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| RESEARCH ARTICLE

Multi-scale Analysis and Synergistic Scenario Simulation of Pollution and Carbon Reduction Efficiency in Guangdong-Hong Kong-Macao Greater Bay Area

Zhengyong Chen[1] ✉ and Zhanjie Wen[2] ✉
[12]*School of Internet Finance and Information Engineering, Guangdong University of Finance, Guangzhou, China*
Corresponding Author: Zhanjie Wen, **E-mail**: 70-154@gduf.edu.cn

| ABSTRACT
In the context of China's "double carbon" goal, pollution and carbon reduction is a consensus. As a demonstration area and model area for China's development, how to take the lead in realizing the synergistic improvement of pollution and carbon reduction and embark on a green and low-carbon development path with Chinese characteristics is a common concern of the scientific community and the public. However, each city in *Guangdong-Hong Kong-Macao Greater Bay Area* (GBA) is different regarding resource endowment, energy structure, development conditions, and technical level. The efficiency, ability, and potential of pollution and carbon reduction must differ. The mission objectives, methods, and methods of promoting the "double carbon" work are also different. Only by considering it from the perspective of system collaboration can the "double carbon" work be safe and sustainable. The study proposes that we can, from the dynamic perspective of the production network and industrial transfer, integrate multi-source and multi-mode data and use a multi-scale evaluation method to analyze the multi-dimensional features and driving factors of the interaction effect of pollution and carbon reduction in GBA. The research results can help cities in GBA to understand their weak links in pollution and carbon reduction in a timely, comprehensive, and accurate manner. In addition, this study is conducive to providing decision-making reference for China to formulate regional synergistic effects.

| KEYWORDS
Carbon efficiency; Energy Conservation and Emission Reduction Policy; carbon productivity; carbon neutral; low carbon economy transition; Guangdong-Hong Kong-Macao Greater Bay Area

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1. Introduction

With the fundamental goal of achieving synergy in pollution and carbon reduction, China has formulated a strategy further to fight the rugged battle of pollution prevention and control and continuously improve the quality of the ecological environment. This strategy is a significant decision and deployment made by China to build a beautiful China with a harmonious coexistence between man and nature, focusing on overall development, improving people's well-being, and striving to build a harmonious coexistence between man and nature. It is an important measure to promote high-quality development with high-level protection and promote new progress in constructing ecological civilization. China and developed countries have adopted a different development course of first basically solving the problem of environmental pollution and then strengthening carbon emission control and addressing climate change. At the current stage, China's ecological civilization construction is facing two major strategic tasks at the same time: how to achieve a fundamental improvement in the ecological environment and how to achieve carbon emissions peak and carbon neutrality.

In recent years, the quality of China's ecological environment has improved significantly, and the people's sense of achievement has increased significantly. However, the structural, root-cause, and trend pressures on ecological environment protection have remained relatively stable. China's ecological civilization construction is still in a critical period of pressure and heavy load. At the same time, China has made a solemn commitment to the world to strive to achieve peaking carbon dioxide emissions by 2030 and carbon neutrality by 2060. Under the circumstances that industrialization and new urbanization still need to be further promoted, and energy consumption will continue to increase rigidly, China's task of achieving peaking carbon dioxide emissions and carbon neutrality faces many difficulties and challenges, such as heavy transformation tasks and tight time windows.

Therefore, if China wants to achieve peaking carbon dioxide emissions and carbon neutrality under this background, it needs to grasp the internal connection between pollution and carbon reduction to realize the synergetic effects of pollution and carbon reduction. First, pollutants and carbon dioxide have a high degree of consistency in emission source categories and spatial and temporal emissions characteristics. Faced with the double pressure and urgent need for environmental quality improvement and greenhouse gas emission reduction, the government must grasp the internal connection between pollution and carbon reduction and plan objectives, tasks, control ideas, and policy measures. On the one hand, the government must fully play the source traction effect of carbon reduction on improving ecological environment quality. On the other hand, the government should fully use the existing ecological environment system to promote low-carbon development, innovate policies and measures, optimize governance routes, and promote the synergetic effects of pollution and carbon reduction.

