Potential Impacts of Fukushima Nuclear Leakage on China's Carbon Neutrality—an Investigation on Nuclear Power Avoidance and Regional Heterogeneity

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Ten years have passed since the Fukushima nuclear accident, but its impact on the environment and energy consumption structure has continued up to now. This accident delayed the process of China's nuclear power construction and may have a certain potential impact on China's goal of carbon neutrality by 2060. This paper aims to properly understand the negative impact of the Fukushima nuclear leakage on China's nuclear power industry, to reawaken the attention of Chinese academic and governmental departments to nuclear energy, and to explore a reasonable path to achieve carbon neutrality. Based on the idea of a quasi-natural experiment, this paper collected the carbon emissions data of 30 provinces and cities in China from 2000 to 2017, and explored the accident impact and mechanism on carbon emissions in the provinces with nuclear power. The research results showed that the Fukushima nuclear accident had different impacts on China's nuclear power provinces. Due to the large proportion of manufacturing industry and high dependence on energy, the carbon emissions in Jiangsu Province rose after being impacted by the incident, in contrast, the research results in Guangdong and Zhejiang provinces were opposite. Through the mechanism test, it was found that the incident impact had reduced the carbon emissions of Guangdong and Zhejiang by improving the industrial structure and energy efficiency, with the explanation ratios of 10.45 and 15.1%, respectively. Technological innovation had obscured the emission reduction effect of the incident impact, and the innovation driving force for green development in nuclear power base provinces was insufficient. These findings are helpful to analyze the regional layout of China's nuclear power and have implications for achieving carbon neutrality. Finally, this study offers relevant policy recommendations.

Keywords: fukushima nuclear leakage, carbon neutrality, nuclear power avoidance, regional heterogeneity, synthetic control method

INTRODUCTION

In September 2021, under the dual pressure of insufficient power supply and actions to control the total and intensity of energy consumption, Northeastern China experienced widespread power outages, causing huge problems for industrial production and residential life, indicating that China's energy demand and emission reduction targets are in a complex interaction relationship. China needs to find a pathway to meet its continuously expanding energy demand and achieve its carbon neutrality targets. In addition to the divergence from energy demand, China's carbon-neutral goal is facing three challenges: First, some effective policy tools and realization paths are needed. Second, the carbon-neutral target reflects the long-term equilibrium of production activities and the natural environment. This goal cannot be realized with a simple method of total amount control. Almost all of the important economic departments will be involved in the project. At the same time, the negative effect of market competition may be revealed, especially the surge and waste in high-carbon consumer products. Third, the path to carbon neutrality is excessively tilted to exploit clean energy, consequently forming a "limping" development. It may create risks for energy security and energy system optimization, especially taking into account indirect and unstable power generation methods such as wind energy and solar energy. The development of the nuclear power industry can overcome these challenges. Therefore, it can be considered as an option for achieving carbon neutrality.

However, since the Fukushima nuclear accident, the public has become sensitive to the construction of nuclear power plants. The deeper reasons for resident's concerns about nuclear power are their dissatisfaction with untimely information disclosure and imperfect participation mechanisms and the like (Huang et al., 2013). Richard AMeserve, chairman of the *United States Nuclear Regulatory Commissio*n, pointed out that public attitude may determine whether nuclear technology can become a part of energy technology. So, how to coordinate the relationship between nuclear power construction projects and residents has become the key point to nuclear energy development.

Also, influenced by public sentiment, countries that originally worked hard to develop nuclear energy had to face the problem of nuclear power evasion. In which, China had issued countermeasures called *National Four Articles*. It brought the following impacts: 28 nuclear power units, already approved by the *National Development and Reform Commission* and started construction, can continue to be constructed. The construction of 6 nuclear power units, which have obtained the construction permit but have not yet started, had been suspended. 14 units that had been approved to enter the preliminary work cannot continue until the safety planning work was completed. Also, although inland provinces were striving for construction, at least 25 nuclear power plants here run aground. After the accident, the national policy for nuclear power development changed from active development to safe development, indicating that China's nuclear power will shift from high-speed development to slow and steady development. Further, the decreased scale and slowdown of nuclear power development may impact China's

carbon neutralization goal in 2060. In the post epidemic period, the use of nuclear energy may change many existing economic behaviors and economic results.

