Bulletin of Monetary Economics and Banking

Volume 26 | Number 4 Article 2

11-30-2023

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Yanwei Lyu
lyuyanwei@126.com

You Wu
wuyou1065@163.com

Wenqiang Wang
wenqiang_rancho@163.com

Jinning Zhang
jnzhang003@163.com

Recommended Citation
Lyu, Yanwei; Wu, You; Wang, Wenqiang; and Zhang, Jinning (2023) "The Impact Of Covid-19 On Carbon Emissions: Empirical Evidence From China," *Bulletin of Monetary Economics and Banking*: Vol. 26: No. 4, Article 2.
DOI: https://doi.org/10.59091/2460-9196.1762
Available at: https://bulletin.bmeb-bi.org/bmeb/vol26/iss4/2

Bulletin of Monetary Economics and Banking, Vol. 26 No. 4, 2023, pp. 571 - 586
p-ISSN: 1410 8046, e-ISSN: 2460 9196

THE IMPACT OF COVID-19 ON CARBON EMISSIONS: EMPIRICAL EVIDENCE FROM CHINA

Yanwei Lyu*, You Wu**, Wenqiang Wang***, and Jinning Zhang****

*School of Business, Shandong University, Weihai, China. Email: lyuyanwei@126.com
**School of Business, Shandong University, Weihai, China. wuyou1065@163.com
***School of Business, Shandong University, Weihai, China. wenqiang_rancho@163.com
**** Corresponding author. School of Business, Shandong University, Weihai, China.
jnzhang003@163.com

ABSTRACT

As the global COVID-19 rages around and world, economic uncertainty increases, and green and sustainable development is facing tough challenges. Based on a panel data of 30 Chinese provinces from January to December 2020, we investigate the short-term impact of the COVID-19 pandemic on China's carbon emissions. The results indicate that carbon emissions in China decreased considerably during the COVID-19 outbreak. This finding remains robust after replacing the core variables. The negative impact of COVID-19 on China's carbon emissions is not sustainable in the long run though. This study provides valuable recommendations for China and other countries to achieve green economic recovery and reach climate goals in the post-epidemic era.

Keywords: COVID-19; Carbon emissions; Emission reduction effects; Green economic recovery; Post-epidemic era.
JEL Classification: E52; E58; E65.

Article history:
Received : June 06, 2022
Revised : December 12, 2022
Accepted : February 12, 2023
Available Online : November 30, 2023

https://doi.org/10.59091/2460-9196.1762

I. INTRODUCTION

The coronavirus pandemic (COVID-19), which began in early 2020, has been raging around the world and has a huge impact on human activities, thus contributing to record declines in global carbon emissions (Liu *et al.*, 2020a; Shamsi *et al.*, 2021; Yang *et al.*, 2021a). According to an authoritative report from International Energy Agency (IEA)[1], global carbon dioxide (CO_2) emissions are nearly 2 billion tons lower in 2020 than in 2019 due to COVID-19 (Jackson *et al.*, 2022). In terms of changing trends in CO_2 emissions, the world is still faced with the huge challenge of curbing greenhouse gas emissions while ensuring economic growth and energy security (Aktar *et al.*, 2021). The COVID-19 pandemic and its after effects and the successive climate changes are the two main challenges that prevent the global economy from achieving green recovery. As an active participant in global public health and safety, China has been under pressure from the international community to lessen carbon emissions (Hu *et al.*, 2022; Tian *et al.*, 2022). Since the announcement of China's "carbon peak" and "carbon neutrality" goals on the 75th United Nations General Assembly, Chinese governments at different levels have been committed to carbon reduction efforts. The goal of creating conditions to achieve "double control" of total carbon emissions and intensity at the earliest possible date was further proposed in the 2022 China Central Economic Work Conference, which will also become an important indicator for the central government's assessment of local provinces. In the context of the normalization of COVID-19 prevention and control, it is urgent to clarify the relationship between the COVID-19 pandemic and carbon emissions in order to achieve the green economic recovery as early as possible, and to better respond to the challenge of the global climate change (Nundy *et al.*, 2021).