Guangdong-Hong Kong-Macao Greater Bay Area (GBA) is one of the regions with the highest degree of openness and the strongest economic vitality in China. It has an important strategic position in the overall development of the country. Therefore, in order to play a demonstration role in peaking carbon dioxide emissions and carbon neutrality work, China continues to promote the green and low-carbon development of GBA. In order to provide a reference for the synergetic effects of pollution and carbon reduction in Beijing, Tianjin, Hebei, Yangtze River Delta, and western regions, China has carried out a pilot demonstration case study of pollution and carbon reduction in GBA. Under the background of China's "double carbon" goal, pollution and carbon reduction are a consensus. However, the Guangdong- Hong Kong-Macao Greater Bay Area has many differences in resource endowment, energy foundation, development conditions, technical level, etc. Therefore, the efficiency, ability, and potential of pollution and carbon reduction in different regions are bound to be very different. The task objectives, ways, and means to promote the "double carbon" work are also different. Therefore, only by considering and measuring from the perspective of system and synergetic effects can the government ensure the safety and sustainability of "double-carbon" work.

To sum up, many vital issues need to be studied urgently: how to realize the interactive effect of pollution and carbon reduction in GBA; How to realize the spatial and temporal characteristics, network characteristics, and dynamic mechanism of regional economic development decarbonization; How to design different regions in the Greater Bay Area and propose scientific and personalized coordinated policies for pollution and carbon reduction. At the same time, this study points out that future research can focus on the measurement of pollution and carbon reduction efficiency in the Guangdong-Hong Kong Kong-Macao Greater Bay Area, the construction of a carbon migration network in GBA, the simulation of pollution and carbon reduction collaborative scenarios in GBA, and the measurement of efficiency gains. Researchers can use multi-scale analysis methods and multi-source and multi-mode data to evaluate pollution and carbon reduction interaction effects and collaborative scenario simulation in GBA to promote the research of pollution and carbon reduction synergetic effects.

2. Pollution and Carbon Reduction Efficiency and Decarbonization Factors

2.1 Measurement of Pollution and Carbon Reduction Efficiency

As the primary yardstick to measure the development of a green economy, most of the international papers on carbon emission efficiency evaluation are based on energy and environmental efficiency. There are many methods to evaluate energy and environmental efficiencies, such as *Data Envelope Analysis* (DEA), *Free Disposal Hull* (FDH), and *Stochastic Frontier Analysis* (SFA). In the past decade, the application of DEA to evaluate environmental efficiency at the macro level has become a trend, especially in regional or national carbon emission studies (e.g., Lin et al., 2020; Zhang et al., 2020; Sueyoshia et al., 2018).

The continuous attention of the international community to climate change problems caused by carbon emissions has further promoted the application of the DEA method in the research of energy and environmental efficiency. DEA has been favored by many scholars for its scientific, rigorous, and universal measurement and has gradually become the mainstream method for the research of total factor energy economic efficiency. Lu et al. (2019) constructed a super-efficient DEA model by selecting input and output variables to calculate the carbon emission control efficiency of different provinces in China to study the regional differences in carbon emission control efficiency. Chen et al. (2019) considered the dual perspectives of regions and sub-sectors. They used DEA to measure the total factor energy efficiency (TFEE) of 9 provinces and 19 manufacturing sub-sectors in China from 2001 to 2011. In addition, some scholars used SFA (Wang et al., 2020) to study the carbon emission efficiency of agricultural industries. Zhang et al. (2020) measured the energy efficiency of 30 provinces in China and found that China's energy efficiency showed a rapid upward trend during the measurement period.