The changed nuclear energy policy also impacted China's energy structure and emission reduction effect. Considering China's commitment to global climate change, if avoid developing nuclear power, accelerating the installed capacity of renewable energy may become a good choice. Economic intuition shows that the proportion of renewable energy in China will rise, accompanied by less total carbon emissions. However, due to the terrain limitation of hydropower and the intermittence of wind energy and solar energy, nuclear energy cannot be fully replaced. This situation urges China to find a new balance between energy policy and environmental protection. Potential impacts like these are a complex matter, whether there exists a relation between the nuclear leakage accident and China's carbon emission needs further investigation.

The possible marginal contributions of this paper are three: First, the SCM used in this paper effectively overcomes the endogeneity of the model and the subjectivity of sample selection, and obtains more accurate estimation results. The robustness of the empirical results was tested by using Permutation Test, Falsification Test, PSM-DID, and controlling other policy influences. Second, this paper examines the impact of the Fukushima nuclear accident on China's nuclear power industry, especially inland nuclear power, and provides early recognition of the possible impact of nuclear accidents on China's carbon neutrality targets. Third, due to the nuclear power industry is related to national strategic security, many data are not available, making it difficult for the relevant literature to validate the model empirically through accurate figures, but only through cases. In addition, most of the research on nuclear power in recent years has been conducted from the legal and regulatory perspectives, and there is very little literature and research results from the economic perspective. This paper fills the relevant research gap and enriches the study of China's nuclear power industry.

LITERATURE REVIEW

Impact of Major Emergency Safety Incidents on Clean Energy

The Fukushima nuclear accident is the biggest nuclear disaster since the Chernobyl nuclear accident in 1986, which once again arouses people's attention to nuclear safety around the world (Butler et al., 2011; Hayashi and Hughes, 2013; Huang et al., 2013; Visschers and Siegrist, 2013), and moral issues related to nuclear safety, such as energy, pollution, environment, and health, have also become hot topics (Butler et al., 2011; Mao et al., 2015; Du et al., 2016).

The first clue is the direct impact of nuclear accidents on the development of nuclear power. After the nuclear accident, some countries changed their nuclear energy development strategy or even gave up nuclear power (Lee and Wang, 2014). Generally speaking, after the accident, the attitudes of various countries towards nuclear power development can be divided into two

camps: the nuclear abandonment faction, represented by Japan and Germany, and the nuclear improvement faction, represented by China and the United States (Butler et al., 2011; Joskow and Parsons, 2012; Kim et al., 2013; Ming et al., 2016). Nuclear abandonment refers to achieving the goal of abandoning nuclear energy by gradually reducing the number of nuclear power plants. In contrast, nuclear improvement emphasizes strengthening the rational development and utilization of nuclear energy, thus improving the safety of nuclear power. Some factors, such as the contradiction between the shortage of energy supply and the urgency of energy demand, and the advantages of nuclear power in terms of emission reduction and cost compared with traditional energy, determine that the overall trend of China's nuclear power development will not be reversed after the accident. However, the Fukushima nuclear accident did, to a certain extent, impacted the low-carbonization process of China's established energy structure, and inhibited the development of China's nuclear power. This is reflected in the following aspects: First, the speed of nuclear power development was affected. By the judgment of the *State Grid Energy Research Institute*, slowing down the start-up of nuclear power for 1–2 years will probably reduce the installed capacity by more than 10 million kW in 2020. Second, the shelving of China's inland nuclear power construction plan will affect the development of the central and western regions, which have a large population and are in urgent need of nuclear power (Zhu and Krantzberg, 2014). Third, the slow restart of nuclear power has a greater impact on equipment manufacturers, such as *Dongfang Electric* and *China Yizhong*, by November 2014, they had not even received orders for nuclear power equipment for the second year, which is bound to put pressure on China's subsequent nuclear power construction.