The Chinese government adopted a policy of activity restrictions and embargoes right after the outbreak, which had a direct impact on key sectors such as energy and industrial production, and also led to changes on the consumption side (Vasiev *et al.*, 2020). Both the supply and demand sides of the economy were hit hard by the epidemic, causing severe socioeconomic losses (Sharma *et al.*, 2020). This further added uncertainty to achieving the established climate goals (Kuramochi *et al.*, 2020; Chen *et al.*, 2022). Specifically, the demand for traditional fossil energy, represented by coal and oil, has declined dramatically due to the sharp decrease in economic activity and mobility, resulting in a significant decline in energy-related carbon emissions (Wang and Su, 2020).

On the other hand, the blockade policy has led to a large reduction in electricity demand, increasing the share of renewables in the electricity supply and thus affecting the energy structure (Mastoi *et al.*, 2022). The IEA pointed out that the energy structure in the blockaded areas is clearly shifting towards low carbon, with the largest reduction in coal-fired power generation in China. Accordingly, this has a remarkable impact on China's carbon emissions and ultimately on global carbon emissions.

In this context, it is necessary to further test the short-term impact of the COVID-19 on carbon emissions and to judge whether the impact is sustainable,

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[1] See more details at: https://www.iea.org/articles/greenhouse-gas-emissions-from-energy-data-explorer

thus better understanding the opportunities and challenges brought by the COVID-19. In fact, studies have been conducted to examine the dynamics of carbon emissions under epidemic shocks. Liu *et al*. (2020b), Weir *et al*. (2021) used real-time satellite monitoring data to compare carbon emissions before and after the outbreak and concluded that the epidemic caused a remarkable decrease in global CO_2 concentration. Ray *et al*. (2022) further noted that strict blockades have played a key role in reducing global carbon emissions, but this carbon reduction effect would be unsustainable as global economic activity gradually recovers. Wang *et al*. (2022) evaluated the impact of the COVID-19 on carbon emission reduction in developing countries using a combinatorial simulation and showed that the impact was greater in developing countries compared to developed countries. While these studies note the benefits of the COVID-19 on air quality improvement, they lack analysis of how the COVID-19 acts on the environment and ignore the heterogeneous impact of the COVID-19 on carbon emissions. In addition, most studies have been conducted from a global perspective, comparing measured data to draw a conclusion on carbon emission reduction. However, fewer studies focus on how the COVID-19 affects China's provincial CO_2 emissions.

In view of this, 30 Chinese provinces are selected for this study. On the basis of the pandemic tracking data and carbon emission data from January to December 2020, econometric regression models are specified, and the pandemic shock is quantified to assess its impact on carbon emissions in China. Moreover, the regional heterogeneity and stage heterogeneity effects of the COVID-19 pandemic on carbon emissions are further discussed.

The main conclusion is that the COVID-19 has led to significant reductions in China's carbon emissions. In addition, the carbon reduction effect of the COVID-19 is more pronounced in carbon emission rights surplus areas. Meanwhile, the first half of 2020 has a greater improvement in air quality resulting from the epidemic than the second half. The main contributions of this study are twofold. First, compared with other related studies, this study focuses on the provincial level in China and uses econometric methods and models to assess the impact of the pandemic on carbon emissions, which can better reflect the dynamic changes of carbon emissions in China under the pandemic. It complements and enriches the studies exploring the COVID-19 and carbon emissions in the China context; for a survey, see Narayan (2021).

Second, although the reduction of carbon emissions during the pandemic is certain, this study assesses the static and dynamic impacts of the COVID-19 pandemic on carbon emissions in China using the GMM and other estimation methods. This provides quantitative evidence of the impact of the COVID-19 pandemic on carbon emissions and facilitates a fuller understanding about how the epidemic affects carbon emissions.

In addition, exploring the impact of the COVID-19 pandemic on China's carbon emissions will not only help China to further synthesize the experience and lessons learned from the pandemic, take timely and appropriate policy measures to promote green economic recovery and achieve the "dual carbon" target without delay.