2.2 Decarbonization Drivers of Regional Economic Growth

Currently, scholars mainly use the method of econometric analysis to decompose the impact of various vital factors on carbon emission reduction. Tian et al. (2021) used the quasi-irrelevant regression method for parameter estimation to study the calculation of interprovincial carbon emissions and the evaluation of low carbonization levels in China. Yang (2019) et al. and Zhang et al. (2021) used the DEA-Malmquist index to evaluate the carbon emission reduction in China's provinces by constructing a carbon emission reduction index system, analyzing the performance features of carbon emission reduction in provinces, and then used the Tobit model to analyze the influencing factors of provincial carbon emission reduction empirically. Chen et al. (2020) found that my country's carbon emissions have duality through correlation analysis among variables and studied their coordination with economic development. Liu et al. (2019) used the panel data of the six central provinces in China to calculate the carbon emission reduction efficiency value using the input-oriented super-efficiency DEA model. Then they used the Tobit model to conduct a specific analysis of the factors that affected the carbon emission reduction efficiency and concluded that the overall level of carbon emission reduction in the six central provinces is not high, the carbon emission reduction potential is enormous, and the economic scale of each province is positively correlated to the carbon emission reduction efficiency. Hainsch et al. (2021) used the Global Energy System Model (GENeSYS-MOD) framework, a linear mathematical optimization model, to calculate low-carbon scenarios for 17 European countries. They show the different decarbonization pathways in Europe by 2050 under different carbon dioxide (CO_2) constraints.

The coordinated development of the economy and the ecological environment is the objective requirement of China's sustainable development strategy. Economic development promotes the protection of the ecological environment. At the same time, the protection of the ecological environment, in turn, promotes economic development. The relationship between the two should be harmonious, sustainable, and win-win. Wang et al. (2021) built a comprehensive evaluation index system for a pollution reduction-carbon reduction economy. By selecting the energy economy, pollutants, and carbon dioxide emission data of 30 provinces (autonomous regions and municipalities directly under the Central Government) in China in 2016 and 2018, scholars used the grey relational degree method to comprehensively evaluate the pollution reduction, carbon reduction and economic indicators in each region, to analyze the development of various indicators. Scholars analyzed the development coordination of indicators in various regions by calculating the binary and ternary coupling coordination degree between indicators. Finally, scholars put forth pollution reduction, carbon reduction, and regional economic development suggestions according to local conditions, according to local evaluation index scores and coordination degree data. For the study of carbon emission, scholars at home and abroad have used the spatial Markov chain for research. Wang et al. (2019) used kernel density estimation, spatial autocorrelation, spatial Markov chain, and panel quantile regression methods to analyze the spatial spillover effects and driving factors of carbon emission intensity in 283 cities in China from 1992 to 2013. Kernel density estimation shows that the overall average carbon intensity of Chinese cities has decreased, and the difference has gradually narrowed. Spatial Markov chain analysis shows that the carbon emission intensity of Chinese cities has the Matthew effect. Second, in cities with low carbon emission intensity, economic growth, technological progress, and appropriate population density play an important role in reducing emissions. In addition, foreign investment intensity and traffic emissions are the main factors that increase carbon emission intensity. In high carbon-intensity cities, population density is essential in reducing emissions, while technological progress has no significant impact. The main factors driving carbon intensity increases are industrial emissions, extensive capital investment, and urban land expansion. Wang et al. (2020) Based on Chinese cities' carbon emission remote sensing data from 1992 to 2013, the relaxation-based super-efficiency measure was used to evaluate the urban carbon emission performance. The results show that the transfer of carbon emission performance in Chinese cities is stable.

