN network is trained, and the best SPREAD is found by circulation. The calculation process is programmed and completed in MATLAB 2012, and the calculation value of the linkage efficiency of the two industries from 2006 to 2016 is taken as the test sample for simulation. From the calculation results, it can be found that when the spread value of the network is 0.44, the prediction effect of the network is the most ideal, the simulation value is consistent with the actual value, and the feasibility of the model is high (**Table 9**). (LE is logistics efficiency; ME is manufacturing efficiency; MLLE is manufacturing and logistics linkage efficiency; SV is sample value; AV is analog value; Me is measurement error.)

Using the established GRNN model, the efficiency of the logistics and manufacturing industries and the linkage efficiency of the two industries in 2017–2025 are simulated (**Table 10**). It can be seen from the table that the linkage efficiency of the two industries will continue to be at a high level in the future and that the overall linkage development is relatively stable at a medium and high level, but there is still room for improvement.

CONCLUSION

In this study, the ecological efficiency of logistics and manufacturing industry is evaluated by the SBM model; the spatial heterogeneity and spatial aggregation of the efficiency of the two industries are analyzed by the spatial correlation analysis; the driving factors of linkage efficiency are analyzed by using the spatial measurement method; and the dynamic evolution of the trend is predicted by using a neural network. It provides a theoretical reference and decision support for improving the linkage efficiency of logistics and manufacturing industry in the Yangtze River Delta.

The calculation results of industrial linkage ecological efficiency show that the ecological efficiency of the manufacturing industry in the study area has steadily improved; the ecological efficiency of the logistics industry has fluctuated greatly, first rising, then falling, and finally steadily improving; and the deviation of the ecological efficiency curve between the logistics and manufacturing industries shows that when considering the undesirable outputs, the logistics and manufacturing industries cannot achieve an absolutely high level of linkage development during the research period, but the ecological efficiency of the logistics and manufacturing industries is relatively stable. The linkage development is at a high level.

The results from spatial heterogeneity show that there is a positive spatial correlation between the indexes of the logistics and manufacturing of 25 cities in the Yangtze River Delta. Areas with similar development levels (high or low) of the logistics and manufacturing industries are concentrated in space. From 2006 to 2016, the Moran index of the logistics and manufacturing industries in the Yangtze River Delta region showed a trend of first rising and then declining, which indicates that the spatial distribution of the logistics and manufacturing industries showed a significantly similar level of agglomeration characteristics.

The results of the local spatial autocorrelation analysis show that the linkage ecological efficiency of the two industries in the Yangtze River Delta presents a development trend from multiple agglomeration areas to one agglomeration area in space, which indicates that the linkage of logistics industry and manufacturing industry in the Yangtze River Delta has entered a relatively centralized development stage.

The results show that FDI, GI, and HC have positive effects on the linkage ecological efficiency, while IS, ER, and EI have negative effects on the linkage ecological efficiency. The future trend of linkage development shows that the linkage ecological efficiency of the two industries will continue to be at a high level in the future and that the overall linkage development is relatively stable, which is at medium and high levels, but there is still room for improvement.

SUGGESTIONS AND POLICY IMPLICATIONS

According to the aforementioned research conclusion, this study presents some suggestions for the linkage development of the logistics and manufacturing industries in the Yangtze River Delta region.

First, although the efficiency of the regional logistics industry is at a high level, this still cannot meet the needs of the manufacturing industry, and the linkage ecological efficiency of the two industries lags behind the efficiency of the manufacturing industry. Therefore, in order to improve the level of linkage development, it needs to continue to make greater effort to develop high-end logistics dominated by high-tech, which can greatly improve the service level, specialization level, and economies of scale that are advantageous for logistics enterprises, and to help the manufacturing industry to reduce costs and to improve efficiency.

Second, the transformation and upgrading of the local manufacturing industry need to be continually promoted. Although the efficiency of the manufacturing industry in the research area is at a high level, there is still room for development. In the future, the transformation and upgrading of China's manufacturing industry should be promoted under the guidance of the Internet of Things, artificial intelligence, big data, cloud computing, and other advanced technologies to achieve the goal of "made in China 2025."

Third, it is increasing concern to society about the environment impact of the development of the logistics and manufacturing industries. The development policies of the logistics and manufacturing industries formulated by relevant managers should not only consider the economic benefits but also consider the impact on the environment.

Fourth, energy conservation and emission-reduction technology should be promoted. The government should increase investment in the development of energy-saving and emission-reduction technology, enhance the exchange of advanced technology and the management experience of energy savings and environmental protection, and actively develop and promote energy savings and emission-reduction technology to effectively improve the increasingly serious problem of environmental pollution.

Fifth, the government should actively develop the circular economy and realize the recycling of resources. Government managers can expand the scope of circular economy pilots to spread all over the country, formulate environmental regulation policies reasonably, encourage industries with high-energy consumption and large amounts of pollution to develop an internal circular economy, and reduce undesirable outputs.

The limitations of this study include the following. Regarding research data acquisition: because the logistics industry is a network industry involved in many other industries, currently, a systematic evaluation index of the efficiency of the logistics industry is still missing; there are currently no authoritative logistics statistical indicators in China; compared to urban logistics and manufacturing data, the availability of undesirable outputs data is poorer.

Regarding future research, with the development of informatization, big data, and the Internet of Things, more extensive research can be conducted on index selection and data acquisition in the future. This study is limited to the

Yangtze River Delta region. The interaction between the logistics and manufacturing industries has a different development status in different regions in China. In the future, the study area can be extended to the entire country.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

X-HM designed the manuscript framework. W-LZ wrote the manuscript. J-WW provided policy recommendations. J-FL provided data.

FUNDING

This research was funded by the Fundamental Research Funds for the Central Universities (Grant Number 300102341513). This work was supported in part by the Fundamental Research Funds for the Central Universities under Grant 300102230501 and in part by the Major Theoretical and Practical Problems Research Project of Social Science Circles in Shaanxi Province in 2020; Project name: Research on coupling mechanism and congestion management strategy of urban comprehensive transportation network system based on hypernetwork, under Project 2020Z033. This work was supported in part by the Innovation capability support plan of Shaanxi Province—Research on the construction of modern industrial system from the perspective of “new infrastructure” —taking Shaanxi Province as an example (2021KRM042). This study is funded by the National Natural Science Foundation of China (Grant Number 52102374). The authors are grateful for the financial support provided by the Natural Science Basic Research Plan in Shaanxi Province of China under Grant 2020JQ-360.

ACKNOWLEDGMENTS

We are thankful for the comments and advice which are given by the reviewers. They have improved the content of this work and pointed out some research directions of particular interest.

REFERENCES

Chames, A., Cooper, W. W., and Rhodes, E. (1978). Measuring the Efficiency of Decision Making Units.J. *Eur. J. Oper. Res.* 2 (6), 429–444.

Chen, C, Chen, J., and Gu, J. (2020). Research on the Evolution of the Linkage Development between Manufacturing Industry and Logistics Industry in China .*J. Shandong Univ. (philosophy Soc. Sci* 02, 73–81. doi:10.19836/j.cnki.37-1100/c.2020.02.008

Chen, J, J., Li, H., and Zheng, T. (2020). Network Evolution of Logistics Service Effect of Port Infrastructure in Coastal China. *J. IEEE Access* 08, 1. doi:10.1109/access.2020.2975364

Choi, T.-M., Wallace, S. W., and Wang, Y. (2016). Risk Management and Coordination in Service Supply Chains: Information, Logistics and Outsourcing. *J. Oper. Res. Soc.* 67 (2), 159–164. doi:10.1057/jors.2015.115

De Koster, R. B. M. (2003). Distribution Strategies for Online Retailers. *IEEE Trans. Eng. Manage.* 50 (4), 448–457. doi:10.1109/tem.82013510.1109/tem.2003.820135

Elahi, E., Khalid, Z., and Cui, W. (2019c). The Public Policy of Agricultural Land Allotment to Agrarians and its Impact on Crop Productivity in Punjab Province of Pakistan.J. *Land Use Policy* 90, 104324. doi:10.1016/j.landusepol.2019.104324

Elahi, E., Abid, M., Zhang, L., ul Haq, S., and Sahito, J. G. M. (2018). Agricultural Advisory and Financial Services; Farm Level Access, Outreach and Impact in a Mixed Cropping District of Punjab, Pakistan. *Land Use Policy* 71, 249–260. doi:10.1016/j.landusepol.2017.12.006

Elahi, E., Khalid, Z., Tauni, M. Z., Zhang, H., and Lirong, X. (2021b). Extreme Weather Events Risk to Crop-Production and the Adaptation of Innovative Management Strategies to Mitigate the Risk: A Retrospective Survey of Rural Punjab, Pakistan. *Technovation*, 102255. doi:10.1016/j.technovation.2021.102255

Elahi, E., Weijun, C., Jha, S. K., and Zhang, H. (2019a). Estimation of Realistic Renewable and Non-renewable Energy Use Targets for Livestock Production Systems Utilising an Artificial Neural Network Method: A Step towards Livestock Sustainability. *Energy* 183, 191–204. doi:10.1016/j.energy.2019.06.084

Elahi, E., Weijun, C., Zhang, H., and Abid, M. (2019b). Use of Artificial Neural Networks to rescue Agrochemical-Based Health Hazards: A Resource Optimisation Method for Cleaner Crop Production. *J. Clean. Prod.* 238, 117900. doi:10.1016/j.jclepro.2019.117900

Elahi, E., Weijun, C., Zhang, H., and Nazeer, M. (2019d). Agricultural Intensification and Damages to Human Health in Relation to Agrochemicals: Application of Artificial Intelligence. *Land Use Policy* 83, 461–474. doi:10.1016/j.landusepol.2019.02.023

Elahi, E., Zhang, H., Lirong, X., Khalid, Z., and Xu, H. (2021a). Understanding Cognitive and Socio-Psychological Factors Determining Farmers' Intentions to Use Improved Grassland: Implications of Land Use Policy for Sustainable Pasture Production. *Land Use Policy* 102, 105250. doi:10.1016/j.landusepol.2020.105250

Elhorst, J. P. (2014). Linear Spatial Dependence Models for Cross-Section Data. *Spat. Econom.* 9, 5–36. doi:10.1007/978-3-642-40340-8_2

Hackius, N., and Petersen, M. (2020). Translating High Hopes into Tangible Benefits: How Incumbents in Supply Chain and Logistics Approach Blockchain. *IEEE Access* 8 (1), 34993–35003. doi:10.1109/access.2020.2974622

Han, J., Chen, C., and Shi, F. (2014). Environmental Efficiency, Industry Heterogeneity and Optimal Regulation Intensity of China's Manufacturing Industry.J. *Stat. Res.* 31 (03), 61–67. doi:10.19343/j.cnki.11-1302/c.2014.03.009

He, D., Yang, J., Wang, Z., and Li, W. (2020). Has the Manufacturing Policy Helped to Promote the Logistics Industry. *PLOS ONE* 15, e0235292. doi:10.1371/journal.pone.023529210.1371/journal.pone.0235292

Huang, Q., Peng, B., and Elahi, E. (2020). Evolution and Driving Mechanism of Ecological Security Pattern: A Case Study of Yangtze River Urban Agglomeration.J. *Integrated Environ. Assess. Manag.* 17, 573–583. doi:10.1002/ieam.4358

Ji, X., Zhou, W., and Ma, T. (2018). Innovation of Logistics Cost Management and Competitiveness of Manufacturing Enterprises in Yangtze River Delta -- Based on the Comparison of Logistics Efficiency between Chinese and American Manufacturing Industries.J. *Discussion Mod. economy* (8), 91–97. doi:10.3969/j.issn.1009-2382.2018.08.012

Jiang, P., Hu, Y. C., and Yen, G. F. (2018). Using a Novel Grey DANP Model to Identify Interactions between Manufacturing and Logistics Industries in China.J. *Sustainability* 10 (10). doi:10.3390/su10103456

John, E. (2018). Spillan,Alma Mintu-Wimsatt,Ali Kara. Role of Logistics Strategy, Coordination and Customer Service Commitment on Chinese Manufacturing Firm Competitiveness.J. *Asia Pac. J. Marketing Logistics* 30 (5), 1365–1378. doi:10.1108/APJML-09-2017-0224

Kant, K., and Pal, A. (2017). Internet of Perishable Logistics. *IEEE Internet Comput.* 21 (1), 22–31. doi:10.1109/mic.2017.19

Li, J., Li, T., and Wang, Y. (2018). Spatial Effect of Regional Logistics Industry Efficiency Considering Undesirable Output.J. *J. Arid Land Resour. Environ.* 032 (008), 67–73. doi:10.13448/j.cnki.jalre.2018.237

Li, Z., Li, Y., Lu, W., and Huang, J. (2020). *Crowdsourcing Logistics Pricing Optimization Model Based on DBSCAN Clustering Algorithm* (IEEE Access), 1. doi:10.1109/access.2020.2995063

Liang, H. (2015). Research on the Influence Mechanism of Logistics Development on Manufacturing Efficiency .J. *Southeast Acad.* (1), 88–97. doi:10.13658/j.cnki.sar.2015.01.011

Liu, H., Fang, C., Zhang, X., Wang, Z., Bao, C., and Li, F. (2017). The Effect of Natural and Anthropogenic Factors on Haze Pollution in Chinese Cities: A Spatial Econometrics Approach. *J. Clean. Prod.* 165, 323–333. doi:10.1016/j.jclepro.2017.07.127

Long, R., Ouyang, H., and Guo, H. (2020). Super-slack-based Measuring Data Envelopment Analysis on the Spatial-Temporal Patterns of Logistics Ecological Efficiency Using Global Malmquist Index Model. *Environ. Techn. Innovation* 18, 100770. doi:10.1016/j.eti.2020.100770

Matlab Chinese Forum (2010). *Analysis of 30 Cases of MATLAB Neural Network*. Beijing, China: M. Beijing University of Aeronautics and Astronautics Press.