II. METHODOLOGY AND DATA

A. Econometric Methodology

An panel data regression model is proposed to explore the impact of the COVID-19 pandemic on carbon emissions in each province of China, with reference to Xu *et al*. (2021). The model has the following form:

$$ce_{it} = \alpha_0 + \alpha_1 cov_{it} + \alpha_2 x_{it} + t_i + \varepsilon_{it} \tag{1}$$

where ce_{it} is the carbon emissions, cov_{it} is the COVID-19, $_{it}$ denotes all control variables, is the intercept term, α_1 and α_2 are the independent variable coefficients, t_i is the time-fixed effect, and ε_{it} is the random disturbance term.

The Generalized Method of Moments (GMM) is further employed in order to alleviate the possible endogeneity problem (Zhang *et al*., 2022). The endogeneity problem caused by the one-period lagged carbon emissions can be solved by the GMM estimator, hence the first-order lagged term of the explanatory variable is introduced and a dynamic panel model is constructed as in Equation (2). And the rationality of the model setting is judged by AR(2) test and Hansen test.

$$ce_{it} = \lambda_0 + \beta ce_{it-1} + \lambda_1 cov_{it} + \lambda_2 x_{it} + t_i + \varepsilon_{it} \tag{2}$$

B. Variables and Data Sources

(i) Explanatory variable. Carbon emissions (*ce*). Total CO_2 emission and carbon emission intensity are the main indicators to assess the level of carbon emissions. Carbon intensity is equal to CO_2 emission divided by Gross Domestic Product (GDP), which is the amount of CO_2 emission per unit of GDP (Ma *et al*., 2019). Compared with total CO_2 emission, carbon emission intensity can better reflect the relationship between regional economy and carbon emissions. Larger values of this indicator indicate larger carbon emissions relative to economic growth, and vice versa. Following Liu *et al*. (2020), we obtain the daily CO_2 emissions data for each sector in each province of China. We sum them up by month to obtain the CO_2 emissions from January to December of 2020, and divide by the monthly GDP of each province to get the monthly carbon emissions intensity of each province in 2020[2].

(ii) Core explanatory variable. COVID-19 (*cov*). The number of confirmed cases or deaths of COVID-19 is mostly used in existing studies to measure the severity of COVID-19 (Shamsi *et al*., 2021). Following Xu *et al*. (2021), the cumulative number of confirmed cases per month is used as the core explanatory variable in this study.

(iii) Control variables. Carbon emissions may also be influenced by other factors. Carbon emissions also tend to rise when energy consumption increases, especially when traditional fossil energy consumption is high (Abbasi *et al*., 2020). China's long-standing coal-based energy consumption structure and single energy consumption pattern have brought about serious environmental pollution. Since

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[2] Since China's National Bureau of Statistics does not publish monthly GDP for each province, GDP for January-December is obtained by dividing each province's quarterly GDP by 3 and deflating using the GDP index.

coal is much more carbon-intensive than other fossil fuels, releasing nearly twice as much CO_2 as gas per unit of coal burned, a coal-based energy structure inevitably leads to higher emissions intensity. In addition, industrial carbon emissions are one of the most important sources of anthropogenic carbon emissions. Many provinces in China are still dominated by heavy industries, and the experience shows a significant positive correlation between industrial development and carbon emissions (Lu *et al*., 2015; Wang and Yang, 2015). Clean energy development is conducive to the transformation of energy consumption structure, and the replacement of coal and oil consumption by clean energy represented by gas is beneficial to the reduction of carbon emissions (Dong *et al*., 2017). Foreign trade boosts a country's productive activities and expands the economic scale, thus increasing carbon emissions (Yan and Yang, 2010).

In light of the above, energy consumption (*ec*), industrial development (*ind*), clean energy development (*gas*), and foreign trade (*tra*) are introduced as control variables with reference to Wang and Wang (2020), Bertram *et al*. (2021), and Hu *et al*. (2022). Energy consumption is measured using monthly electricity production by province. Industrial development is measured by the value added of industry. Clean energy development is measured by the production of natural gas. And foreign trade is measured by the total import and export of goods. Since the core explanatory variable is expressed by the cumulative value of the statistics at each month-end, the cumulative growth rate is finally chosen to measure each control variable for consistency with its data characteristics. The cumulative growth rate refers to the development difference between the current month and the fixed base period, which can reflect the total growth rate of each indicator over a period of time.