3. Characteristics of Carbon Migration Network and Dynamic Mechanisms

3.1 Characteristics of Carbon Migration Network

The phenomenon of carbon migration caused by industrial transfer has attracted the attention of scholars at home and abroad. Existing studies have focused on the measurement of interregional carbon migration, the rough outline of the spatial features of the transfer, and the fair assumption of regional carbon responsibilities caused by carbon migration. Existing studies have explored the measurement of carbon migration network features and influencing factors. Wang et al. (2019) showed that the spatial aggregation of carbon emission intensity is significant through the spatial autocorrelation Moran I index. Secondly, there are apparent "spatial spillover effects" in urban carbon emission intensity. Spillover effects in different regional backgrounds are heterogeneous. Suppose a city is close to a city with a lower carbon emission intensity. In that case, the carbon emission intensity of the first city has a higher upward transition probability and vice versa. The group quantile results show that economic growth, technological progress, and appropriate population density play an important role in reducing emissions in cities with low carbon emission intensity. Yu et al. (2020) used the MRIO-SNA model to construct a global carbon migration network based on the latest WIOD environmental accounts and the World Input-Output Table and visually analyzed the features of the global carbon migration network from the perspective of "relationship". At the same time, scholars have used the QAP method to reveal the main reasons for the formation of the global carbon migration network. Yan et al. (2022) calculated the scale of implied carbon emission transfer between provinces in China based on the MRIO model. They used the social network analysis method to characterize the direction of implied carbon migration and the spatial network architecture features to explore the correlation and clustering features of inter-provincial carbon migration networks from the perspective of economic and domestic circulation.

Scholars conduct research on pollution and carbon reduction synergetic effects, identify critical paths and significant policy needs, and serve as an essential theoretical and scientific basis for the overall breakthrough point of promoting the comprehensive green transformation of economic and social development. Carbon emission reduction paths and quantities are essential for mitigating climate change and promoting urban social and economic green transformation. Xu et al. (2020) conducted a statistical analysis of the coverage of environmental cooperation in GBA and a comparative analysis of the environmental regulation policy text of GBA. Scholars have sorted out the process of collaborative environmental governance of GBA, studied its characteristics, problems, and limiting factors, and sought the possibility of further collaborative governance. Wu et al. (2021) analyzed the environmental governance cooperation data of 11 GBA cities from 2008 to 2017 through UCINET software tools. The research results show that: the GBA environmental governance cooperation network has gradually evolved from a "central coordination" to a "flat" network feature, forming a "center-sub-center-edge city" cooperation situation, and the cooperation of small circles within the network is presented as a two-pair reciprocal and triangular model. Zheng et al. (2021) discussed the primary connotation of pollution and carbon reduction synergetic effects in terms of the synergistic system of target indicators, management and control areas, control objects, measures and tasks, and policy tools. Scholars focus on the importance of current atmospheric environmental governance and carbon reduction in China and address the need for a policy system for collaborative governance of pollution and carbon reduction. They put forward three suggestions: a) overall optimization of pollution and carbon reduction coordination goals; b) the establishment of coordinated regulations and standards; c) the establishment of pollution and carbon reduction coordination management systems.

Xiong (2022) proposed that the energy domain is the main battlefield to promote pollution and carbon reduction synergetic effects, and proposed six aspects from the dual control of energy consumption intensity and total amount, energy structure, industrial structure, industrial sector, urban and rural construction, and transportation. Path and measures to promote pollution and carbon reduction synergetic effects through energy transformation. Jiang et al. (2021) analyzed and sorted out the significance and necessity of pollution and carbon reduction synergetic effects and further expounded the rich connotation of pollution and carbon reduction synergetic effects from the perspectives of goals, paths, management, effects, and departmental collaboration. At the same time, scholars put forward countermeasures and suggestions in terms of economic and social green transformation, top-level design of pollution and carbon reduction, key measures to achieve goals, and scientific and technological support, in order to promote pollution and carbon reduction synergetic effects and build a beautiful and harmonious coexistence between man and nature. Wang et al. (2021) take China's primary coal-consuming industries, electricity, heating, transportation, and forest carbon sinks, as research objects to construct a multi-objective model based on low-cost peaking carbon dioxide emissions and carbon neutrality paths. Scholars take the minimum cost, the minimum carbon dioxide emissions, and the minimum air pollutant emissions as the model for multiple goals and set corresponding constraint conditions with China's peaking carbon dioxide emissions before 2030 and carbon neutrality before 2060 as the research goals to set industry demand, electricity demand, heating demand, transportation demand, the proportion of new energy in various industries, pollutant control, and other constraint conditions.