Moran, P. A. P . (1953). The Statistical Analysis of the Canadian Lynx Cycle.J. *Aust. J. Zoolog.* 1. doi:10.1071/zo9530291

Notice (2020). On Printing and Distributing the Implementation Plan for Promoting the Deep Integration and Innovative Development of Logistics Manufacturing Industry. *J. Shanghai Building Materials* (05), 9–12.

Peng, B., Wang, Y., and Zahid, S. (2020a). Platform Ecological circle for Cold Chain Logistics Enterprises: the Value Co-creation Analysis.J. *Ind. Manag. Data Syst.* doi:10.1108/IMDS-10-2019-0531

Peng, B., Li, Y., Elahi, E., and Wei, G. (2019a). Dynamic Evolution of Ecological Carrying Capacity Based on the Ecological Footprint Theory: A Case Study of Jiangsu Province. *Ecol. indicators* 99 (APR), 19–26. doi:10.1016/j.ecolind.2018.12.009

Peng, B., Wang, Y., Elahi, E., and Wei, G. (2018). Evaluation and Prediction of the Ecological Footprint and Ecological Carrying Capacity for Yangtze River Urban Agglomeration Based on the Grey Model. *Ijerph* 15 (11), 2543. doi:10.3390/ijerph15112543

Peng, B., Zheng, C., Wei, G., and Elahi, E. (2020b). The Cultivation Mechanism of green Technology Innovation in Manufacturing Industry: From the Perspective of Ecological Niche. *J. Clean. Prod.* 252, 119711. doi:10.1016/j.jclepro.2019.119711

Peng, B., Huang, Q., Elahi, E., and Wei, f. (2019b). Ecological Environment Vulnerability and Driving Force of Yangtze River Urban Agglomeration. *Sustainability* 11 (23), 6623. doi:10.3390/su11236623

Schaltegger, S., and Sturm, A. (1990). Kologische Rationalitt (German/in English: Environmental Rationality). *J. Die Unternehmung* 4 (4), 117–131.

Shi, Y., Zhang, A., Arthanari, T., Liu, Y., and Cheng, T. C. E. (2016). Third-party purchase: An Empirical Study of Third-Party Logistics Providers in China. *Int. J. Prod. Econ.* 171 (jan2), 189–200. doi:10.1016/j.ijpe.2015.08.028

Sueyoshi, T., Yuan, Y., and Goto, M. (2016). A Literature Study for DEA Applied to Energy and Environment.J. *Energ. Econ.* 62 (FEB.), 104–124. doi:10.1016/j.eneco.2016.11.006

Tone, K. (2001). A Slacks-Based Measure of Efficiency in Data Envelopment Analysis. *Eur. J. Oper. Res.* 130 (3), 498–509. doi:10.1016/s0377-2217(99)00407-5

Tone, K. (2002). A Slacks-Based Measure of Super-efficiency in Data Envelopment Analysis. *Eur. J. Oper. Res.* 143 (1), 32–41. doi:10.1016/s0377-2217(01)00324-1

Tone, K. (2003). *Dealing with Undesirable Outputs in DEA: A Slacks2 Based Measure (SBM)Approach, I-2003-0005.* Toronto: J.GR IPS Research Report Series.

Wang, B., Wu, Y., and Yan, P. (2010). China's Regional Ecological Efficiency and Environmental Total Factor Productivity Growth. *J. Sci. Technol. Commun.* 05 (05), 95–109.

Wang, J. J., Wang, M., Liu, F., and Chen, F. (2015). Multistakeholder Strategic Third-Party Logistics Provider Selection:. *Transportation J.* 54 (3), 312–338. doi:10.5325/transportationj.54.3.0312

Wang, Y., Peng, B., Wei, G., and Elahi, E. (2019). Comprehensive Evaluation and Spatial Difference Analysis of Regional Ecological Carrying Capacity: A Case Study of the Yangtze River Urban Agglomeration. *Ijerph* 16 (18), 3499. doi:10.3390/ijerph16183499

Wang, Z. (2017). Efficiency Evaluation of the Linkage Development of China's Manufacturing and Logistics Industry -- Based on Super Efficiency Ccr-Dea Model. *J. China's Circulation Economy* 2 (2). doi:10.14089/j.cnki.cn11-3664/f.2017.02.003

Watanabe, M., and Tanaka, K. (2007). Efficiency Analysis of Chinese Industry: A Directional Distance Function Approach. *Energy Policy* 35 (12), 6323–6331. doi:10.1016/j.enpol.2007.07.013

Wen-Long, Z., Jian-Wei, W., Shi-Qing, Z., Rehman Khan, S. A., An-Ding, J., Xu-Quan, Y., et al. (2021). Evaluation of Linkage Efficiency between Manufacturing Industry and Logistics Industry Considering the Output of Unexpected Pollutants. *J. Air Waste Manag. Assoc.* 71, 304–314. doi:10.1080/10962247.2020.1811799

Yuan, Ci., Zhang, Q., and Rui, Xi. (2016). Spatiotemporal Evolution and Difference Analysis of Transportation Carbon Emissions in China. *J. J. Environ. Sci.* 12 (12). doi:10.13671/j.hjkxxb.2016.0206

Zhang, F., Shi, Z., and song, X. (2019). Green Technology Innovation Efficiency and Environmental Regulation Threshold Effect of Advanced Manufacturing Industry .J. *Prog. Countermeasures Sci. Technol.* 36472 (12), 68–76. doi:10.6049/kjbydc.2018100165

Zhang, L. (2019). Research on the Efficiency and Influencing Factors of China's Logistics Industry under the Constraint of Low Carbon .J. *Value Eng.* 38 (26), 129–131.

Zhang, S., Wang, J., and Zheng, W. (2017). Spatiotemporal Difference Analysis of Carbon Emissions and Influencing Factors of Transportation in China. *J. J. Environ. Sci.* 12 (12), 4787–4797. doi:10.13671/j.hjkxxb.2017.0242

Zhang, Y., Guo, Z., Lv, J., and Liu, Y. (2018). A Framework for Smart Production-Logistics Systems Based on CPS and Industrial IoT. *IEEE Trans. Ind. Inf.* 14 (9), 4019–4032. doi:10.1109/tii.2018.2845683

Zhang, Z., Hui, J., and Shi, Z. (2020). Cycle Condition Identification of Loader Based on Optimized KNN Algorithm, *J. IEEE Access* 08 1. doi:10.1109/access.2020.2985052

Zheng, W L, W. L., Wang, J. W., and Zhang, S. Q. (2018). Road Transportation Network Planning and Design Based on the BP Neural Network.J. *Adv. Transportation Stud.* 3, 117–124. doi:10.4399/978882552166515

Zheng, W., Wang, J., and Zhang, Sg. (2018). Analysis on Carbon Emission Decoupling Effect and Driving Factors of Environmental Pollution in China Transportation Industry. *J. Chem. Eng. Trans.* 66, 637–642. doi:10.3303/CET1866107

Zhou, P., Ang, B. W., and Poh, K. L. (2008). Measuring Environmental Performance under Different Environmental DEA Technologies. *Energ. Econ.* 30 (1), 1–14. doi:10.1016/j.eneco.2006.05.001

Zhou, Y., Zhang, M. X., and Yang, J. (2015). *A Study on the Eco-Efficiency of Logistics Industry in Provincial Domain Based on SE-DEA Method*. Beijing, China: Journal of Beijing Jiaotong University(Social Sciences Edition.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers | Frontiers in Energy Research

ORIGINAL RESEARCH
published: 09 May 2022
doi: 10.3389/fenrg.2022.784709

Economic Impacts and Challenges of Chinese Mining Industry: An Input–Output Analysis

*Binyuan Zhang, Jinge Yao and Hyuck-Jin Lee**

Department of Economics, Sejong University, Seoul, South Korea

The mining industry (MI) has played a key role in ensuring a stable supply of minerals for industrial production and human survival. The Chinese government is implementing various policies to promote the MI and needs quantitative information on the economic role and effects of the MI. Thus, this article uses comprehensive and multi-period input-output (IO) analysis to investigate the roles of four mining sectors, including the entire mining sector in the Chinese national economy, from the period 2007–2017. To this end, three models are employed. First, the production-inducing effects, value-added creation effects, and wage-inducing effects of 1 dollar of production in the MI sector are analyzed using a demand-driven model. One dollar of production or investment in the sector causes 0.862–1.171 dollars of production, 0.271–0.333 dollar of value-added, and 0.106–0.125 dollar of wage, respectively. Second, by applying a supply-driven model, it is found that one dollar of supply shortage in the MI causes 4.383–5.949 dollars of production failure throughout the national economy. Third, by utilizing a price-side model, it is discovered that a 10% increase in the price of output of the MI raises the overall price level by 0.108%–0.171%. The results of this article were critical to enlighten policy-makers to forward ever-improvement on the MI and combine the MI within national economic system reform and planning, by offering a clear vision of how MI will affect the various sectors and the economic system as a whole.

Keywords: input-output analysis, mining industry, economic impacts, China, national economy

OPEN ACCESS

Edited by:
Pu-yan Nie,
Guangdong University of Finance and Economics, China

Reviewed by:
Abdul Rehman,
Henan Agricultural University, China
Muhammad Mohsin,
Jiangsu University, China

****Correspondence:***
Hyuck-Jin Lee
lhj@sejong.ac.kr

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *28 September 2021*
Accepted: *19 April 2022*
Published: *09 May 2022*

Citation:
Zhang B, Yao J and Lee H-J (2022) Economic Impacts and Challenges of Chinese Mining Industry: An Input–Output Analysis. Front. Energy Res. 10:784709. doi: 10.3389/fenrg.2022.784709

1 INTRODUCTION

The mining industry (MI) plays an essential role in accelerating industrialization and urbanization, as it provides raw materials to meet the growing demand for resources. In addition, it contributes to increased foreign capital investment, exports, and employment, key factors in socio-economic development (Chen et al., 2020; Jiskani et al., 2020). In other words, the MI's primary purpose is to offer energy resources, metallic materials, and non-metallic minerals for the development of other industries, and extensive and multi-level direct and indirect links with other industries in the economy (Lei et al., 2013; Kim et al., 2020).

China has discovered 173 minerals and has proven reserves in 163 minerals, ranking third globally after the United States and Russia. These resources include 13 energy, 59 metal, 95 non-metal, and 6 water and gas minerals, with some resources' reserves being relatively abundant (The Report of China Mineral Resources, 2020). Furthermore, from 2003 to 2014, the annual growth rate of mining investment in China consistently exceeded 10% (Fan et al., 2017), and with the implementation of the "*Made in China 2025*" strategy, the enormous potential and growth space of China's economy transitioning to a high-quality development stage will continue to boost demand for mineral resources (Feng et al., 2019; The Stats Council of the People's Republic of China, 2020), with China expected to become the world's largest coal market by 2035 (Wang et al., 2019). However, the traditional extensive development model is unsustainable, and pressures on resource security, economic security and ecological security are growing. Therefore, the development of the mining industry must accelerate structural optimization and adjustment, improve the efficiency of development and utilization, promote the transformation and upgrading of the mining industry and green development, realize the modernization of governance capabilities, so as to comprehensively promote the high-quality development of the mining industry (Al Asbahi et al., 2019; Yang et al., 2021). In addition, green and efficient mining of advantageous minerals through new digitalization and new technologies, such as tantalum, niobium, lithium, rare earth, scandium, germanium, gallium, indium, rhenium, tellurium, and arsenic has become a global concern as these minerals are in short supply in the United States, Europe and other Western countries. Thus, China's MI is a major stimulant for both the local and global economies.

The input-output (IO) analysis suggested by Leontief (1936) is thought to be an effective top-down approach to underpin embodiment accounting. The inverse matrix is used to solve the inter-industry transaction table's mathematical relationship in IO analysis based on the general framework of the IO table. Additionally, the IO model is significant in various areas, notably energy issues, regional economies, environmental issues, and employment (Beylot and Villeneuve, 2015; Ju et al., 2016; Means et al., 1939; Wang and Wang, 2019). Furthermore, IO analysis has broad applicability to mining and mining-related businesses in regional and national economies. For example, between 1971 and 1993, Stilwell et al. (2000) used the IO table to analyze the impact of gold, coal, and other mining activities on the South African economy. Based on this model, San Cristóbal and Biezma (2006) employed IO analysis to identify three significant subsectors: the German coal mining industry, the Swedish iron ore mining business, and the Austrian mining and quarrying industry. In empirical studies, Ivanova (2014) used input-output modeling to analyze the economic diversity of Australia's Queensland region to identify key sectoral, backward, and forward linkages. In addition, Kim et al. (2020) used IO tables published by the Bank of Korea in 2015 to conduct an input-output analysis identifying Korean mining industry characteristics, such as production-induced effects and supply shortage impacts.