Panel data for 30 provinces in China from January to December 2020 are used as the sample in this study (Tibet, Hong Kong, Macau and Taiwan are excluded due to missing data). The data are mainly obtained from Carbon Monitor website, China's National Health Commission, China's National Bureau of Statistics and EPS database. Descriptive statistics of the variables are shown in Table 1.

Table 1.
Statistical Description of Variables

This table provides detail data description of all variables considered in this study.

Variables	Definition	N	Mean	SD	Min	Max
ce	Carbon emissions	360	−4.435	0.748	−6.779	−2.840
cov	Covid−19	360	5.965	1.432	2.197	11.13
ec	Energy consumption	330	−1.130	6.798	−26.10	13.20
ind	Industrial development	330	−1.875	7.195	−46.20	6.900
gas	Clean energy development	330	5.211	20.63	−65.20	152.3
tra	Foreign trade	329	−3.666	16.23	−64.70	26.40

III. EMPIRICAL RESULTS AND ANALYSIS

A. Results and Analysis of Baseline Regression

First, OLS and LSDV regression methods are applied to test the impact of COVID-19 on carbon emissions in each province of China, and the estimated results are shown in Models (1)-(4) of Table 2. Among them, Models (1) and (3) examine the impact of COVID-19 on China's carbon emissions before the introduction of control variables, and Models (2) and (4) examine the impact of COVID-19 when control variables are introduced. The results show that the estimated coefficients of COVID-19 in both OLS and LSDV models are remarkably negative at least at the 5% level of significance. A substantial suppressive effect of the COVID-19 pandemic on carbon emissions in China during the observation period is evidenced. The goodness of fit of the equation is obviously improved after introducing control variables. The estimated coefficient of the core explanatory variable is still significant, although slightly decreasing in absolute value, indicating that COVID-19 and each control variable are more likely to be independent of each other and the addition of control variables has little effect on the estimated coefficients.

Second, considering that the current period carbon emissions are likely to be influenced by the previous period carbon emissions, the GMM model is further applied for regression to alleviate the endogeneity problem. The estimation results are shown in Models (5)-(6) in Table 2. According to the estimation results, the p-values of the AR(2) test and Hansen test are greater than 0.1, indicating that no second-order and higher-order serial autocorrelation is found in the disturbance terms, the instrumental variables are used appropriately, and the GMM estimation results are valid. Therefore, further analysis based on the GMM model is described below.

In the regression results of Models (5)-(6), the first-order lagged term of carbon emissions is significantly positive at the 1% level, indicating that the "time inertia" of carbon emissions exists. If the carbon emissions in the previous period is at a high level, the carbon emissions in the next period may continue to grow (Zhang et al., 2022). This suggests that carbon emissions growth in China is cumulative over time and is a problem that needs to be considered over the long term.

The estimated coefficient of COVID-19 in the GMM model is negative at least at the 5% significance level, indicating that a remarkable inhibitory effect of COVID-19 on carbon emissions is still found after controlling for the time-lagged effect of carbon emissions on itself. This is also in line with the reality that the epidemic lockdown policy has led to a reduction in people's activities outside the home, forced delays in the resumption of work in industries with a drop in demand for electricity, thus leading to a dramatic drop in carbon emissions. COVID-19 directly affects the consumption side and the production side, which translates into an impact on carbon emissions. On the one hand, the epidemic caused a delayed resumption of work in various industries after the Spring Festival holiday, resulting in a massive reduction in electricity demand and a marked drop in coal consumption by power generation enterprises, thus leading to a decline in carbon emissions compared to the same period last year. Specifically, the lockdown policy forced companies to shut down their production and operations to prevent further deterioration of the outbreak. Especially, production activities in industrial sectors that are more dependent on traditional fossil fuels were halted, leading to a dramatic fall in carbon emissions (Guan *et al.,* 2020). On the other hand, renewable energy has made an essential contribution to the low-carbon energy consumption structure. In addition, the strict lockdown policy led to a decrease in travel intensity, which also benefited air quality (Baldasano, 2020).