Combining the research results of China's medium-term and long-term planning and academic literature at home and abroad, Cai et al. (2021) fully consider China's current industrial structure dominated by industry and coal-dominated energy structure. At the same time, they combine new technology research and development and put it into the use cycle. They used the China high-resolution emission gridded database (CHRED), top-down (based on China's medium- and long-term emission and intensity targets and referenced IPCC-SSPs emission scenarios), and bottom-up (based on CHRED's 50km grid sub-sectoral emissions, using a spatial equity convergence model), to establish China's carbon neutrality target CO_2 emission path from 2020 to 2060 (CAEP-CP 1.1). Li et al. (2020) The study first used the difference-in-difference (DID) model to assess the impact of carbon emission trading on the carbon emission intensity of construction land (CEICL). Based on data from China in 2012, Wen et al. used the non-competitive input-output table (I-O table), combined with structural path analysis (SPA) and multi-dimensional data analysis framework (MAF) methods to analyze the current status of intersectoral carbon emission transfer. They achieved the identification of key sectors and critical paths from multiple perspectives.

3.2 Synergistic Emission Reduction Pathways

Scholars have put forward practical policy suggestions in different domains, such as industry, transportation, and production, through targeted research. Gao et al. (2021) constructed an evaluation index to quantify the synergistic effect of air pollution control and greenhouse gas emission reduction based on a two-dimensional four-quadrant map. Secondly, they established a quantization evaluation synergistic effect method. They carried out a synergistic effect quantization implementation effect evaluation for the energy structure adjustment and industrial structure adjustment measures in evaluating the Air Pollution Prevention and Control Action Plan. The results show that:

a. All implemented measures to reduce pollutants have positive CO_2 emission reduction synergistic effects and should be actively encouraged and recommended.
b. The measure to achieve the most significant synergistic effect of CO_2 and SO_2 emission reduction is reducing total coal consumption.
c. The replacement of coal and oil by electricity and coal by natural gas can also achieve more significant SO_2 emission reduction, but the CO_2 emission reduction effect is relatively small.
d. Eliminating small coal-fired boilers can achieve higher NO_2 and CO_2 emission reductions.
e. The elimination of backward production capacity and the resolution of excess production capacity also has a high synergistic effect.
f. The highest evaluation index of SO_2 and CO_2 synergistic effect is the measure of energy consumption reduction, followed by fuel substitution measures.
g. The highest evaluation index of NO_2 and CO_2 synergistic effect is the measure to phase out coal-fired boilers, replacing coal-fired with natural gas.
h. The most extensive evaluation index of the synergistic effect of soot and CO_2 is the alternative coal-fired measures, followed by the energy consumption reduction measures.

Wang et al. (2021) conducted a quantization analysis on the effect of NO_x pollution control synergistic control of greenhouse gases in industrial enterprises. They found that the effect of NO_x control measures using end-of-pipe treatment as a means of synergistic control of greenhouse gases was negative. In addition, reducing urea use and increasing the degree of low carbonization of electricity can help reduce the negative synergistic effect of NO_x reduction on CO_2 emissions in the industrial domain.

Li et al. (2021) took a printing company in Beijing as an example to evaluate the coordinated emission reduction of volatile organic compounds (VOCs) and CO_2 after introducing waterless printing technology at the enterprise level. They obtained data through on-site monitoring and public literature to conduct empirical research. The results show that: (a) Compared with the baseline scenario, using waterless printing technology and installing end-treatment facilities can reduce the emission of VOCs. However, waterless printing technology's VOCs emission reduction effect is better, and the emission reduction rate is about 60%. (b) CO_2 emissions decreased significantly after waterless printing technology, and the installation of end treatment facilities will increase CO_2 emissions. (c) Source substitution technology represented by waterless printing can achieve synergistic emission reduction of VOCs and CO_2.