The second clue is the indirect effect of the nuclear accident, which means the impact of the nuclear fear triggered by the nuclear leakage. In general, due to the NIMBY effect, residents living near nuclear power plants have a negative attitude towards nuclear energy (Dan, 2007; Guo and Ren, 2017). This sentiment became more significant after the Fukushima nuclear accident (Kessides, 2012; Srinivasan and Rethinaraj, 2013; Lee and Wang, 2014). According to a survey of 18,787 adults in 24 countries by Laes et al. (2011), 62% of respondents opposed nuclear energy, and 26% reported that the Fukushima accident changed their original views. Among them, the Chinese people's attitude towards nuclear power has changed obviously, and residents around nuclear power plants are generally unwilling to build new nuclear power projects (Huang et al., 2013; Huang et al., 2018).

Under the nuclear fear sentiment, many anti-nuclear demonstrations and mass incidents broke out one after another in China. The nuclear fuel treatment plants in Heshan City, Guangdong Province, Lianyungang Nuclear Cycle Treatment Station Project, and Pengze Nuclear Power Plant Construction Project were all shelved due to opposition from residents. Under this situation, to balance the deviation between the international development trend and the domestic public opinion demand, the government adopted a conservative approach in formulating the nuclear power policy agenda. At

present, the fear of nuclear has brought far more losses to China than the nuclear leakage itself.

The third clue is the impact of the Fukushima nuclear accident on the rapid development of other clean energy sources in China. Before this nuclear leakage, scholars were already highly concerned about the development of clean energy, especially solar energy (Du et al., 2014). Studies have shown that more people support renewable energy than nuclear energy (McGowan and Sauter, 2005; Pidgeon et al., 2008). This trend was more obvious after the Fukushima nuclear accident. Research from Wallard et al. (2012) showed that the public prefers renewable energy sources, such as solar energy (97%), wind energy (93%), and hydropower (91%) to nuclear energy (38%). A group of scholars has turned their attention to renewable energy that may replace nuclear energy (Notter, 2015; Sorensen, 2017; Bilgili et al., 2021).

Methods for Evaluating the Impact of Exogenous Incidents

As a natural disaster and exogenous event, the Fukushima nuclear accident had different impacts on China's areas that had built nuclear power plants (Guangdong, Jiangsu, and Zhejiang), and those not. It can be regarded as a natural experiment. To study the impact of Fukushima nuclear accident on regional carbon emissions, we compared the changes of carbon emissions in experimental areas before and after the exogenous shock. However, many factors can affect regional carbon emissions.

A common measurement method to eliminate the general factors affecting regional carbon emissions is the Difference in Difference Method (DID). Its principle is to construct a treatment group with incident influence and a control group not. When studying the influence of exogenous shock effect on the treatment group, the control group naturally becomes a reference. The application of DID must satisfy the randomness hypothesis and the homogeneity hypothesis, in which the randomness hypothesis requires the sample selection to be random, and the homogeneity hypothesis requires the treatment group and the control group to have similar development trends before the implementation of exogenous shocks. But these hypotheses are often difficult to meet.

Compared to DID, the Synthetic Control Method (SCM) proposed by Abadie and Gardeazabal (2003) gives different weights to different control group individuals. Based on these weights, a counterfactual control group of policy intervention individuals is constructed to simulate the characteristics of the treatment group before being affected by a event, and the real treatment group value is compared with the synthetic value to obtain the event effect. SCM uses a data-driven method to give weights to synthetic individuals, and calculates out the contribution of each synthetic individual to the counterfactual control group. It effectively overcomes the subjectivity and endogeneity of sample selection, and makes up for the limitations of DID method in policy evaluation. In recent years, SCM has been applied to policy evaluation research in different fields. For example, Adhikari and Alm (2016) evaluated the economic effects of single tax reform through SCM and Kim

and Kim (2016) used it to test the implementation effects of green gas initiative policies implemented in the northeastern United States.