It is noteworthy that the lockdown policy is an unsustainable option for solving environmental problems (He *et al.,* 2020). Changes in lifestyle and energy use attitudes of consumers may be the primary way to support a low carbon transition in the post-epidemic era (O'Garra and Fouquet, 2022).

An empirical study by Iqbal *et al.* (2021) on energy consumption and CO_2 emissions in Pakistan during the epidemic is consistent with our research. That is, COVID-19 has changed the energy consumption pattern in Pakistan with a negative impact on CO_2 emissions. Energy demand falls sharply due to COVID-19. As a major generator of global carbon emissions, the energy sector, with its demand constraints, will inevitably lead to a reduction in its carbon emissions (Jiang *et al.,* 2021). It is worth pointing out that the negative impact of COVID-19 on carbon emissions maybe exist only in the short run, while this kind of impact may diminish in the long term. A rebound effect on carbon emissions in the post-epidemic era has been observed, and improving energy efficiency is the key to avoid retributive increase in carbon emissions (Wang and Wang, 2020; Li and Li, 2021).

As for the control variables, energy consumption and foreign trade have positive but insignificant effects on carbon emissions, while industrial development and clean energy development have negative impact on carbon emissions and pass the significance tests. The regression results for the control variables illustrate the following points. First, the current energy consumption structure of China requires urgent adjustment. The level of energy consumption, as characterized by electricity generation indicators, also indirectly reflects the deep-rooted problems on the energy supply side. That is, the fossil-based energy supply is adverse to the reduction of carbon emissions, so the impact coefficient is positive. However, the possible reason for the insignificant results is that the energy sector suffered a huge shock during the epidemic and the significant reduction in demand for electricity translated into an impact on carbon emissions (Haxhimusa and Liebensteiner, 2021). Consequently, no contribution is made to carbon emissions in the short run. Second, the larger the scale of foreign trade, the higher the carbon emissions. This indicates that a high energy-consuming and high-emissions trade growth model is still underway in China, and little low-carbon technology is found in exported goods. Foreign trade has somewhat sacrificed environmental quality and contributed to carbon emissions (Shahbaz *et al.,* 2017; Liddle, 2018). The development of foreign trade under the epidemic lockdown is stagnant, making this impact insignificant in the short term. Third, the higher the level of industrial development, the lower the carbon emissions. It indicates a downward trend in CO_2 emissions generated from industry per unit of output. In an indirect way, it reflects that the green transformation of China's industries has been effective, and the economic growth considering environmental benefits has a positive development trend. Fourth, the more clean energy represented by natural gas is developed, the more obvious the carbon reduction effect is. It shows that the root of the green transition depends on the cleanliness of energy. Effective and high-level provision of clean energy availability from the supply side and policy assurance is the key for decoupling economic growth from carbon emissions (Zhou *et al.,* 2017).

Table 2.
Results of Baseline Regression

This table reports the results of baseline regression. Symbols *, ** and *** indicate significance at the 10%, 5% and 1% statistical levels, respectively. Figures in () are the standard errors and those in [] are the *p*-values of the corresponding test statistics.

Variable	OLS		LSDV		GMM	
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
L.ce					0.184*** (0.008)	0.129*** (0.019)
Cov	−0.105** (0.027)	−0.073** (0.029)	−0.133*** (0.028)	−0.103*** (0.023)	−0.049** (0.020)	−0.081*** (0.024)
Ec		0.020*** (0.007)		0.010 (0.006)		0.002 (0.002)
Ind		−0.001 (0.007)		−0.018** (0.007)		−0.006** (0.003)
gas		−0.011*** (0.002)		−0.010*** (0.000)		−0.001*** (0.000)
tra		0.006** (0.002)		0.004*** (0.001)		0.002 (0.001)
cons	−3.809*** (0.166)	−3.879*** (0.178)	−3.926*** (0.131)	-4.371*** (0.181)		
R^2	0.041	0.147	0.119	0.220		
AR(2)					−0.439 [0.661]	1.106 [0.269]
Hansen					22.856 [0.821]	20.042 [0.272]