Feng et al. (2021) took the coordinated management of pollutants and greenhouse gases in China's transportation sector as an entry point. First, they carried out future demand forecasts for various sub-sectors such as road, rail, water, aviation, and pipeline. Next, they used the Long-Term Energy Alternative Planning system model (LEAP). Then, they simulated and analyzed energy demand trends, pollutants, and carbon emissions in China's transportation domain by constructing baseline scenarios, pollution reduction scenarios, green low-carbon scenarios, and enhanced low-carbon scenarios. The results show that: (a) Under the enhanced low-carbon scenario, China's transportation sector energy consumption will peak in 2037, and CO_2 emissions will peak in 2035. (b) Under the green and low-carbon scenario, CO_2 emissions will peak in 2040. (c) Policy measures such as phasing out old cars, "railway to iron", and "railway to water" will effectively reduce the emission of pollutants such as NO_x and PM2.5. Technical measures such as developing hydrogen fuel and natural aviation oil will further reduce pollutant emissions. (d) To achieve green and low-carbon development in the transportation domain, it is necessary to implement relevant energy conservation and carbon reduction measures and coordinated emission reduction for passenger and freight transportation, respectively. Comprehensive measures are an essential guarantee for completing the goals of energy consumption and carbon emission peaking.

Qian et al. constructed and analyzed a company-level database of nearly 80,000 observations. At the same time, they used scenario simulations to estimate co-benefits. The results show that: (a) Three specific interventions can achieve substantial co-benefits: Improve energy intensity; Scale and structure adjustment (eliminating small enterprises and developing large enterprises); Reach 70% of electricity generation from non-fossil fuels; Significant reductions in SO_2, NO_x, PM2.5, and CO_2 emissions from the non-power sector. (b) Stricter and more rational environmental policies for industrial enterprises can accelerate China's sustainable transformation.

Zhou et al. (2021) investigated the interdependence of air quality, health, and carbon across provinces in northern China, as well as household costs of using electricity (heat pumps or resistive heaters), natural gas, or clean coal for residential heating. The study found: (a) Clean heating solutions significantly benefit air quality and health, while carbon emissions vary and heating costs increase. (b) With increased subsidies for the purchase of heat pumps, governments can promote further improvements in air quality and carbon emissions reductions during the clean heating transition.

Liu et al. (2021) estimated the total annual cost of replacing coal stoves with popular clean energy options for rural households in various cities/counties in the Beijing-Tianjin-Hebei region. The study found: (a) Without subsidies, the use of improved coal stoves and clean coal (CCIS) has the lowest total cost of all cleaning options. (b) The cost of unsubsidized CCIS is about twice the cost of raw coal, while the cost of unsubsidized electricity/gas heaters is 3-5 times that of CCIS. Therefore, governments must financially support households to replace coal stoves with clean heaters to promote widespread adoption. There is great potential for governments to reduce heating bills by improving building energy efficiency, especially in severe cold regions. The cost advantage of gas hydrates varies with gas prices.

Mathijs et al. (2020) conducted a scenario analysis of black carbon (BC) -centric mitigation strategies based on a comprehensive assessment model. The study found: (a) Measures targeting BC emissions (including reducing co-emissions of organic carbon, sulfur dioxide, and nitrogen dioxide) can significantly reduce premature mortality from ambient air pollution. (b) In some cases, governments can reduce climate change by reducing BC emissions in the residential sector and under high BC emission scenarios. (c) Strong climate policies will improve air quality by reducing the use of fossil fuels.
Governments can maximize net health benefits by combining air quality and climate targets.

Tibrewal et al. (2020). Evaluating the climate co-benefits of air quality and clean energy policies using multiple indicators (global warming and temperature change potential), projected emission reduction potentials of -0.1 to -1.8 CO_2 content in 2030. Residential clean energy policies (biomass cooking) and air pollution regulations (curbing emissions from brick production and burning of agricultural residues) These policies effectively reduce black carbon generation. Meanwhile, policies in the power generation and transport sectors reduce cooling SLCFs (SO_2 and NO_2), potentially reducing 0.1-2.4 CO_2 content per year. Governments integrating these interventions into national climate policies can strengthen climate action and sustainability, while black carbon should be included in international climate agreements.