Methodology and Data

Based on the idea of counterfactual analysis, this paper used SCM to analyze the impact of Fukushima nuclear accident on China's nuclear power-owning provinces. The carbon emission (CE) index used in this paper was calculated according to energy consumption data and emission factors, following the emission accounting method of the *Intergovernmental Panel on Climate Change* (IPCC). The inventory includes energy-related emissions (17 fossil fuels in 47 fields) and process-related emissions (cement production). The calculation formula is as follows:

$$CE_{ik} = AD_{ik} \times NCV_k \times CC_k \times O_{ik} \qquad (1)$$

CE_{ik} refers to carbon dioxide emissions in area i; AD_{ik} is the consumption of fuel in area i; NCV_{ik} refers to the net calorific value, that is, the calorific value generated per unit of fossil fuel combustion. CC_k is CO_2 emissions per unit of net heat generated by fossil fuel k; O_{ik} refers to the oxidation rate of fossil fuels during combustion.

According to existing research, factors such as population size, economic development level, industrial structure, energy intensity, and opening-up level will affect carbon emissions. This paper selected these indicators as control variables, among which the urbanization level is the proportion of the urban population at the end of the year, and the data was taken from the *National Bureau of Statistics*. The level of economic development is expressed by the logarithm of regional GDP per capita. The data was taken from the *National Bureau of Statistics* and deflated with 2000 as the base period. The level of opening to the outside world is the ratio of total exports of domestic destinations and sources of goods to GDP. Import and export data came from the *General Administration of Customs* and was converted by the average exchange rate of RMB against the United States dollar in the current year. Data related to coal consumption and thermal power generation were taken from *China Energy Statistics Yearbook* (2001–2018). The energy intensity is the ratio of 10,000 tons of standard coal to the constant price of 10,000 yuan GDP. The relevant data came from *China Energy Statistics Yearbook* (2001–2018). The industrial structure is the ratio of regional industrial added value to regional GDP, and the data came from *China Statistical Yearbook* (2001–2018). The symbols and meanings of each variable were shown in **Table 1** and **Table 2** includes the descriptive statistics of the main variables.

Impact Effect Evaluation of Fukushima Nuclear Accident

With the different weights of the control group, SCM can minimize the Root Mean Square Prediction Error (RMSPE) of the experimental and synthetic control group before the exogenous event. The fitting of predictive control variables is shown in **Table 3**. It shows that the difference of RMSPE among Guangdong, Jiangsu, and Zhejiang is small, which are all less than

10. The predictive control variables, such as economic development level (*lngdppc*), population size (*lnpop*), urbanization level (*urb*), and industrial structure (*is*) in each area are very close to the real level. Among them, the carbon emissions of the synthetic area in 2000 and 2005 are highly similar to those of the experimental area, indicating that the SCM method in this paper fitted well.

The synthetic regional weights of the experimental provinces were shown in **Table 4**. Synthetic areas of Guangdong Province are Hebei (0.592), Liaoning (0.094), and Shanghai (0.315), indicating that the carbon emissions in Guangdong Province were closest to those in Hebei. Synthetic areas of Jiangsu Province are Liaoning (0.353), Shandong (0.489), and Shanghai (0.158), indicating that the carbon emissions in Shandong were most similar to those in Jiangsu. For Zhejiang, synthetic areas are Fujian (0.162), Henan (0.276), Shandong (0.154), and Shanghai (0.408). The basic situation in Shanghai was closest to Zhejiang.