B. Results and Analysis of Robustness Test

The robustness of the findings is tested by replacing the explanatory and explanatory variables in this study. First, replacing the explanatory variables. Considering the different population base and infection base in each province of China, the data in absolute terms do not take into account the differences due to population size. Hence the COVID-19 infection rate is used to re-estimate the impact of COVID-19 on carbon emissions in each province of China. The COVID-19 infection rate is the cumulative number of confirmed COVID-19 cases at the month-end as a proportion of the total population in each province. Based on the GMM model, the regression results are shown in Models (7) and (8) in Table 3. Second, replacing the explanatory variables. The reduction of carbon intensity is a “relative reduction”, while the reduction of total CO_2 emissions is an “absolute reduction”. In terms of carbon emission stages, it takes some time to move from “relative reduction” to “absolute reduction” (Wang and Song, 2013). Since the total CO_2 emission is also one of the indicators for carbon emissions assessment, and the current status of carbon emissions in each region can be reflected more intuitively after excluding the economic growth factor, thus the regression is re-run with total CO_2 emissions as the replacement explanatory variable. The regression results are presented in Models (9) and (10) in Table 3. The regression results indicate that the higher the COVID-19 infection rate is, the more the carbon emissions tends to decrease during the observation period, and the higher the number of confirmed cases, the lower the CO_2 emissions. As for the estimated coefficients of the core explanatory variables, though the coefficient values changed slightly, the significance and signs are consistent with the baseline regression, demonstrating the robustness of the study results.

Table 3.
Results of the Robustness Test

This table reports robustness test results for two measures of replacing the explanatory and explanatory variables. Symbols *, ** and *** indicate significance at the 10%, 5% and 1% statistical levels, respectively. Figures in () are the standard errors and those in [] are the *p*-values of the corresponding test statistics.

Variable	Replacement of Explanatory Variable		Replacement of Interpreted Variable	
	Model (7)	Model (8)	Model (9)	Model (10)
L.ce	0.151*** (0.011)	0.132*** (0.027)	0.115*** (0.017)	0.132*** (0.042)
cov	−0.180*** (0.020)	−0.518** (0.024)	−0.055* (0.032)	−0.052* (0.026)
ec		−0.007** (0.003)		0.043*** (0.004)
ind		0.013 (0.009)		−0.016*** (0.005)
gas		−0.001*** (0.000)		−0.001*** (0.000)
tra		-0.000 (0.002)		0.000 (0.002)
AR(2)	1.235 [0.217]	1.022 [0.307]	1.186 [0.236]	1.106 [0.269]
Hansen	22.613 [0.794]	20.070 [0.141]	25.472 [0.602]	18.326 [0.369]