4. Synergistic Scenario Simulation and Efficiency Measurement of Pollution and Carbon Reduction

Currently, most scholars use the LEAP, IPAT-LMDI, and InVEST models to study collaborative scenario simulation to predict carbon emission trends. Chinese scholars have innovatively constructed a new comprehensive assessment model including China's endpoint departments-RICE-LEAP model to simulate China's peak carbon dioxide emissions path and global climate change trends. Pang (2021), based on the LEAP model, constructed the benchmark (BAU) scenario of "zero measures" for road traffic development in Lanzhou from 2015 to 2040 and the two energy-saving and emission-reduction scenarios of low carbon (LC) and enhanced low carbon (ELC). This study simulates and evaluates energy consumption and the synergistic emission reduction effect of greenhouse gases and air pollutants under various policies and measures. The results show that the LC scenario energy consumption and CO_2 emissions will peak in 2026. The ELC carbon scenario energy consumption and CO_2 emissions will peak in 2020. Under the two scenarios, the emissions of pollutants such as NO_x, CO, HC, PM2.5, and PM10 began to decline significantly between 2015 and 2017. The downward trend gradually slowed down around 2023. Li et al. (2021) analyzed the associated features of carbon and air pollutant emissions based on the expanded IPAT-LMDI model theory. They then used the propensity score matching-double difference model (PSM-DID) to conduct quantitative analysis and internal mechanism tests on carbon trading policies' synergistic emission reduction effect. Feng et al. (2021) took the coordinated treatment of pollutants and greenhouse gases in China's transportation sector as the breakthrough point. This study carried out future demand forecasts for various subsectors such as roads, railways, water transportation, aviation, and pipeline transportation. At the same time, this study uses the long-term energy alternative planning system model (LEAP) to simulate and analyze the energy demand, pollutants, and carbon emission trends in China's transportation field by constructing baseline scenarios, pollution reduction scenarios, green and low-carbon scenarios, and enhanced low-carbon scenarios.

Hong et al. (2021) innovatively constructed a new comprehensive evaluation model, including China's endpoint sector, the RICE-LEAP model, by coupling the top-down and the bottom-up models. At the same time, they dynamically simulated China's peak carbon dioxide emissions path and global climate change trend from 2020 to 2050 by setting reference scenarios, carbon emission constraint scenarios, and supply-side structural reform scenarios. Lin et al. (2021) took GBA as the research area. They used the InVEST model to evaluate four ecosystem services in GBA from 1995 to 2018. Scholars set the historical trend, planning, and ecological protection scenarios and use the GeoSOS-FLUS model to analyze ecosystem services scenarios in 2030 to explore the trade-offs and synergy between various ecosystem services. Wang et al. (2020) Based on the remote sensing data of urban carbon emissions in China from 1992 to 2013, the traditional Markov probability transfer matrix and spatial Markov probability transfer matrix were constructed. At the same time, scholars explored the temporal and spatial evolution of carbon emission performance in Chinese cities for the first time. They predicted the long-term trend of carbon emission performance.

In terms of health benefits and clean air benefits, scholars use air quality model simulation, apply Goddard Earth Observation System (GEOS), and concentration-response function to predict the concentration of air pollutants and estimate the impact on population health and air. Shi et al. (2021) Predict pollutant emissions in China based on carbon neutrality roadmap and clean air policy evolution. They used air quality models to simulate national and regional PM2.5 and O3 concentrations in 2030 (the carbon peak target year), 2035 (the "Beautiful China 2035" target year launched by the Chinese government to improve air quality fundamentally), and 2060 (the carbon neutrality target year). Nakarmi et al. (2020) developed a national-level SLCP, CO_2, and air pollutant emission inventory for Nepal. At the same time, they estimated impacts on human health, agriculture, and climate using the Goddard Earth Observation System (GEOS), concentration-response functions, based on projections of their impacts from the Reference (REF) and Mitigation Policy (POL) scenarios.