Many scholars have proven the link between energy resources and economic development, such as the fact that recycling and using natural resources increases economic growth potential (Upadhyay et al., 2021), and the mining industry adds to the economy's demand for materials for productive activities (Suh, 2021). Also, in the process of economic transformation, sustainable economic growth can be stimulated through the transformation of natural resources (Sun et al., 2020). Agyekum et al. (2021) examined the environment in the renewable energy sector through a mix of PESTLE-AHP methodologies and found economic factors as key challenges. Several scholars have focused on the MI of China. For instance, Lei et al. (2013) conducted a quantitative analysis of sub-sectors in China's MI using data from the China Statistical Yearbook 2004–2010 and China's 2007 IO tables to identify input-output, industry linkage, and income distribution effects. Further research evaluated the contribution of mining-related industries. Xu (2011) used an IO model to analyze the Chinese petroleum industry's direct and indirect economic impact coefficients and inducing effects. Wu and Zhang (2016) examined the rising demand in China's coal sector from 1997 to 2012 using an IO structural decomposition analysis (IO SDA) model, concluding that industrial upgrading could successfully restrict coal demand growth with a contribution of 108.6%. Song et al. (2019) used the same model to analyze the drivers of metal consumption in China at the national, industry, and sub-industry levels. Furthermore, Wang and Ge (2020) used a multi-regional IO model to calculate external demand for coal consumption in mainland China, deconstructed critical elements using structural decomposition analysis, and then calculated the impact of external demand on direct and indirect coal consumption in mainland China.

Most previous studies of China's MI focused on a single mining sub-sector, such as coal, metal ores, or petroleum. In addition, few studies conducted a comprehensive assessment of the economic impact of China's entire mining sector. Therefore, this study analyzed the economic and social effects of the Chinese MI through an IO analysis, using China's recent official data from 2007, 2012, and 2017 IO tables (National Bureau of Statistics of China, 2012; National Bureau of Statistics of China, 2017; National Bureau of Statistics of China, 2019). An additional four MI sub-sectors were recovered, and their outputs were extracted to create a set of MI sector models. The results were estimated as the production-inducing, wage-inducing, and value-added creation effects of MI investment (demand-driven model), the effect of MI loss in supply shortage (supply-driven model), the effects of a 10% increase in the price of MI products (price-side model), and the inter-industry linkage effect. The major goal of these studies was to show how the MI interacts with the primary, secondary, and tertiary industries, as well as other sectors within the mining industry. In this way, the industrial association and industrial spread effect of the mining industry are revealed, and the contribution of the mining industry to China's national economy is quantified. In addition, another purpose of studying the mining industry is to provide data support for decision-makers who are developing mining development policies. The findings of this paper can be used to better understand the status and role of the mining industry and its internal departments in the development of the national economy, as well as to guide the formulation of China's mineral product price adjustment policies and how to use industrial policies to promote the development of the mining industry.

This study is structured as follows: **Section 1** shows the introduction; **Section 2** describes the current status of China's mining industry; **Section 3** introduces the data and methodology for examining the MI's contribution to the national economy

TABLE 1 | The categories of the four major mining sectors.

Category	Specific sectors
Coal	CMW
Crude Petroleum and Natural Gas	PNGE
Metal Ores	FMOMP
	NFMOMP
Non-Metallic Mineral Mining	NOMP

from four aspects: the demand-driven model, the supply shortage model, the price-side model, and the inter-industry linkage model; **Section 4** analyzes the results; and, finally, **Section 5** draws the conclusions and critical policy implications.

2 CURRENT STATUS OF THE MINING INDUSTRY IN CHINA

According to the industry classification in the National Bureau of Statistics of the People's Republic of China (NBSC), the MI consists of five main sub-sectors: non-ferrous metal ore mining and processing (NFMOMP), coal mining and washing (CMW), ferrous metal ore mining and processing (FMOMP), petroleum and natural gas extraction (PNGE), and non-metal ore mining and processing (NOMP) (Wang and Feng, 2017). As shown in **Table 1**, the MI is divided into four sections in the Chinese IO table: coal, crude petroleum and natural gas, metal ores, and non-metallic mineral mining, with FMOMP and NFMOMP counted as metal ores.

The MI is an essential sector in the national economy since it provides raw materials for manufacturing (Shen et al., 2015; Wang and Sun, 2017). However, the global mining industry is currently in flux due to economic restructuring and price drops in most mineral products. Between 2003 and 2011, China's mining economy was in a high-speed development phase, with the output value increasing from 0.74 trillion yuan to 5.86 trillion yuan and an average annual growth rate of 29.6%, but since 2012, China's MI has been in a "transition period" (Chen et al., 2015), with an average annual growth rate of 3.5% between 2012 and 2014. As shown in **Figure 1**, the fixed-asset investment growth rate in China's MI has declined, even in 2016 and 2017, with successive negative growth, and has since only maintained an average annual growth rate of around 2%. In 2020, among the mining sector's fixed-asset investments, those in the coal and non-metallic sectors grew slightly, by 2.2 and 4.9%, respectively. Meanwhile, due to the plunge in crude oil prices, fixed-asset investments in crude petroleum and natural gas fell sharply by 21.8%. In addition, fixed-asset investments in FMOMP and NFMOMP narrowed, down 9.9 and 6.1% year-on-year, up 8.9% points and 21.5% points from last year, respectively. It has been said that China's mining economy is in a new phase dubbed "new normal," characterized by medium-speed growth, economic restructuring, and upgrading (Cheng et al., 2015; Tung, 2016).

This year (2021) is the opening year of China's 14th Five-Year Plan when China officially starts a new journey to build a comprehensive socialist modern state. Moreover, with its expected population peak in 2030, China will remain the primary driver of global economic growth in the next decade, and the demand for mineral resources will continue to grow (Guo et al., 2021). In particular, bulk minerals such as iron ore and copper, closely related to new infrastructure, are in solid demand, driven by investment. In 2019, the total number of people employed in China's MI and MI-related sectors reached 3.677 million, accounting for 2.14% of national employment (National Bureau of Statistics of China, 2020). In the background, implementing China's "*One Belt, One Road*" strategy will bring development opportunities for China's MI, and the rational development and utilization of mineral resources will effectively promote economic recycling and protect the ecological environment (Zhou et al., 2020).

3 MATERIALS AND METHODS

3.1 Data Sources

We used China's IO tables for 2007, 2012, and 2017 compiled every 5 years by the NBSC (National Bureau of Statistics of China, 2019), to analyze the roles of China's MI. Furthermore, the essential data, such as value contributed, total output value, and employee remuneration, were from the China Mineral

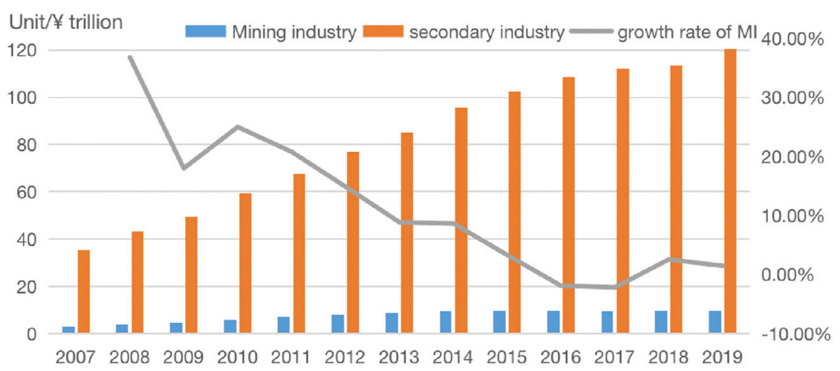

FIGURE 1 | China's fixed-assest investment in mining and secondary industry from 2007 to 2019.

TABLE 2 | Sector classification adopted in this study.

Number	Sectors	Number	Sectors
1	Products and Service of Farming, Forestry, Animal Husbandry and Fishery	22	Production and Supply of Tap Water
2	Food and Tobacco	23	Construction
3	Textile Products	24	Wholesale and Retail Trade
4	Manufacture of Leather, Fur, Feather and Its Products	25	Traffic, Transport, Storage and Mail
5	Timber Processing and Furniture	26	Accommodation and Restaurants
6	Paper making, Printing, Cultural and Educational Goods	27	Information Transfer, Computer and Software Services
7	Processing of Petroleum, Coking, Processing of Nucleus Fuel	28	Banking
8	Chemical Products	29	Real Estate Trade
9	Nonmetal Mineral Products	30	Renting and Leasing, Business Services
10	Products of Smelting and Pressing of Metals	31	Research and Development
11	Metal Products	32	Technical Service
12	General Machinery	33	Management of Water Conservancy, Environment and Public Establishment
13	Special Purpose Machinery	34	Resident Services, Repair and Other Services
14	Transport Equipment Machinery	35	Education
15	Electric Equipment and Machinery	36	Health Care and Social Work Activities
16	Communication Equipment, Computer and other Electronic Equipment	37	Culture, Sports and Entertainment
17	Instruments and Meters	38	Public Management, Social Security and Social Organization
18	Other Manufacture, Waster and Flotsam	39	Coal
19	Repair Services of Metal Products Equipment and Machinery	40	Crude Petroleum and Natural Gas
20	Production and Supply of Electric Power, Steam and Hot Water	41	Metal Ores
21	Production and Supply of Gas	42	Non-Metallic Mineral Mining

Resources report and the National Plan for Mineral Resources 2016-2020(Ministry of Natural Resources), issued by the Ministry of Natural Resources (Ministry of Natural Resources PRC).

The entire mining sector was not available in China's IO tables. Therefore, based on the sectoral analysis, the main issue was summing up the sub-sectors of the mining industry in the IO table to obtain data for the entire mining industry. The steps were as follows: first, the Chinese mining industry's four major sub-sectors were identified (**Table 1**) based on the industry classification standard and main mining activities. Next, based on statistics, such as total output value and value-added for the four mining sub-sectors, we aggregated the entire mining industry, the sum of all sub-sectors. They are the basis for further evaluation on economic effects of MI on the national economy of China.

IO analysis is the analysis method to quantitatively grasp the interrelation among the industries produced through production activity by using the input-output table covering the whole of national economy. It is possible for this analysis to analyze the interrelation among the industries which does not deal with macro-analysis. It is useful to analyze a concrete economic structure (Ghosh, 1958; Wu and Chen, 1990). Exogenous specification can examine the influence which one variable has on the endogenous economy sector by treating the variable exogenously. By using the exogenous specification, we can know the influence which the output of a specific sector has and the effect that the output causes other industries.

3.2 General Framework of the IO Model

The first researcher to employ an IO matrix depiction of a national or regional economy was Leontief (1966), who employed an inverse matrix to solve the mathematical relationship of inter-industry transaction tables based on the IO table's general framework. In an IO table, the columns indicate the input values for each sector, while the rows represent the output values. For example, if the IO table is divided into N sectors: sector i's total input is denoted by X_i; Y_i signifies the final demand for items in the industry i; a_{ij} denotes the sector-between direct input coefficients matrix (from sector i to sector j). The sector-between direct output coefficients matrix (from each sector i to each sector j) is denoted by r_{ij}; the total output value of sector j is denoted by X_j; and the added value of sector j is denoted by Z_j. The primary assumption is related to the basic Leontief model and can be used as an indicator to assess the contribution of a specific sector over a given period. The traditional representation of IO equations is as follows (Miller and Blair, 1985):

$$X_i = \sum_{j=1}^{n} x_{ij} + Y_i = \sum_{j=1}^{n} a_{ij} X_j + Y_i \tag{1}$$

$$X_j = \sum_{i=1}^{n} x_{ij} + Z_j = \sum_{i=1}^{n} r_{ij} X_i + Z_j \tag{2}$$

3.3 Demand-Driven Model

The inducement effects on production, value-added, and wage-inducing can be evaluated in the demand-driven model. These effects mean that how much the production, value-added, and wages of other industries, excepting for the target industry increase, when the production of the target industry which is the industry related to the China's MI increases with $1. The following equations to evaluate the inducement effects of the production, value-added, and wage-inducing by treating the industry regarding with the China's MI (hereinafter referred to as "H sector") as exogenous. The process to induce each

TABLE 3 | Production-inducing effects of mining industry.