IV. HETEROGENEITY ANALYSIS

China promised to achieve carbon peak by 2030, and actively take both administrative means and market mechanisms to reduce carbon orderly, taking a gradual qualitative transition from carbon intensity control and total carbon control to carbon neutrality. The provincial allocation of carbon credits is a viable path for China to achieve the double carbon goal. As a scarce resource, carbon emission rights have to be prioritized to regions with better economic efficiency. Based on the actual situation of each region, the carbon emission right balance of each region is obtained by subtracting the theoretical allocation from the actual carbon emission right. A positive difference is a surplus of carbon emission rights, while a negative difference is a deficit of carbon emission rights. Regional differences in carbon emission rights are likely to affect the carbon emissions and carbon reduction potential of provinces during the epidemic. Hence, the study of Tian and Lin (2021) is drawn upon to further examine the impact of COVID-19 on carbon emissions by dividing the whole country into regions with a surplus and a deficit of carbon emission rights. 14 provinces with carbon emission rights surplus are observed: Beijing, Shanghai, Hubei, Jiangsu, Henan, Guangdong, Hainan, Qinghai, Heilongjiang, Sichuan, Yunnan, Jilin, Jiangxi and Guangxi, while the remaining 16 provinces are deficient in carbon emission rights. The estimation results of GMM are presented in Models (11)-(12) of Table 4. The results show that the impact coefficients of COVID-19 on carbon emissions are notably different in carbon emission rights surplus and deficit regions. The effect of COVID-19 on carbon emissions is remarkably negative in the carbon emission rights surplus region, while it is not significant in the carbon emission rights deficit region. This indicates that the carbon emission reduction potential by region is affected by the difference in the assignment of carbon emission rights. The decrease in carbon emissions nationwide during the epidemic is mainly brought about by the carbon emission rights surplus region. Possible reasons are as follows. First, provinces with carbon emission rights surplus have either a low level of energy consumption or a relatively reasonable energy use structure, hence objectively contribute to a low level of carbon emissions. The relatively small economy of individual provinces somewhat inhibits the energy consumption and thus increases the carbon reduction effect (Zhou *et al.,* 2021). Second, most of the provinces in the carbon emissions deficit region are in the middle level of economic development nationwide, and each of them is under pressure to reduce emissions. The relatively low rate of clean energy promotion and the widespread use of carbon-intensive sources are key drivers of their high carbon emissions (Nurdiawati and Urban, 2021). Third, Hubei Province, which is classified as a carbon emission rights surplus region, is the most affected by COVID-19 in 2020, with economic activity almost halted. And most of the provinces among the carbon emission rights deficit region are less affected by COVID-19 in socio-economic terms, resulting in significant heterogeneity in the carbon reduction impacts from COVID-19 (Wang and Su, 2020). Therefore, in general, the carbon emission reduction potential is more prominent under the COVID-19 outbreak in the carbon emission rights surplus region.

Epidemic prevention and control achieved a milestone victory in the second half of 2020 in China. Resumption of work and production is orderly promoted in localities, and carbon emissions will be increased by related social activities without doubt. For examining the stage-specific effects of COVID-19 on carbon emissions, the full sample is divided into two intervals for comparison, the first half and the second half. The GMM regression results are shown in Models (13) and (14) of Table 4. From the coefficients of the estimated results, the negative impact of COVID-19 on carbon emissions occurs mainly in the first half of 2020. The impact of COVID-19 on carbon emission reductions diminished noticeably later in the year, further demonstrating that the impact of COVID-19 is short-term. This is also consistent with the social reality that carbon emission reduction by COVID-19 is not a structural change as COVID-19 prevention and control goes normal, China's socio-economic operation gets normalized, and the order of production and life is restored with speed. Although COVID-19 has led to a substantial reduction in CO_2 emissions in the short term, bringing an additional contribution to the climate (Hu *et al.,* 2022), a rebound effect of carbon emissions in the post-epidemic era is inevitable. Adhering to the overall direction of green and low-carbon is the first. And coordinating epidemic prevention and control with economic development may be an effective way to prevent retaliatory growth in carbon emissions during economic recovery (Yang *et al.,* 2021b).

Table 4.
Heterogeneity Estimation Results

This table reports heterogeneity estimation results of Spatial heterogeneity and temporal heterogeneity. Symbols *, ** and *** indicate significance at the 10%, 5% and 1% statistical levels, respectively. Figures in () are the standard errors and those in [] are the *p*-values of the corresponding test statistics.

Variable	Spatial Heterogeneity		Temporal Heterogeneity	
	Model (11)	Model (12)	Model (13)	Model (14)
L.ce	0.335***	0.433***	0.233***	0.499***
	(0.060)	(0.058)	(0.029)	(0.021)
cov	−0.510***	0.053	−0.181**	−0.073*
	(0.124)	(0.041)	(0.077)	(0.039)
ec	0.011	−0.025**	−0.042**	0.106***
	(0.013)	(0.009)	(0.004)	(0.012)
ind	0.011	0.054***	0.061***	−0.040***
	(0.012)	(0.016)	(0.003)	(0.010)
gas	0.143***	−0.007***	−0.002	−0.002***
	(0.026)	(0.001)	(0.002)	(0.000)
tra	0.015	−0.001	0.002	0.004
	(0.011)	(0.003)	(0.002)	(0.003)
AR(2)	1.124	−0.075	0.324	−1.076
	[0.261]	[0.940]	[0.746]	[0.282]
Hansen	6.137	15.080	22.115	28.541
	[0.524]	[0.237]	[0.140]	[0.125]