5. Discussion and Conclusion

Scholars have conducted multi-level discussions on pollution and carbon reduction, which has laid a solid foundation for developing this research. Through combing and analyzing the current research results and development trends at home and abroad, this study finds that the above research on pollution and carbon reduction has three common research conclusions. First, the energy efficiency and pollution, and carbon reduction between different provinces in China are significantly different. Second, China's energy efficiency and environmental efficiency are still at the middle and lower levels, and the potential space for pollution and carbon reduction still exists. Finally, under China's "double carbon" goal, it has become a consensus to promote regional environmental collaborative governance and pollution and carbon reduction synergetic effects. The existing literature presents the following characteristics:

a. Because researchers have different subjective ideas, the existing literature has different criteria for selecting input and output indicators. The established index system and analysis method need to be more comprehensive and systematic, and the research results differ.
b. The large-scale coordinated control system of pollution and carbon reduction is a production network with the deep participation of multiple regions, departments, and subjects. Different regions have significant differences in the economic foundation, industrial structure, energy consumption structure, etc. The efficiency, capacity, and potential of pollution and carbon reduction are bound to differ. There still needs to be a research framework to include networked production systems in evaluating the interactive effects of pollution and carbon reduction. Scholars have considered that production activities will produce pollution to evaluate pollution and carbon reduction efficiency, but environmental governance is also an indispensable part of production. Only some studies have considered the dual effects of environmental governance on pollution and carbon reduction efficiency, the internal relationship between pollution and carbon reduction, and the coexistence and resonance of governance and pollution under the scenario of multiple participants.
c. Scholars have considered that pollution and carbon reduction policies will cause decarbonization changes or carbon migration and use single-modal data to predict the trend of carbon emissions. Promoting pollution and carbon reduction synergetic effects is a complex trade-off, systematic, and long-term project. Existing studies must consider the lag of decarbonization changes caused by pollution and carbon reduction policies and the time lag between influencing factors. There needs to be more comprehensive and comprehensive carbon emission trend prediction research using multi-source and multi-mode data, and there needs to be more synergistic measurement research based on pollution and carbon reduction collaborative scenario simulation.

Under the background of China's "double carbon" goal, pollution and carbon reduction are the consensuses. The Guangdong-Hong Kong Kong-Macao Greater Bay Area is one of the regions with the highest degree of openness and the most vital economic vitality in China. It has an important strategic position in the overall development of the country. Continuing to promote the green and low-carbon development of the Guangdong-Hong Kong Kong-Macao Greater Bay Area can play an exemplary role in China's work of peaking carbon dioxide emissions and carbon neutrality. However, GBA regions are different regarding resource endowment, energy base, development conditions, and technical level. The efficiency, capability, and potential of pollution and carbon reduction are bound to vary greatly. The country's task objectives, ways, and means to promote the "double carbon" work are also different. Only when the government considers and measures it from the perspective of system and coordination can it ensure the safety and sustainability of the "double carbon" work. This study proposes that future research can choose GBA to conduct a case study of the collaborative leading demonstration area of pollution and carbon reduction. From the dynamic perspective of the production network and industrial transfer, scholars can adopt a multi-scale assessment method, integrate multi-source and multi-mode data, and analyze the multi-dimensional characteristics and driving factors of the interactive effects of pollution and carbon reduction. At the same time, future research plans can gather to build a quantitative assessment model of regional pollution and carbon reduction synergy state. They can simulate the carbon emission scenarios of GBA under the baseline model and synergy model and measure the synergy of population health and air quality in different situations. Finally, this paper can further enrich the assessment method system of pollution and carbon reduction efficiency. This paper can help cities in GBA to understand their weak links in pollution and carbon reduction in a timely, comprehensive, and accurate manner. This paper can provide a theoretical basis and decision-making reference for the country to decompose pollution and carbon reduction goals according to regions and formulate synergetic effects policies.

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