Number	Sectors	Coal			Crude petroleum and natural gas			Metal ores			Non-metallic mineral mining			Entire mining industry		
		Value			Value			Value			Value			Value		
		2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017
1	Products and Service of Farming, Forestry, Animal Husbandry and Fishery	0.035	0.025	0.021	0.022	0.020	0.016	0.032	0.031	0.025	0.036	0.037	0.032	0.027	0.023	0.020
2	Food and Tobacco	0.025	0.023	0.019	0.020	0.023	0.017	0.028	0.032	0.030	0.031	0.037	0.035	0.022	0.023	0.021
3	Textile Products	0.012	0.011	0.010	0.011	0.009	0.006	0.014	0.014	0.008	0.016	0.015	0.015	0.011	0.010	0.009
4	Manufacture of Leather, Fur, Feather and Its Products	0.011	0.007	0.012	0.010	0.005	0.006	0.013	0.007	0.008	0.013	0.008	0.010	0.010	0.006	0.009
5	Timber Processing and Furniture	0.018	0.031	0.026	0.011	0.004	0.005	0.012	0.008	0.008	0.010	0.008	0.006	0.012	0.015	0.013
6	Paper making, Printing, Cultural and Educational Goods	0.018	0.016	0.014	0.016	0.013	0.011	0.021	0.023	0.016	0.024	0.022	0.022	0.017	0.015	0.013
7	Processing of Petroleum, Coking, Processing of Nucleus Fuel	0.066	0.043	0.022	0.083	0.075	0.029	0.127	0.103	0.082	0.110	0.121	0.094	0.079	0.063	0.043
8	Chemical Products	0.106	0.093	0.069	0.110	0.111	0.094	0.164	0.157	0.134	0.266	0.221	0.212	0.125	0.109	0.099
9	Nonmetal Mineral Products	0.024	0.015	0.009	0.022	0.014	0.009	0.024	0.018	0.013	0.059	0.047	0.033	0.025	0.016	0.012
10	Products of Smelting and Pressing of Metals	0.181	0.133	0.077	0.168	0.127	0.051	0.150	0.113	0.066	0.120	0.141	0.093	0.142	0.111	0.064
11	Metal Products	0.048	0.037	0.041	0.030	0.024	0.015	0.052	0.044	0.040	0.035	0.055	0.049	0.036	0.033	0.033
12	General Machinery	0.116	0.041	0.033	0.112	0.037	0.027	0.139	0.054	0.043	0.120	0.058	0.048	0.106	0.039	0.033
13	Special Purpose Machinery	0.038	0.029	0.026	0.031	0.047	0.043	0.047	0.041	0.037	0.050	0.070	0.069	0.035	0.035	0.035
14	Transport Equipment Machinery	0.053	0.014	0.016	0.042	0.014	0.014	0.059	0.022	0.025	0.046	0.033	0.036	0.044	0.015	0.019
15	Electric Equipment and Machinery	0.038	0.025	0.021	0.037	0.026	0.018	0.041	0.035	0.030	0.036	0.042	0.038	0.033	0.026	0.023
16	Communication Equipment, Computer and other Electronic Equipment	0.017	0.029	0.024	0.025	0.031	0.025	0.018	0.033	0.028	0.015	0.040	0.039	0.017	0.027	0.025
17	Instruments and Meters	0.008	0.005	0.005	0.005	0.020	0.017	0.009	0.010	0.009	0.011	0.013	0.013	0.007	0.009	0.009
18	Other Manufacture, Waster and Flotsam	0.014	0.003	0.008	0.012	0.001	0.006	0.014	0.002	0.007	0.022	0.003	0.010	0.013	0.002	0.007
19	Repair Services of Metal Products Equipment and Machinery	0.158	0.007	0.001	0.166	0.007	0.001	0.284	0.007	0.002	0.180	0.009	0.002	0.167	0.006	0.001
20	Production and Supply of Electric Power, Steam and Hot Water	0.002	0.002	0.075	0.003	0.003	0.065	0.007	0.003	0.145	0.008	0.004	0.128	0.004	0.002	0.087
21	Production and Supply of Gas	0.003	0.095	0.002	0.003	0.115	0.002	0.004	0.193	0.002	0.004	0.160	0.004	0.003	0.113	0.002
22	Production and Supply of Tap Water	0.003	0.001	0.001	0.002	0.001	0.001	0.002	0.002	0.001	0.002	0.002	0.002	0.002	0.001	0.001
23	Construction	0.088	0.001	0.002	0.050	0.001	0.001	0.092	0.002	0.002	0.110	0.002	0.002	0.071	0.001	0.001
24	Wholesale and Retail Trade	0.001	0.006	0.051	0.001	0.005	0.033	0.001	0.007	0.056	0.001	0.009	0.073	0.001	0.005	0.046
25	Traffic, Transport, Storage and Mail	0.011	0.038	0.055	0.009	0.034	0.037	0.011	0.048	0.061	0.011	0.059	0.084	0.009	0.036	0.051
26	Accommodation and Restaurants	0.034	0.057	0.015	0.030	0.042	0.012	0.038	0.080	0.018	0.040	0.090	0.022	0.030	0.054	0.014
27	Information Transfer, Computer and Software Services	0.024	0.013	0.010	0.019	0.010	0.008	0.026	0.017	0.013	0.029	0.018	0.015	0.021	0.012	0.010
28	Banking	0.049	0.007	0.080	0.036	0.006	0.058	0.047	0.010	0.069	0.047	0.010	0.081	0.039	0.007	0.066
29	Real Estate Trade	0.007	0.084	0.017	0.005	0.054	0.012	0.007	0.080	0.015	0.008	0.088	0.019	0.006	0.067	0.014
30	Renting and Leasing, Business Services	0.018	0.009	0.061	0.013	0.007	0.042	0.019	0.010	0.054	0.019	0.012	0.066	0.015	0.008	0.051

(Continued on following page)

TABLE 3 | (*Continued*) Production-inducing effects of mining industry.

Number	Sectors	Coal			Crude petroleum and natural gas			Metal ores			Non-metallic mineral mining			Entire mining industry		
		Value			Value			Value			Value			Value		
		2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017
31	Research and Development	0.004	0.045	0.000	0.004	0.029	0.000	0.003	0.049	0.000	0.003	0.051	0.000	0.003	0.037	0.000
32	Technical Service	0.014	0.017	0.015	0.016	0.026	0.012	0.019	0.022	0.019	0.015	0.031	0.024	0.014	0.019	0.015
33	Management of Water Conservancy, Environment and Public Establishment	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.003	0.004	0.005	0.005	0.002	0.002	0.002
34	Resident Services, Repair and Other Services	0.018	0.011	0.013	0.012	0.008	0.007	0.013	0.008	0.007	0.014	0.013	0.012	0.013	0.009	0.009
35	Education	0.004	0.001	0.001	0.002	0.001	0.001	0.003	0.001	0.001	0.005	0.001	0.001	0.003	0.001	0.001
36	Health Care and Social Work Activities	0.005	0.001	0.001	0.002	0.000	0.000	0.005	0.001	0.001	0.005	0.001	0.001	0.004	0.000	0.001
37	Culture, Sports and Entertainment	0.004	0.003	0.003	0.003	0.003	0.003	0.006	0.005	0.004	0.007	0.004	0.004	0.004	0.003	0.003
38	Public Management, Social Security and Social Organization	0.000	0.001	0.001	0.001	0.001	0.001	0.000	0.002	0.001	0.000	0.002	0.001	0.000	0.001	0.001
39	Coal				0.035	0.043	0.020	0.055	0.066	0.044	0.042	0.069	0.052			
40	Crude Petroleum and Natural Gas	0.046	0.027	0.014				0.097	0.064	0.044	0.089	0.075	0.052			
41	Metal Ores	0.030	0.027	0.016	0.028	0.025	0.011				0.021	0.032	0.020			
42	Non-Metallic Mineral Mining	0.005	0.008	0.008	0.005	0.112	0.142	0.007	0.013	0.012						
	Total	1.360	1.044	0.896	1.214	1.134	0.880	1.711	1.439	1.185	1.687	1.716	1.522	1.171	0.965	0.862

equation can refer to a large number of papers on IO analysis (Yoo and Yang, 1999; Oosterhaven, 2019).

3.3.1 Production-Inducing Effects

$$\Delta X^{e} = (I - A^{e})^{-1} (A_{H}^{e} \Delta X_{H}) \quad (3)$$

ΔX^{e} represents the emission variation of the other sectors with except of sector H, $(1 - A^{e})^{-1}$ is the Leontief inverse matrix of reduced input coefficient matrix, with elimination of the row and column of sector H, A_{H}^{e} denotes a column vector except for an element of sector H, $A_{H}^{e}\Delta X_{H}$ identifies the scalar of the change in the sectorial gross output of H.

3.3.2 Value-Added Creation Effects

$$\Delta V_{e} = \hat{A}_{v}^{e} (I - A^{e})^{-1} (A_{H}^{e} \Delta X_{H}) \quad (4)$$

ΔV_{e} represents the value-added of the other sectors with except of sector H, $\hat{A}_{v}^{e}$ represents the matrix of reduced diagonal matrix of value-added coefficient upon eliminating the row and column of sector H.

3.3.3 Wage-Inducing Effects

$$\Delta W_{e} = \hat{A}_{W}^{e} (I - A^{e})^{-1} (A_{H}^{e} \Delta X_{H}) \quad (5)$$

ΔW_{e} represents the wage-inducing of the other sectors with except of sector H, $\hat{A}_{W}^{e}$ represents the matrix of reduced diagonal matrix of wage-inducing coefficient upon eliminating the row and column of sector H.

3.4 Inter-Industry Linkage Model

The industry linkage model is proposed to measure the backward and forward relationship between one industry and other sectors in order to examine the strengths of the industry linkage within the national economy account. That is, the backward linkage represents the importance of the MI as demanders, whereas the forward linkage represents the importance of the MI as suppliers (Hirschman, 1958).

In terms of dispersion power, the backward linkage reflects a column vector analysis of the Leontief inverse matrix. This model examines the effects on all sectors of production when the MI's ultimate demand increases by one unit. All sectors have a societal average level of 1. When the MI's backward linkage is more than one, it implies that the sector's influence on the national economy surpasses the societal average level of all sectors. The backward linkage effect can be expressed as follows:

$$F_{i} = \sum_{j=1}^{n} b_{ij} \Big/ \left((1/n) \sum_{i=1}^{n} \sum_{j=1}^{n} b_{ij} \right) \quad (6)$$

Where F_{i} denotes the backward linkage effect, $\sum_{j=1}^{n} b_{ij}$ is the sum of the Leontief inverse matrix column vector, and $(1/n)\sum_{i=1}^{n}\sum_{j=1}^{n} b_{ij}$ is the average of the Leontief inverse matrix.

TABLE 4 | Value-added creation effects of mining industry.

Number	Sectors	Coal			Crude petroleum and natural gas			Metal ores			Non-metallicmineral mining			Entire mining industry		
		Value			Value			Value			Value			Value		
		2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017
1	Products and Service of Farming, Forestry, Animal Husbandry and Fishery	0.021	0.015	0.007	0.013	0.012	0.005	0.018	0.018	0.007	0.021	0.021	0.009	0.009	0.007	0.006
2	Food and Tobacco	0.006	0.002	0.006	0.005	0.002	0.006	0.007	0.002	0.009	0.008	0.009	0.010	0.007	0.007	0.006
3	Textile Products	0.002	0.001	0.003	0.002	0.001	0.002	0.003	0.001	0.002	0.003	0.003	0.004	0.003	0.003	0.002
4	Manufacture of Leather, Fur, Feather and Its Products	0.002	0.001	0.003	0.002	0.001	0.002	0.003	0.001	0.002	0.003	0.002	0.003	0.003	0.002	0.002
5	Timber Processing and Furniture	0.004	0.003	0.006	0.003	0.000	0.001	0.003	0.001	0.002	0.002	0.002	0.002	0.003	0.003	0.003
6	Paper making, Printing, Cultural and Educational Goods	0.004	0.002	0.005	0.004	0.001	0.004	0.005	0.003	0.005	0.006	0.005	0.007	0.005	0.005	0.005
7	Processing of Petroleum, Coking, Processing of Nucleus Fuel	0.012	0.002	0.007	0.015	0.003	0.010	0.023	0.004	0.022	0.020	0.022	0.025	0.019	0.014	0.012
8	Chemical Products	0.022	0.006	0.019	0.022	0.007	0.029	0.033	0.010	0.034	0.054	0.042	0.053	0.030	0.024	0.025
9	Nonmetal Mineral Products	0.007	0.002	0.003	0.006	0.001	0.003	0.007	0.002	0.004	0.016	0.012	0.009	0.007	0.004	0.003
10	Products of Smelting and Pressing of Metals	0.035	0.007	0.019	0.033	0.007	0.015	0.029	0.006	0.017	0.024	0.025	0.023	0.032	0.023	0.016
11	Metal Products	0.010	0.003	0.011	0.006	0.002	0.005	0.011	0.004	0.010	0.007	0.011	0.013	0.008	0.007	0.008
12	General Machinery	0.027	0.004	0.008	0.026	0.004	0.008	0.032	0.005	0.011	0.028	0.012	0.012	0.025	0.009	0.008
13	Special Purpose Machinery	0.007	0.003	0.007	0.006	0.005	0.012	0.009	0.004	0.009	0.010	0.015	0.017	0.009	0.008	0.008
14	Transport Equipment Machinery	0.009	0.001	0.006	0.007	0.001	0.005	0.010	0.002	0.007	0.008	0.007	0.010	0.010	0.004	0.006
15	Electric Equipment and Machinery	0.006	0.002	0.006	0.006	0.002	0.006	0.007	0.002	0.008	0.006	0.007	0.010	0.009	0.006	0.006
16	Communication Equipment, Computer and other Electronic Equipment	0.004	0.003	0.007	0.005	0.003	0.008	0.004	0.003	0.009	0.003	0.007	0.011	0.004	0.007	0.007
17	Instruments and Meters	0.002	0.001	0.002	0.001	0.002	0.005	0.002	0.001	0.003	0.003	0.003	0.004	0.002	0.002	0.002
18	Other Manufacture, Waster and Flotsam	0.011	0.000	0.003	0.010	0.000	0.002	0.011	0.000	0.002	0.018	0.001	0.003	0.004	0.001	0.002
19	Repair Services of Metal Products Equipment and Machinery	0.044	0.000	0.000	0.046	0.000	0.000	0.079	0.000	0.001	0.050	0.007	0.001	0.046	0.001	0.000
20	Production and Supply of Electric Power, Steam and Hot Water	0.000	0.000	0.023	0.001	0.000	0.023	0.001	0.000	0.045	0.002	0.001	0.039	0.001	0.000	0.027
21	Production and Supply of Gas	0.001	0.007	0.001	0.001	0.009	0.001	0.002	0.014	0.001	0.002	0.041	0.001	0.001	0.029	0.001
22	Production and Supply of Tap Water	0.001	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000
23	Construction	0.041	0.000	0.001	0.023	0.000	0.000	0.042	0.001	0.001	0.051	0.001	0.001	0.028	0.000	0.001
24	Wholesale and Retail Trade	0.001	0.001	0.024	0.000	0.001	0.013	0.001	0.001	0.024	0.001	0.002	0.031	0.000	0.002	0.021
25	Traffic, Transport, Storage and Mail	0.007	0.008	0.021	0.005	0.007	0.014	0.007	0.010	0.022	0.007	0.041	0.030	0.003	0.016	0.019
26	Accommodation and Restaurants	0.020	0.010	0.006	0.018	0.007	0.005	0.023	0.014	0.006	0.024	0.033	0.007	0.012	0.018	0.005
27	Information Transfer, Computer and Software Services	0.009	0.004	0.004	0.007	0.003	0.003	0.010	0.005	0.005	0.011	0.007	0.006	0.007	0.004	0.004
28	Banking	0.034	0.001	0.039	0.025	0.001	0.027	0.032	0.002	0.030	0.033	0.005	0.034	0.018	0.003	0.031
29	Real Estate Trade	0.006	0.016	0.008	0.004	0.010	0.005	0.006	0.015	0.006	0.006	0.052	0.008	0.003	0.031	0.006
30	Renting and Leasing, Business Services	0.006	0.001	0.022	0.004	0.001	0.016	0.006	0.001	0.019	0.006	0.009	0.022	0.005	0.004	0.018

(Continued on following page)

TABLE 4 | (*Continued*) Value-added creation effects of mining industry.