VI. CONCLUSION AND POLICY IMPLICATIONS

In this study, econometric regression models are constructed based on the COVID-19 tracking data and carbon emissions data for each province in China from January to December 2020. Robustness of the baseline regression results is demonstrated by replacing variables. The impact of COVID-19 on carbon emissions in China is further analyzed based on the differences in carbon emission rights allocation and the phasing of the epidemic prevention and control. The following conclusions are drawn. As a whole, COVID-19 has a remarkable negative impact on the growth of carbon emissions in China. However, the carbon emissions reduction brought about by COVID-19 is not a structural change. Obvious regional and temporal differences are found in the effects of COVID-19 on carbon emissions. Carbon emissions are notably reduced by COVID-19 in the carbon emission rights surplus region, while this kind of impact is not significant in the carbon emission rights deficit region. The nationwide decline in carbon emissions owing to COVID-19 is mainly driven by CO_2 emissions reduction in carbon emission rights surplus areas. The positive impact of COVID-19 on carbon emissions reduction is more pronounced in the first half of 2020 than in the second half. And such influence is short-term and not sustainable. In accordance with the above findings, the subsequent policy recommendations are proposed.

First, it is essential to integrate epidemic prevention and economic development in a comprehensive manner, continue to adjust industrial and energy structures, and promote green and low-carbon economic development. In the post-epidemic era, it is time to sum up the experience and lessons learned from the crisis and take the resumption of work and production as a new opportunity for green low-carbon economic evolution. In the process of economic recovery, short-term economic stimulus policy instruments leading to concentrated projects with high pollution and emissions should be avoided, and the dependence on traditional industries should be reduced. Meanwhile, the adjustment of energy structure should be accelerated. On the one hand, traditional energy consumption represented by coal consumption should be lowered through efficiency improvement and machine renovation. On the other hand, the support for the development of renewable energy should be increased. Thus, to promote low carbonization of energy structure and explore the growth point of economic green recovery outside the traditional energy-consuming industries.

Second, regional heterogeneity should be taken into account and the carbon trading system should be gradually improved to promote regional coordinated emission reduction in the normalization of epidemic prevention and control. To cope with COVID-19, it is worthwhile to timely adjust the related business of carbon trading to ensure the normal operation of the carbon trading market. While clean technology penetration increases, it is also necessary to keep pace with the times to improve the carbon trading mechanism and make it a meaningful decarbonization driver for each region. For one thing, the overall plan should be reasonably formulated, and the provincial allocation model of carbon emission rights should be adjusted in a timely manner according to the differences in the economic development characteristics. For another thing, the dynamic evaluation mechanism should be fully implemented. Relevant laws and regulations should be improved to strengthen the management and supervision of carbon emission trading and create a favorable policy environment for carbon market operation. Thus, to make carbon trading more efficient and achieve the “dual-carbon” targets as early as possible.

Third, the driving factors of carbon emissions in the short and long term should be considered, and long-term carbon emission targets should be focused to prevent retaliatory growth of carbon emissions in the post-epidemic era. Green recovery measures that are consistent with long-term climate goals and sustainable development are required in accordance with local conditions. Specifically, the short-term carbon reduction effect generated by COVID-19 may be converted into a long-term sustainable carbon reduction effect by accelerating the “new infrastructure” and creating green job opportunities. Meanwhile, the publicity and promotion of low-carbon ideas should be stepped up, and the advancement and innovation of energy-efficient and emission-cutting technologies need to be encouraged. The application of energy-efficientand emission-cutting technologies also need to be emphasized to optimize the sustainable impact of technological achievements on carbon emission reduction effects.

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