Number	Sectors	Coal			Crude petroleum and natural gas			Metal ores			Non-metallicmineral mining			Entire mining industry		
		Value			Value			Value			Value			Value		
		2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017
31	Research and Development	0.002	0.007	0.000	0.002	0.005	0.000	0.001	0.008	0.000	0.001	0.017	0.000	0.001	0.013	0.000
32	Technical Service	0.008	0.003	0.006	0.008	0.005	0.005	0.010	0.004	0.007	0.008	0.012	0.009	0.006	0.006	0.006
33	Management of Water Conservancy, Environment and Public Establishment	0.001	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.001	0.001	0.001
34	Resident Services, Repair and Other Services	0.008	0.004	0.006	0.005	0.003	0.003	0.006	0.003	0.003	0.006	0.007	0.005	0.005	0.004	0.004
35	Education	0.002	0.001	0.000	0.001	0.000	0.000	0.001	0.001	0.000	0.003	0.001	0.000	0.001	0.001	0.000
36	Health Care and Social Work Activities	0.002	0.000	0.000	0.001	0.000	0.000	0.002	0.000	0.000	0.002	0.000	0.000	0.001	0.000	0.000
37	Culture, Sports and Entertainment	0.002	0.001	0.001	0.001	0.001	0.001	0.003	0.001	0.002	0.003	0.002	0.001	0.002	0.001	0.001
38	Public Management, Social Security and Social Organization	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.001	0.000	0.000	0.000
39	Coal				0.016	0.011	0.007	0.025	0.017	0.015	0.019	0.034	0.018			
40	Crude Petroleum and Natural Gas	0.027	0.003	0.004				0.058	0.008	0.012	0.053	0.046	0.014			
41	Metal Ores	0.011	0.004	0.004	0.010	0.004	0.003				0.007	0.013	0.005			
42	Non-Metallic Mineral Mining	0.002	0.002	0.003	0.002	0.022	0.063	0.003	0.002	0.004						
	Total	0.426	0.131	0.300	0.356	0.144	0.322	0.536	0.179	0.368	0.537	0.539	0.460	0.333	0.271	0.276

In terms of dispersion sensitivity, the forward linkage examines the change in one mining sector when the ultimate usage in the remaining sectors increases by one unit. A row vector analysis of the Leontief inverse matrix is reflected in the forward linkage. The following is an expression for the forward linkage effect:

$$\mathrm{E_i} = \sum_{i=1}^{n} \mathrm{b_{ij}} \Big/ \left((1/n) \sum_{i=1}^{n} \sum_{j=1}^{n} b_{ij} \right) \tag{7}$$

Where $\mathrm{E_i}$ denotes the backward linkage effect, $\sum_{i=1}^{n} \mathrm{b_{ij}}$ is the sum of the Leontief inverse matrix row vector.

3.5 Supply-Driven Model

Equation 2 in the IO table can also be expressed as $\mathrm{X'} = \mathrm{V'}\,(\mathrm{I} - \mathrm{R})^{-1}$. The upper mark ($'$) denotes the transposition of the given matrix, R represents the direct distribution coefficient matrix, and $(\mathrm{I} - \mathrm{R^e})^{-1}$ denotes the complete distribution matrix for eliminating the row and column of the MI (Giarratani, 1976; Davis and Salkin, 1984). Thus, the supply shortage effect can be expressed as follows:

$$\Delta \mathrm{X}^{\mathrm{e'}} = \mathrm{R_H^e} \Delta \mathrm{X_H}\,(\mathrm{I} - \mathrm{R^e})^{-1} \tag{8}$$

Where $\Delta \mathrm{X}^{\mathrm{e'}}$ denotes the supply shortage effect; In addition, this approach may also be used to calculate the cost of loss in the MI's supply shortfall.

3.6 Price-Side Model

The price-side model or Leontief price model can be used to assess the impact of price changes in one sector on the price levels of other sectors (Hirschman, 1958). The IO price-side model does not take into account the impact of changes in net wages or production taxes and operating earnings on prices (Yoo and Yoo, 2009). The price-side effect can be modified as follows:

$$\Delta \bar{\mathrm{P}}_{\mathrm{e}} = \left(I - \mathrm{A}^{\mathrm{e'}} \right)^{-1} \mathrm{A}_{\mathrm{H}}^{\mathrm{e'}}\, \Delta \bar{\mathrm{P}}_{\mathrm{H}} \tag{9}$$

where $\Delta \bar{\mathrm{P}}_{\mathrm{e}}$ denotes the vector of the price change excluding sector H; $\Delta \bar{\mathrm{P}}_{\mathrm{H}}$ presents a scalar of the price change of sector H. Assuming that the cost change in each sector is able to completely transferred, plus the annual sectorial outputs are offered, how the cost change of the MI sector will drive the wholesale price changes on the economic system can be investigated by **Eq. 9**.

4 RESULTS AND DISCUSSION

4.1 Data

The MI is divided into four sub-sectors in the basic scale IO table: coal, crude petroleum and natural gas, metal ores, and non-metallic mineral mining. The sector categorization utilized in this study is shown in **Table 2**, comprising 38 large-scale sectors and four MI sub-sectors. Consequently, five analysis findings are presented: one for the whole MI and one for each of the four sub-sectors. In addition, all findings are based on research identifying the MI sector as exogenous rather than endogenous.

TABLE 5 | Wage-inducing effects of mining industry.

Number	Sectors	Coal			Crude petroleum and natural gas			Metal ores			Non-metallic mineral mining			Entire mining industry		
		Value			Value			Value			Value			Value		
		2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017
1	Products and Service of Farming, Forestry, Animal Husbandry and Fishery	0.020	0.015	0.004	0.012	0.012	0.003	0.018	0.018	0.003	0.020	0.022	0.004	0.004	0.003	0.003
2	Food and Tobacco	0.002	0.002	0.003	0.001	0.002	0.003	0.002	0.002	0.004	0.002	0.003	0.004	0.002	0.003	0.003
3	Textile Products	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001
4	Manufacture of Leather, Fur, Feather and Its Products	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
5	Timber Processing and Furniture	0.002	0.003	0.003	0.001	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001
6	Paper making, Printing, Cultural and Educational Goods	0.001	0.002	0.003	0.001	0.001	0.002	0.002	0.003	0.003	0.002	0.002	0.003	0.002	0.002	0.002
7	Processing of Petroleum, Coking, Processing of Nucleus Fuel	0.003	0.002	0.003	0.004	0.003	0.005	0.007	0.004	0.005	0.006	0.004	0.006	0.006	0.005	0.003
8	Chemical Products	0.006	0.006	0.008	0.007	0.007	0.013	0.010	0.010	0.012	0.016	0.015	0.019	0.010	0.010	0.010
9	Nonmetal Mineral Products	0.002	0.002	0.001	0.002	0.001	0.002	0.002	0.002	0.001	0.006	0.005	0.004	0.002	0.002	0.001
10	Products of Smelting and Pressing of Metals	0.009	0.007	0.008	0.009	0.007	0.007	0.008	0.006	0.007	0.006	0.008	0.010	0.010	0.009	0.007
11	Metal Products	0.003	0.003	0.005	0.002	0.002	0.003	0.004	0.004	0.005	0.002	0.005	0.006	0.003	0.003	0.004
12	General Machinery	0.010	0.004	0.004	0.010	0.004	0.004	0.012	0.005	0.005	0.010	0.006	0.005	0.009	0.004	0.004
13	Special Purpose Machinery	0.003	0.003	0.003	0.002	0.005	0.006	0.004	0.004	0.004	0.004	0.007	0.008	0.003	0.004	0.004
14	Transport Equipment Machinery	0.003	0.001	0.003	0.002	0.001	0.003	0.003	0.002	0.003	0.002	0.003	0.004	0.003	0.002	0.003
15	Electric Equipment and Machinery	0.002	0.002	0.003	0.002	0.002	0.003	0.002	0.002	0.003	0.002	0.003	0.004	0.003	0.002	0.003
16	Communication Equipment, Computer and other Electronic Equipment	0.001	0.003	0.004	0.002	0.003	0.004	0.002	0.003	0.004	0.001	0.004	0.005	0.002	0.003	0.004
17	Instruments and Meters	0.001	0.001	0.001	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
18	Other Manufacture, Waster and Flotsam	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.001	0.000	0.001
19	Repair Services of Metal Products Equipment and Machinery	0.011	0.000	0.000	0.011	0.000	0.000	0.019	0.000	0.000	0.012	0.000	0.000	0.012	0.001	0.000
20	Production and Supply of Electric Power, Steam and Hot Water	0.000	0.000	0.008	0.000	0.000	0.009	0.001	0.000	0.015	0.001	0.001	0.013	0.000	0.000	0.009
21	Production and Supply of Gas	0.001	0.007	0.000	0.001	0.009	0.000	0.001	0.014	0.000	0.001	0.012	0.001	0.000	0.009	0.000
22	Production and Supply of Tap Water	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	Construction	0.011	0.000	0.000	0.006	0.000	0.000	0.011	0.001	0.000	0.013	0.001	0.000	0.008	0.000	0.000
24	Wholesale and Retail Trade	0.000	0.001	0.011	0.000	0.001	0.006	0.000	0.001	0.011	0.000	0.001	0.014	0.000	0.001	0.010
25	Traffic, Transport, Storage and Mail	0.001	0.008	0.010	0.001	0.007	0.007	0.001	0.010	0.010	0.001	0.012	0.014	0.001	0.006	0.009
26	Accommodation and Restaurants	0.005	0.010	0.003	0.004	0.007	0.002	0.006	0.014	0.003	0.006	0.016	0.004	0.003	0.008	0.003
27	Information Transfer, Computer and Software Services	0.003	0.004	0.002	0.002	0.003	0.002	0.003	0.005	0.002	0.003	0.005	0.002	0.002	0.002	0.002
28	Banking	0.009	0.001	0.018	0.006	0.001	0.013	0.008	0.002	0.013	0.008	0.002	0.015	0.005	0.001	0.014
29	Real Estate Trade	0.001	0.016	0.004	0.000	0.010	0.002	0.001	0.015	0.003	0.001	0.016	0.004	0.001	0.010	0.003
30	Renting and Leasing, Business Services	0.002	0.001	0.014	0.001	0.001	0.009	0.002	0.001	0.011	0.002	0.001	0.012	0.002	0.001	0.011

(Continued on following page)

TABLE 5 | (*Continued*) Wage-inducing effects of mining industry.

Number	Sectors	Coal			Crude petroleum and natural gas			Metal ores			Non-metallic mineral mining			Entire mining industry		
		Value			Value			Value			Value			Value		
		2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017
31	Research and Development	0.001	0.007	0.000	0.001	0.005	0.000	0.001	0.008	0.000	0.001	0.008	0.000	0.000	0.006	0.000
32	Technical Service	0.004	0.003	0.003	0.004	0.005	0.002	0.005	0.004	0.004	0.004	0.006	0.005	0.003	0.003	0.003
33	Management of Water Conservancy, Environment and Public Establishment	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000
34	Resident Services, Repair and Other Services	0.002	0.004	0.004	0.002	0.003	0.002	0.002	0.003	0.001	0.002	0.005	0.003	0.001	0.002	0.003
35	Education	0.002	0.001	0.000	0.001	0.000	0.000	0.001	0.001	0.000	0.002	0.001	0.000	0.001	0.000	0.000
36	Health Care and Social Work Activities	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000
37	Culture, Sports and Entertainment	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
38	Public Management, Social Security and Social Organization	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000
39	Coal				0.008	0.011	0.003	0.012	0.016	0.005	0.009	0.017	0.007			
40	Crude Petroleum and Natural Gas	0.006	0.003	0.002				0.013	0.008	0.003	0.012	0.009	0.003			
41	Metal Ores	0.004	0.004	0.002	0.004	0.004	0.001				0.003	0.005	0.002			
42	Non-Metallic Mineral Mining	0.001	0.002	0.002	0.001	0.022	0.033	0.001	0.002	0.001						
	Total	0.137	0.131	0.145	0.117	0.144	0.158	0.169	0.179	0.149	0.171	0.212	0.190	0.106	0.108	0.125

4.2 Results of the Demand-Driven Model

The sectoral impacts of mining investment are summarized in **Tables 3–5**. **Table 3** shows the results of the demand-driven model in analyzing the MI's production-inducing impact. The sum of $1 of production or investment in the other sectors is $0.896–$1.360 (coal), $0.880–$1.214 (crude petroleum and natural gas), $1.185–$1.711 (metal ores), and $1.522–$1.716 (non-metallic mineral mining), respectively. Thus, the overall production-inducing effect of $1 of mining production or investment on other sectors is $0.862–$1.171.

Table 4 evaluates an impact analysis of the MI's value-added creation on other sectors. Production or investment of $1 in the coal, crude petroleum and natural gas, metal ores, and non-metallic mineral mining sectors, respectively, generates $0.131–$0.426, $0.144–$0.356, $0.179–$0.536, and $0.460–$0.539 of value-added for other sectors. Thus, the effect of $1 production or investment in value-added creation in the entire MI on other sectors is $0.271–$0.333.

Table 5 presents the conclusions of calculating the MI's wage-inducing effects. Production or investment of $1 in the coal, crude petroleum and natural gas, metal ores, and non-metallic mineral mining sectors, respectively, produces $0.131–$0.145, $0.117–$0.158, $0.149–$0.179, and $0.171–$0.212 of wages in other sectors. Thus, the wage-inducing effect of $1 of MI production or investment on other sectors is $0.106–$0.125.

4.3 Results of the Supply-Driven Model

Table 6 depicts the costs of sectoral mining supply shortages in 2007, 2012, and 2017. Each figure represents how much output loss would be suffered in other sectors in the case of a $1 supply failure in the MI. The total impact of a supply failure in each MI sub-sector on the national economy can be obtained by combining the effects of a supply shortfall in each sector. The supply shortage effects of the coal, crude petroleum and natural gas, metal ores, non-metallic mineral mining sectors, and the entire MI is calculated to be $4.026–$5.280, $5.045–$9.553, $9.300–$13.755, $5.294–$6.557, and $4.383–$5.949, respectively. All of the results are significantly greater than one. In other words, a $1 failure in MI supply could substantially influence the overall national economy, implying that MI products are critical to manufacturing in other industries.

4.4 Results of the Price-Side Model

Table 7 shows the effect of a 10% rise in the price of MI products on the price levels of other sectors. For example, in the food and tobacco industry, the MI price-pervasive effect is given as 0.037–0.063, meaning that a 10% rise in the price of MI products increases the price of food and tobacco by 0.037%–0.063%.

When calculating the impact of price changes in the mining sector on the whole economy, the percentage values for each industry are summed and averaged, and the total impact is overestimated. Therefore, the price-pervasive effect on the economy can be calculated by weighted averaging of each sector's price-pervasive

TABLE 6 | Supply shortage effects of mining industry.

Number	Sectors	Coal			Crude petroleum and natural gas			Metal ores			Non-metallicmineral mining			Entire mining industry		
		Value			Value			Value			Value			Value		
		2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017
1	Products and Service of Farming, Forestry, Animal Husbandry and Fishery	0.038	0.051	0.042	0.041	0.121	0.037	0.060	0.066	0.053	0.062	0.055	0.053	0.048	0.050	0.046
2	Food and Tobacco	0.040	0.063	0.041	0.042	0.114	0.028	0.067	0.072	0.055	0.052	0.048	0.045	0.049	0.050	0.042
3	Textile Products	0.042	0.105	0.036	0.032	0.168	0.027	0.052	0.071	0.055	0.043	0.054	0.039	0.041	0.051	0.040
4	Manufacture of Leather, Fur, Feather and Its Products	0.028	0.088	0.020	0.026	0.153	0.020	0.064	0.043	0.038	0.033	0.024	0.033	0.036	0.025	0.027
5	Timber Processing and Furniture	0.043	0.107	0.026	0.040	0.177	0.023	0.087	0.081	0.049	0.085	0.075	0.095	0.059	0.063	0.046
6	Paper making, Printing, Cultural and Educational Goods	0.079	0.140	0.064	0.075	0.196	0.044	0.138	0.131	0.081	0.133	0.093	0.095	0.098	0.085	0.069
7	Processing of Petroleum, Coking, Processing of Nucleus Fuel	0.311	0.194	0.237	1.515	2.108	1.783	0.636	0.603	0.477	0.286	0.204	0.206	0.767	0.774	0.613
8	Chemical Products	0.215	0.281	0.224	0.339	0.532	0.321	0.269	0.277	0.213	0.582	0.354	0.290	0.319	0.274	0.254
9	Nonmetal Mineral Products	0.183	0.270	0.205	0.062	0.276	0.038	0.169	0.183	0.105	0.687	0.771	0.802	0.211	0.218	0.248
10	Products of Smelting and Pressing of Metals	0.261	0.329	0.200	0.120	0.299	0.060	2.352	2.364	2.279	0.225	0.140	0.167	0.651	0.700	0.612
11	Metal Products	0.084	0.215	0.048	0.083	0.233	0.046	0.283	0.217	0.146	0.162	0.117	0.150	0.138	0.114	0.089
12	General Machinery	0.095	0.162	0.050	0.108	0.201	0.060	0.322	0.262	0.160	0.121	0.078	0.092	0.151	0.119	0.084
13	Special Purpose Machinery	0.048	0.158	0.039	0.049	0.201	0.066	0.131	0.140	0.141	0.059	0.056	0.065	0.068	0.080	0.071
14	Transport Equipment Machinery	0.088	0.141	0.017	0.067	0.194	0.026	0.174	0.054	0.044	0.095	0.026	0.034	0.101	0.030	0.028
15	Electric Equipment and Machinery	0.038	0.190	0.061	0.040	0.236	0.035	0.088	0.121	0.082	0.045	0.064	0.084	0.050	0.075	0.064
16	Communication Equipment, Computer and other Electronic Equipment	0.176	0.115	0.027	0.176	0.177	0.025	0.346	0.086	0.055	0.163	0.038	0.047	0.204	0.050	0.036
17	Instruments and Meters	0.046	0.123	0.158	0.043	0.175	0.132	0.146	0.319	0.191	0.074	0.126	0.127	0.072	0.233	0.149
18	Other Manufacture, Waster and Flotsam	0.248	0.142	0.146	0.150	0.232	0.072	1.718	0.132	1.287	0.312	0.061	0.163	0.539	0.082	0.379
19	Repair Services of Metal Products Equipment and Machinery	0.695	0.039	0.150	0.279	0.065	0.109	0.679	2.807	0.256	0.269	0.248	0.184	0.493	0.864	0.167
20	Production and Supply of Electric Power, Steam and Hot Water	0.132	0.168	0.616	0.228	0.213	0.205	0.431	0.550	0.501	0.183	0.217	0.206	0.233	0.302	0.433
21	Production and Supply of Gas	0.118	0.648	0.069	0.125	0.262	0.300	0.319	0.657	0.114	0.156	0.215	0.073	0.168	0.549	0.130
22	Production and Supply of Tap Water	0.007	0.089	0.054	0.002	0.285	0.053	0.003	0.142	0.107	0.220	0.061	0.081	0.033	0.119	0.069
23	Construction	0.088	0.150	0.004	0.108	0.127	0.001	0.258	0.199	0.002	0.155	0.085	0.213	0.144	0.107	0.038
24	Wholesale and Retail Trade	0.062	0.165	0.049	0.067	0.217	0.055	0.168	0.009	0.117	0.098	0.129	0.093	0.092	0.021	0.073
25	Traffic, Transport, Storage and Mail	0.057	0.027	0.059	0.056	0.062	0.071	0.210	0.125	0.155	0.084	0.067	0.107	0.093	0.075	0.092
26	Accommodation and Restaurants	0.053	0.079	0.037	0.064	0.422	0.040	0.167	0.253	0.096	0.087	0.109	0.070	0.086	0.132	0.056
27	Information Transfer, Computer and Software Services	0.049	0.042	0.019	0.062	0.084	0.018	0.140	0.122	0.043	0.078	0.056	0.041	0.078	0.066	0.028

(Continued on following page)

TABLE 6 | (*Continued*) Supply shortage effects of mining industry.

Number	Sectors	Coal			Crude petroleum and natural gas			Metal ores			Non-metallicmineral mining			Entire mining industry		
		Value			Value			Value			Value			Value		
		2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017
28	Banking	0.108	0.055	0.065	0.100	0.088	0.065	0.267	0.068	0.182	0.132	0.035	0.103	0.144	0.037	0.098
29	Real Estate Trade	0.019	0.028	0.018	0.020	0.068	0.019	0.046	0.310	0.045	0.029	0.105	0.032	0.027	0.159	0.027
30	Renting and Leasing, Business Services	0.067	0.018	0.059	0.082	0.037	0.072	0.154	0.050	0.137	0.107	0.020	0.105	0.097	0.027	0.088
31	Research and Development	0.103	0.076	0.001	0.124	0.245	0.000	0.323	0.232	0.002	0.149	0.101	0.000	0.162	0.129	0.001
32	Technical Service	0.105	0.080	0.031	0.127	0.194	0.031	0.283	0.168	0.073	0.153	0.089	0.148	0.154	0.090	0.060
33	Management of Water Conservancy, Environment and Public Establishment	0.043	0.083	0.031	0.043	0.164	0.026	0.089	0.099	0.066	0.047	0.037	0.034	0.056	0.056	0.038
34	Resident Services, Repair and Other Services	0.066	0.065	0.032	0.062	0.118	0.033	0.151	0.117	0.065	0.072	0.054	0.056	0.086	0.067	0.045
35	Education	0.009	0.028	0.004	0.006	0.061	0.002	0.015	0.010	0.004	0.010	0.004	0.003	0.010	0.006	0.003
36	Health Care and Social Work Activities	0.018	0.122	0.003	0.012	0.225	0.003	0.039	0.005	0.005	0.018	0.002	0.002	0.021	0.004	0.004
37	Culture, Sports and Entertainment	0.050	0.047	0.022	0.047	0.095	0.024	0.124	0.114	0.058	0.068	0.046	0.035	0.069	0.060	0.032
38	Public Management, Social Security and Social Organization	0.005	0.041	0.003	0.002	0.109	0.002	0.003	0.009	0.003	0.003	0.003	0.003	0.003	0.005	0.003
39	Coal				0.373	0.111	0.361	0.740	0.834	0.636	0.329	0.306	0.335			
40	Crude Petroleum and Natural Gas	0.478	0.085	0.456				0.979	1.200	0.855	0.497	0.641	0.581			
41	Metal Ores	0.433	0.144	0.375	0.219	0.253	0.129				0.395	0.280	0.335			
42	Non-Metallic Mineral Mining	0.161	0.127	0.226	0.143	0.258	0.580	0.276	0.453	0.268						
Total		4.990	5.280	4.026	5.355	9.553	5.045	12.967	13.755	9.300	6.557	5.294	5.428	5.852	5.949	4.383

effect on each sector's output. For example, the weighted averages of the price-pervasive effect of a 10% increase in the price of coal, crude petroleum and natural gas, metal ores, and non-mineral mining sectors, and the entire MI sector, are estimated to be 0.033%–0.055%, 0.041%–0.087%, 0.033%–0.049%, 0.014%–0.018%, and 0.108%–0.171%, respectively.

4.5 The Inter-Industry Linkage Effect

Table 8 shows the mining sector's inter-industry forward and backward linkage effects in 2007, 2012, and 2017. Two interesting facts were uncovered. First, except for metal ores (2007), the mining sector's sensitivity to dispersion was less than one, implying that the MI's forward linkage impact is less than the total of other industries. In other words, the MI is unaffected by changes in other industries and contributes significant input to the country's economy. Second, the MI's dispersion power is greater than one, indicating that mining exerts considerable economic influence on other industries. Therefore, the MI should be classified as a final manufacturer, as it has high backward and low forward linkages (Ivanova, 2014).

4.6 Discussion of the Results

This paper investigated the influence of the four MI sectors, including the overall MI sector, on the Chinese national economy from 2007 to 2017 using extensive IO analyses, including the demand-driven, supply-driven, and price-side models, and inter-industry linkage effect. The economic consequences of the IO analysis had three significant implications.

First, we used the demand-driven model to evaluate the MI's economic consequences. As a result, the production-inducing effects, value-added creation effects, and wage-inducing effects of \$1 of MI production or investment on the national economy were calculated to be \$0.862–\$1.171, \$0.271–\$0.333, and \$0.106–\$0.125, respectively. The figures on sectoral impacts of MI investments from the demand-driven model can be interpreted as benefits which ensue from development projects. As a result, policy decisions on whether to conduct a proposed MI project or not could, in principle, be deduced from an examination of costs and benefits associated with the project (Heo et al., 2010).

Since the study also estimated the economic effects for each sector, it is possible to examine the impacts of increased production or investment in the MI on each sector. In particular, the chemical products sector is the most affected by production or investment in the MI. This means that if the MI is activated, the Chemical Products sector will be activated the most. That is, the MI demands output from the Chemical Products sector more than it does from other sectors. However, production

TABLE 7 | Price-pervasive effects of 10% increase in the price for the output of mining industry.

Number	Sectors	Coal			Crude petroleum and natural gas			Metal ores			Non-metallicmineral mining			Entire mining industry		
		Value			Value			Value			Value			Value		
		2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017
1	Products and Service of Farming, Forestry, Animal Husbandry and Fishery	0.014	0.018	0.011	0.031	0.032	0.016	0.006	0.005	0.004	0.004	0.006	0.004	0.049	0.052	0.031
2	Food and Tobacco	0.020	0.022	0.015	0.037	0.031	0.016	0.009	0.007	0.005	0.005	0.006	0.005	0.063	0.057	0.037
3	Textile Products	0.035	0.038	0.029	0.058	0.043	0.028	0.013	0.010	0.008	0.009	0.009	0.007	0.102	0.085	0.064
4	Manufacture of Leather, Fur, Feather and Its Products	0.029	0.032	0.024	0.053	0.039	0.027	0.012	0.010	0.008	0.007	0.008	0.007	0.089	0.077	0.057
5	Timber Processing and Furniture	0.036	0.041	0.024	0.056	0.047	0.027	0.024	0.021	0.015	0.008	0.010	0.008	0.109	0.102	0.066
6	Paper making, Printing, Cultural and Educational Goods	0.037	0.054	0.038	0.060	0.051	0.031	0.021	0.036	0.026	0.009	0.013	0.010	0.112	0.133	0.095
7	Processing of Petroleum, Coking, Processing of Nucleus Fuel	0.087	0.096	0.079	0.649	0.644	0.531	0.022	0.019	0.009	0.005	0.071	0.075	0.682	0.689	0.594
8	Chemical Products	0.061	0.080	0.054	0.148	0.121	0.078	0.025	0.024	0.017	0.033	0.029	0.023	0.237	0.217	0.153
9	Nonmetal Mineral Products	0.099	0.118	0.096	0.086	0.079	0.048	0.029	0.035	0.025	0.089	0.101	0.095	0.265	0.287	0.237
10	Products of Smelting and Pressing of Metals	0.071	0.096	0.069	0.101	0.088	0.056	0.237	0.268	0.252	0.010	0.016	0.013	0.359	0.401	0.349
11	Metal Products	0.054	0.074	0.045	0.078	0.067	0.040	0.118	0.125	0.108	0.012	0.014	0.010	0.227	0.240	0.182
12	General Machinery	0.045	0.054	0.032	0.070	0.058	0.032	0.088	0.088	0.065	0.009	0.012	0.009	0.183	0.181	0.123
13	Special Purpose Machinery	0.038	0.053	0.030	0.065	0.057	0.031	0.068	0.082	0.053	0.009	0.012	0.009	0.157	0.175	0.110
14	Transport Equipment Machinery	0.046	0.046	0.027	0.076	0.054	0.029	0.099	0.071	0.049	0.011	0.012	0.009	0.201	0.156	0.101
15	Electric Equipment and Machinery	0.033	0.061	0.038	0.059	0.065	0.036	0.038	0.104	0.080	0.011	0.016	0.013	0.123	0.211	0.148
16	Communication Equipment, Computer and other Electronic Equipment	0.037	0.039	0.025	0.063	0.048	0.025	0.042	0.041	0.034	0.013	0.011	0.009	0.135	0.119	0.083
17	Instruments and Meters	0.040	0.042	0.026	0.062	0.048	0.026	0.043	0.051	0.037	0.012	0.013	0.010	0.137	0.132	0.088
18	Other Manufacture, Waster and Flotsam	0.006	0.079	0.015	0.009	0.062	0.018	0.006	0.041	0.016	0.001	0.014	0.005	0.020	0.169	0.047
19	Repair Services of Metal Products Equipment and Machinery	0.185	0.016	0.035	0.088	0.018	0.036	0.022	0.014	0.061	0.004	0.004	0.009	0.267	0.044	0.126
20	Production and Supply of Electric Power, Steam and Hot Water	0.095	0.062	0.210	0.582	0.061	0.041	0.022	0.081	0.014	0.004	0.012	0.009	0.629	0.185	0.254
21	Production and Supply of Gas	0.050	0.295	0.049	0.049	0.076	0.511	0.015	0.021	0.007	0.005	0.012	0.071	0.105	0.359	0.543
22	Production and Supply of Tap Water	0.051	0.106	0.039	0.080	0.552	0.020	0.060	0.020	0.009	0.038	0.060	0.005	0.200	0.616	0.066
23	Construction	0.030	0.064	0.040	0.149	0.035	0.038	0.016	0.013	0.045	0.004	0.007	0.032	0.177	0.104	0.138
24	Wholesale and Retail Trade	0.020	0.060	0.006	0.058	0.062	0.011	0.015	0.066	0.004	0.004	0.034	0.002	0.086	0.190	0.020
25	Traffic, Transport, Storage and Mail	0.015	0.011	0.017	0.025	0.018	0.062	0.014	0.006	0.008	0.003	0.003	0.010	0.050	0.032	0.084
26	Accommodation and Restaurants	0.013	0.034	0.012	0.032	0.133	0.017	0.008	0.016	0.004	0.002	0.016	0.004	0.050	0.167	0.033
27	Information Transfer, Computer and Software Services	0.018	0.016	0.009	0.035	0.025	0.010	0.008	0.005	0.007	0.004	0.004	0.003	0.057	0.043	0.025
28	Banking	0.008	0.020	0.006	0.019	0.025	0.010	0.005	0.017	0.004	0.001	0.005	0.002	0.029	0.057	0.019
29	Real Estate Trade	0.006	0.011	0.004	0.015	0.020	0.006	0.005	0.006	0.002	0.002	0.003	0.001	0.025	0.035	0.012
30	Renting and Leasing, Business Services	0.026	0.007	0.015	0.062	0.012	0.029	0.023	0.005	0.012	0.006	0.002	0.006	0.102	0.022	0.055

(Continued on following page)

TABLE 7 | (*Continued*) Price-pervasive effects of 10% increase in the price for the output of mining industry.

Number	Sectors	Coal			Crude petroleum and natural gas			Metal ores			Non-metallicmineral mining			Entire mining industry		
		Value			Value			Value			Value			Value		
		2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017	2007	2012	2017
31	Research and Development	0.025	0.029	0.019	0.048	0.072	0.023	0.028	0.022	0.014	0.008	0.011	0.007	0.096	0.114	0.055
32	Technical Service	0.017	0.029	0.015	0.042	0.055	0.029	0.018	0.023	0.013	0.004	0.010	0.006	0.071	0.099	0.056
33	Management of Water Conservancy, Environment and Public Establishment	0.024	0.034	0.020	0.051	0.047	0.024	0.016	0.015	0.009	0.006	0.010	0.007	0.086	0.090	0.053
34	Resident Services, Repair and Other Services	0.025	0.024	0.014	0.051	0.034	0.019	0.016	0.015	0.009	0.006	0.007	0.005	0.087	0.068	0.042
35	Education	0.021	0.011	0.008	0.035	0.018	0.010	0.010	0.005	0.003	0.004	0.003	0.003	0.062	0.032	0.021
36	Health Care and Social Work Activities	0.038	0.038	0.025	0.074	0.054	0.033	0.019	0.014	0.010	0.016	0.012	0.010	0.130	0.101	0.069
37	Culture, Sports and Entertainment	0.020	0.019	0.011	0.040	0.027	0.015	0.011	0.009	0.005	0.006	0.005	0.004	0.068	0.052	0.031
38	Public Management, Social Security and Social Organization	0.019	0.017	0.009	0.040	0.032	0.011	0.010	0.008	0.004	0.004	0.005	0.003	0.065	0.053	0.024
39	Coal				0.050	0.032	0.016	0.030	0.027	0.017	0.005	0.009	0.009			
40	Crude Petroleum and Natural Gas	0.032	0.036	0.017				0.026	0.022	0.009	0.005	0.112	0.141			
41	Metal Ores	0.055	0.065	0.042	0.107	0.074	0.050				0.007	0.015	0.013			
42	Non-Metallic Mineral Mining	0.041	0.059	0.045	0.094	0.076	0.052	0.020	0.028	0.018						
Weighted average		0.046	0.055	0.033	0.087	0.074	0.041	0.048	0.049	0.033	0.014	0.018	0.015	0.171	0.168	0.108

TABLE 8 | The inter-industry linkage effect.

Sectors	Sensitivity of dispersion			Power of dispersion			Overall effects		
	Value			Value			Value		
	2007	2012	2017	2007	2012	2017	2007	2012	2017
Coal	0.906	0.837	0.833	1.624	1.720	1.688	2.530	2.556	2.521
Crude Petroleum and Natural Gas	0.784	0.744	0.701	2.564	3.165	2.904	3.347	3.910	3.606
Metal Ores	1.040	0.973	0.912	2.462	2.495	2.661	3.502	3.468	3.573
Non-Metallic Mineral Mining	0.985	0.936	0.948	1.252	1.679	1.556	2.237	2.616	2.504
Entire Mining Industry	0.896	0.846	0.825	2.228	2.467	2.350	3.124	3.312	3.175

and investment in the MI have little influence on the Production and Supply of Tap Water sector.

Second, we used the supply-driven model to investigate the MI impact on supply shortages. Using the supply-driven model in IO analysis has increased in recent years due to the increased frequency of global natural disasters, such as COVID-19 pandemics and earthquakes, as it is helpful in setting economic reliability standards in the MI industry, but also in determining pricing and load management strategies (Howe et al., 1994). The effects of $1 of supply shortages in the Coal, Crude Petroleum and Natural Gas, Metal Ores, Non-Metallic Mineral Mining sectors, and the entire MI on the national economy were calculated to be $4.0262–$5.280, $5.045–$9.553, $9.300–$13.755, $5.294–$6.557, and $4.383–$5.949, respectively.

The results demonstrate that these numbers are much higher than one, indicating that MI production failure would significantly negatively impact the national economy because MI output is a primary input in other sectors' manufacturing. Therefore, the government should make every effort to guarantee a steady MI supply, as a MI supply deficit could substantially negatively impact the economy (Feng et al., 2019). Supply shortages effects of the Metal Ores sector would be the most serious in the four MI sub-sectors.

Third, we employed a price-side model to analyze the impact of increased MI pricing on other industries. In addition, as the MI is exogenous in classic models, we attempted to consider the MI as an exogenous sector in this research. The impacts of a 10% price increase in the MI sector on the national economy were 0.033%–0.055%, 0.041%–0.087%, 0.033%–0.049%, 0.014%–0.018%, and 0.108%–0.171%, for the Coal, Crude Petroleum and Natural Gas, Metal Ores, Non-Metallic Mineral Mining sectors, and the entire MI, respectively. Thus, the price effects were minor overall.

For some reasons, there may be changes in the price of the output of the MI. A rise in raw material prices or labor expenses for the MI, tighter government regulations linked to safety and the environmental protection for the MI, or a decrease in yield due to a natural reduction in mineral deposits may cause an increase in the price of production in the MI (Ilankoon et al., 2018). Therefore, these results can be useful in formulating a MI pricing strategy based on the price-side model. Furthermore, it is possible to predict the sectors with significant or minor influence because mining costs have a high and low impact on different industry sectors. For example, the price effect of the MI is the largest for the Products of the Smelting and Metal Pressing sector.

5 CONCLUSION AND IMPLICATIONS

5.1 Main Findings and Conclusions

This study investigated the influence of the MI sector on the Chinese national economy from 2007 to 2017 using comprehensive IO analyses, such as the demand-driven, supply-driven, and price-side models and inter-industry linkage effects. Except for our inter-industry linkage effects analysis, the MI sector was treated as exogenous to evaluate the net effects by changes in investment, supply, or price in each sector.

Based on the analytical results from the demand-driven model, a \$1.0 change in the MI sector investment induced \$0.862–\$1.171 of the output, \$0.271–\$0.333 of the value-added, and \$0.106–\$0.125 of the wages in the national economy.

According to the analytical results from the supply-driven model, the supply shortage effect of the MI sector was \$4.383–\$5.949. In detail, sectors including "Processing of Petroleum, Coking, Processing of Nucleus Fuel", "Products of Smelting and Pressing of Metals", and "Repair Services of Metal Products Equipment and Machinery" presented high shortage effect.

According to the analysis based on price-side model, the national economic effect under 10% increase in the MI sector rate was 0.108%–0.171%. High sectoral price impacts were found in "Processing of Petroleum, Coking, Processing of Nucleus Fuel", "Products of Smelting and Pressing of Metals", and "Production and Supply of Electric Power, Steam and Hot Water".

Finally, in the inter-industry linkage effect, the backward linkage effect of the MI sector was found greater than one, as 2.228–2.350, and the forward linkage effect was less than one, as 0.825–0.896. This indicated that the MI sector can be classified as a final manufacturer. This implies that the MI has bigger impacts in terms of investment expenditures on the national economy than other business. That is, the MI has a relatively strong capacity for pulling in other industries.

In conclusion, the temporal analysis shows that MI sectors play an increasingly important role in China from 2007 to 2017. The total contribution of the MI sectors shows a significant increase in this decade, but the growth rate slows down between 2012 and 2017. This may be caused by the lack of new mining economic motivation in the process of China's mining restructuring. Another reason may be the global concern for environmental protection issues and mining sustainability strategy. The Chinese National 13th 5-year plan (2016–2020) recommends low carbon, clean, safe and modern energy systems (e.g., replace coal power generation with nuclear power) (Xing et al., 2017). However, with the promotion a series of mining regulations, such as the development of Green Mining Construction (GMC), the sustainable mining industry is gradually recovering.

5.2 Policy Implications

While our findings verified the positive effects of MI on national economy based on the evidence of China, much more work is needed to really integrate MI as an economic system innovation. Enlightened by the experiences of China and the key findings from our analysis, several policy implications were proposed and discussed as follows:

- First, the IO analysis was found to be beneficial in evaluating the economic effects of the Chinese MI, which is in line with prior study findings (Wang et al., 2019; Kim et al., 2020). IO analysis is a useful tool for studying various MI-related policy concerns, despite its inherent constraint of assuming fixed input needs. To modernize the MI and develop a sustainable, low-carbon, safe and efficient energy system, it is necessary for the Chinese government to transform the extensive mining paradigm by adopting new technologies, processes and equipment.
- Second, The analysis results from the price-side model showed that the adjustment of mining prices had little impact on household consumer goods. Considering the affordability of various industries in the national economy and people's lives, it is necessary to reform the price of mineral products, change the unreasonable price relationship between mineral products and industrial products, and formulate a reasonable price system for mineral products.
- Third, in response to the environmental pollution caused by MI, the Chinese government has adopted a series of environmental control measures, such as setting up relevant environmental regulations to regulate the industry. However, due to the significant contribution of MI to the national economy, other measures should be taken by the Chinese government to overcome the lagging effect of the regulations on the industry development in addition to the implementation of them, so as to achieve a healthy and sustainable development of MI.

5.3 Research Limitations and Future Concerns

This paper used IO analysis to assess the feasibility of the mining sector's overall economic contribution in China and produced a set of important indicators that could be utilized to build policy and the MI economy. However, the limitation of this article is that we treat the investments of MI projects as accumulative value rather than on-site survey data, while the NBSC is published every 5 years, hence the data match and timeliness issue might generate some uncertainty on the result.

As a follow-up to this study, future related studies may be carried out in two directions. First, although the article used the national IO table, multi-regional IO analysis can be carried out by employing a multi-regional IO table. This allows quantitative analysis of inter-regional effects as well as intra-regional effects. Second, the aim of the study is to assess the value of both direct and indirect contributions of China's MI; however, it only considers the benefits of mining economy activities. Therefore, in future research, factors such as environmental pollution and shortage of mining resources should be taken into consideration to examine both the advantageous and disadvantageous impacts of the MI on the national economy.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The three authors have equally participated in conceptualization, literature review, data analysis and writing of the paper.

REFERENCES

Agyekum, E. B., Amjad, F., Mohsin, M., and Ansah, M. N. S. (2021). A Bird's Eye View of Ghana's Renewable Energy Sector Environment: A Multi-Criteria Decision-Making Approach. *Util. Policy* 70, 101219. doi:10.1016/j.jup.2021.101219

Asbahi, A. A. M. H. A., Gang, F. Z., Iqbal, W., Abass, Q., Mohsin, M., and Iram, R. (2019). Novel Approach of Principal Component Analysis Method to Assess the National Energy Performance via Energy Trilemma Index. *Energy Rep.* 5, 704–713. doi:10.1016/j.egyr.2019.06.009

Beylot, A., and Villeneuve, J. (2015). Assessing the National Economic Importance of Metals: An Input-Output Approach to the Case of Copper in France. *Resour. Policy* 44, 161–165. doi:10.1016/j.resourpol.2015.02.007

Chen, J., Jiskani, I. M., Jinliang, C., and Yan, H. (2020). Evaluation and Future Framework of Green Mine Construction in China Based on the DPSIR Model. *Sustain. Environ. Res.* 30 (1), 1–10. doi:10.1186/s42834-020-00054-8

Chen, Q. S., Yu, W. J., and Zhang, Y. F. (2015). Considerations on the Strengthening Mineral Resources Reserve in China. *China Mining Magazine* 2015 (1), 20–23. doi:10.3969/j.issn.1004-4051.2015.01.005

Davis, H. C., and Salkin, E. L. (1984). Alternative Approaches to the Estimation of Economic Impacts Resulting from Supply Constraints. *Ann. Reg. Sci.* 18 (2), 25–34. doi:10.1007/BF01287372

Fan, S., Yan, J., and Sha, J. (2017). Innovation and Economic Growth in the Mining Industry: Evidence from China's Listed Companies. *Resour. Policy* 54, 25–42. doi:10.1016/j.resourpol.2017.08.007

Feng, C., Huang, J.-B., and Wang, M. (2019). The Sustainability of China's Metal Industries: Features, Challenges and Future Focuses. *Resour. Policy* 60, 215–224. doi:10.1016/j.resourpol.2018.12.006

Ghosh, A. (1958). Input-output Approach in an Allocation System. *Economica* 25 (97), 58–64. doi:10.2307/2550694

Giarratani, F. (1976). Application of an Interindustry Supply Model to Energy Issues. *Environ. Plan. A* 8, 447–454. doi:10.1068/a080447

Guo, J., Yan, W. D., Xu, S. G., Cui, R. G., Hu, R. B., Lin, B. L., et al. (2021). A Discussion on Evaluation Criteria and List of Critical Minerals in China. *Acta Geosci. Sin.* 42 (2), 151–158. doi:10.3975/cagsb.2020.090601

Heo, J.-Y., Yoo, S.-H., and Kwak, S.-J. (2010). The Role of the Oil Industry in the Korean National Economy: An Input-Output Analysis. *Energy Sources, Part B Econ. Plan. Policy* 5 (4), 327–336. doi:10.1080/15567240802533880

Hirschman, A, O. (1958). *The Strategy of Economic Development*. New Haven: Yale University Press.

Howe, C. W., Smith, M. G., Bennett, L., Brendecke, C. M., Flack, J. E., Hamm, R. M., Mann, R., Rozaklis, L., and Wunderlich, K. (1994). The Value of Water Supply Reliability in Urban Water Systems. *J. Environ. Econ. Manag.* 26 (1), 19–30. doi:10.1006/jeem.1994.1002

Ilankoon, I. M. S. K., Tang, Y., Ghorbani, Y., Northey, S., Yellishetty, M., Deng, X., et al. (2018). The Current State and Future Directions of Percolation Leaching in the Chinese Mining Industry: Challenges and Opportunities. *Miner. Eng.* 125, 206–222. doi:10.1016/j.mineng.2018.06.006

Ivanova, G. (2014). The Mining Industry in Queensland, Australia: Some Regional Development Issues. *Resour. Policy* 39, 101–114. doi:10.1016/j.resourpol.2014.01.005

Jiskani, I. M., Cai, Q., Zhou, W., Chang, Z., Chalgri, S. R., Manda, E., et al. (2020). Distinctive Model of Mine Safety for Sustainable Mining in Pakistan. *Min. Metallurgy Explor.* 37 (4), 1023–1037. doi:10.1007/s42461-020-00207-8

Ju, H.-C., Yoo, S.-H., and Kwak, S.-J. (2016). The Electricity Shortage Cost in Korea: An Input-Output Analysis. *Energy Sources, Part B Econ. Plan. Policy* 11 (1), 58–64. doi:10.1080/15567249.2011.567226

Kim, K.-H., Kim, J.-H., and Yoo, S.-H. (2020). An Input-Output Analysis of the Economic Role and Effects of the Mining Industry in South Korea. *Minerals* 10, 624. doi:10.3390/min10070624

Lei, Y., Cui, N., and Pan, D. (2013). Economic and Social Effects Analysis of Mineral Development in China and Policy Implications. *Resour. Policy* 38 (4), 448–457. doi:10.1016/j.resourpol.2013.06.005

Lin, C. (2015). China's New Normal of Economy and the Optimization and Upgrading of the Economic Structure. *Int. Conf. Logist. Eng. Manag. Comput. Sci.* 117, 1810–1813. doi:10.2991/lemcs-15.2015.365

Means, G. C., Montgomery, D. E., Clark, J. M., Hansen, A. H., and Ezekiel, M. (1939). *The Structure of the American Economy*. New York: Oxford University Press.

Miller, R. E., and Blair, P. D. (1985). *Input-output Analysis: Foundations and Extensions*. Englewood Cliffs: Bergen. doi:10.1017/cbo9780511626982.003

Ministry of Natural Resources, The Report of China Mineral Resources. Available at: http://www.mnr.gov.cn.

Ministry of Natural Resources, The National Plan for Mineral Resources 2016-2020. Available at: https://www.cgs.gov.cn/tzgg/tzgg/201612/t20161206_418714.html

National Bureau of Statistics of China (2020). *China Statistics Yearbook*. Beijing: China Statistics Press.

National Bureau of Statistics of China (2012). *China's 2007 Input-Output Table*. China Statistics Press.

National Bureau of Statistics of China (2017). *China's 2012 Input-Output Table*. China Statistics Press.

National Bureau of Statistics of China (2019). *China's 2017 Input-Output Table*. China Statistics Press.

Oosterhaven, J. (2019). "Rethinking Input-Output Analysis," in *Briefs in Regional Science* (Springer). doi:10.1007/978-3-030-33447-5

San Cristóbal, J. R., and Biezma, M. V. (2006). The Mining Industry in the European Union: Analysis of Inter-industry Linkages Using Input-Output Analysis. *Resour. Policy* 31 (1), 1–6. doi:10.1016/j.resourpol.2006.03.004

Shen, L., Muduli, K., and Barve, A. (2015). Developing a Sustainable Development Framework in the Context of Mining Industries: AHP Approach. *Resour. Policy* 46, 15–26. doi:10.1016/j.resourpol.2013.10.006

Song, Y., Huang, J., Zhang, Y., and Wang, Z. (2019). Drivers of Metal Consumption in China: an Input-Output Structural Decomposition Analysis. *Resour. Policy* 63, 101421. doi:10.1016/j.resourpol.2019.101421

Stilwell, L. C., Minnitt, R. C. A., Monson, T. D., and Kuhn, G. (2000). An Input-Output Analysis of the Impact of Mining on the South African Economy. *Resour. Policy* 26, 17–30. doi:10.1016/s0301-4207(00)00013-1

Suh, D. H. (2021). Exploring the U.S. Mining Industry's Demand System for Production Factors: Implications for Economic Sustainability. *Resour. Policy* 74, 101214. doi:10.1016/j.resourpol.2018.06.005

Sun, H., Pofoura, A. K., Adjei Mensah, I., Li, L., and Mohsin, M. (2020). The Role of Environmental Entrepreneurship for Sustainable Development: Evidence from 35 Countries in Sub-saharan Africa. *Sci. Total Environ.* 741, 140132. doi:10.1016/j.scitotenv.2020.140132

The Stats Council of the People's Republic of China (2020). Made in China 2025. Available at: http://www.gov.cn/.

Tung, R. L. (2016). Opportunities and Challenges Ahead of China's "New Normal". *Long. Range Plan.* 49 (5), 632–640. doi:10.1016/j.lrp.2016.05.001

Upadhyay, A., Laing, T., Kumar, V., and Dora, M. (2021). Exploring Barriers and Drivers to the Implementation of Circular Economy Practices in the Mining Industry. *Resour. Policy* 72, 102037. doi:10.1016/j.resourpol.2021.102037

Wang, G., Xu, Y., and Ren, H. (2019). Intelligent and Ecological Coal Mining as Well as Clean Utilization Technology in China: Review and Prospects. *Int. J. Min. Sci. Technol.* 29 (2), 161–169. doi:10.1016/j.ijmst.2018.06.005

Wang, M., and Feng, C. (2017). Analysis of Energy-Related CO_2 Emissions in China's Mining Industry: Evidence and Policy Implications. *Resour. Policy* 53, 77–87. doi:10.1016/j.resourpol.2017.06.002

Wang, Q., and Ge, S. (2020). Uncovering the Effects of External Demand on China's Coal Consumption: A Global Input-Output Analysis. *J. Clean. Prod.* 245, 118877. doi:10.1016/j.jclepro.2019.118877

Wang, Y., and Wang, N. (2019). The Role of the Marine Industry in China's National Economy: An Input-Output Analysis. *Mar. Policy* 99, 42–49. doi:10.1016/j.marpol.2018.10.019

Wang, Z., and Sun, J. (2017). Analysis of Interregional Industry Linkage and Economic Distance in China: Evidence from the Mining Industry. *Appl. Econ.* 49 (6), 606–617. doi:10.1080/00036846.2016.1203062

Wu, R.-H., and Chen, C.-Y. (1990). On the Application of Input-Output Analysis to Energy Issues. *Energy Econ.* 12 (1), 71–76. doi:10.1016/0140-9883(90)90010-d

Wu, Y., and Zhang, W. (2016). The Driving Factors behind Coal Demand in China from 1997 to 2012: An Empirical Study of Input-Output Structural Decomposition Analysis. *Energy Policy* 95, 126–134. doi:10.1016/j.enpol.2016.05.007

Xing, W., Wang, A., Yan, Q., and Chen, S. (2017). A Study of China's Uranium Resources Security Issues: Based on Analysis of China's Nuclear Power Development Trend. *Ann. Nucl. Energy* 110, 1156–1164. doi:10.1016/j.anucene.2017.08.019

Xu, T., Baosheng, Z., Lianyong, F., Masri, M., and Honarvar, A. (2011). Economic Impacts and Challenges of China's Petroleum Industry: An Input–Output Analysis. *Energy* 36 (5), 2905–2911. doi:10.1016/j.energy.2011.02.033

Yang, Z., Abbas, Q., Hanif, I., Alharthi, M., Taghizadeh-Hesary, F., Aziz, B., et al. (2021). Short- and Long-Run Influence of Energy Utilization and Economic Growth on Carbon Discharge in Emerging SREB Economies. *Renew. Energy* 165, 43–51. doi:10.1016/j.renene.2020.10.141

Yoo, S.-H., and Yang, C.-Y. (1999). Role of Water Utility in the Korean National Economy. *Int. J. Water Resour. Dev.* 15, 527–541. doi:10.1080/07900629948745

Yoo, S.-H., and Yoo, T.-H. (2009). The Role of the Nuclear Power Generation in the Korean National Economy: An Input-Output Analysis. *Prog. Nucl. Energy* 51, 86–92. doi:10.1016/j.pnucene.2007.12.001

Zhou, Y., Zhou, W., Lu, X., Jiskani, I. M., Cai, Q., Liu, P., et al. (2020). Evaluation Index System of Green Surface Mining in China. *Min. Metallurgy Explor.* 37, 1093–1103. doi:10.1007/s42461-020-00236-3

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Advantages of publishing in Frontiers

OPEN ACCESS
Articles are free to read for greatest visibility and readership

FAST PUBLICATION
Around 90 days from submission to decision

HIGH QUALITY PEER-REVIEW
Rigorous, collaborative, and constructive peer-review

TRANSPARENT PEER-REVIEW
Editors and reviewers acknowledged by name on published articles

Frontiers
Avenue du Tribunal-Fédéral 34
1005 Lausanne | Switzerland

Visit us: www.frontiersin.org
Contact us: frontiersin.org/about/contact

REPRODUCIBILITY OF RESEARCH
Support open data and methods to enhance research reproducibility

DIGITAL PUBLISHING
Articles designed for optimal readership across devices

FOLLOW US
@frontiersin

IMPACT METRICS
Advanced article metrics track visibility across digital media

EXTENSIVE PROMOTION
Marketing and promotion of impactful research

LOOP RESEARCH NETWORK
Our network increases your article's readership