Taking the time of the Fukushima nuclear accident as a boundary, we divided the sample divided into two parts: the pre-incident period (2000–2010) and the post-incident period (2011–2017). Then, we carried out SCM on three experimental areas with completed nuclear power facilities (Guangdong, Jiangsu, and Zhejiang), and the results were shown in **Figure 1**. Before the Fukushima nuclear accident, the actual carbon emissions of Guangdong, Jiangsu, and Zhejiang provinces generally had a good fit with the synthetic areas. After the incident, the carbon emissions of Guangdong and Zhejiang showed a downward trend, in contrast, Jiangsu showed a significant upward trend. This result is inconsistent with economic intuition: due to other clean energy in China cannot be increased quickly after the nuclear suspension, thermal power naturally became an important energy source to make up the energy gap, carbon emissions in the three provinces will then increase. We realize that this may be an important finding, and in subsequent analyses we will examine the reasons for this anomaly based on regional heterogeneity.

Validity and Robustness Test

A core issue, whether any relationship between Fukushima nuclear leakage and China's carbon emissions exists, needs to be confirmed. Because of losing the supply of nuclear energy, carbon emission increased in Jiangsu is foreseeable. However, carbon emission decreased in Guangdong and Zhejiang may be affected by other factors, for example, the carbon trading pilot policy launched in 2011, and other emission reduction measures implied by regional provinces. In general, carbon emission reduction is a global trend, even if there was no nuclear leakage, China's carbon emissions may present a decline. However, the occurrence of the Fukushima nuclear accident has almost affected all nuclear power countries, especially Japan and Germany, which changed energy strategy for public opinion and energy security. The prospect of China's nuclear power had been doubted by the mass and even some scientists. Some government officials believed China's nuclear power may fall into long-term stagnation. To address possible energy crises and emission reduction pressure, governments that lost nuclear power

TABLE 1 | Main indexes and calculation methods of synthetic control method research.

Variable type	Variable name	Symbol	Definition
Explained variable	Carbon emissions	CE	Calculated based on energy consumption data and emission factors. Unit: million tons
	Economic development level	lngdp	The logarithm of real regional GDP. Unit: 100 million yuan
	Industrial structure	is	The added value of secondary industry/regional GDP.
Control variable	Population size	lnpop	The logarithm of the population at the end of the year. Unit: 10,000 persons
	Coal consumption	lncoal	The logarithm of regional raw coal consumption. Unit: 10,000 tons
	Thermal power generation	lnthe	The logarithm of regional thermal power generation. Unit: 100 million kWh
	Energy intensity	ei	Consumption of standard coal (10,000 tons)/constant price GDP (10,000 yuan)
	Level of opening to the outside world	open	Total regional exports/regional GDP.
	Urbanization level	urb	Year-end urban population/year-end total regional population

TABLE 2 | Descriptive statistics for key indicators.

	(1) N	(2) Mean	(3) Sd	(4) Min	(5) Max
CE	540	236.141	177.377	8.700	842.200
lnthe	540	6.457	0.985	3.262	8.545
lngdppc	540	10.342	1.011	7.923	12.357
lnpop	540	8.155	0.757	6.248	9.321
lncoal	540	8.920	0.954	5.256	10.668
ei	540	1.683	0.933	0.459	7.102
open	540	0.235	0.295	0.008	1.787
is	540	0.463	0.078	0.190	0.615
urb	540	0.498	0.152	0.232	0.896

adopted new energy policies and stricter environmental regulations. Although nuclear power accounts for a small proportion of primary energy, the Fukushima nuclear leakage had a profound impact on regional and even national energy strategies.

To confirm the relationship between the nuclear leakage and China's carbon emissions, as well as test the robustness of the previous research results, we combined with the research experience of Abadie and Gardeazabal (2003), Abadie et al. (2010), and conducted the Permutation Test, Falsification Test, PSM-DID, and a method of controlling other policy impacts.

Permutation Test

The permutation test was used to eliminate the interference of other factors. We assumed all the control group areas had nuclear power and were impacted by the Fukushima nuclear accident in

2011. The synthetic objects are re-constructed through SCM, and compared with the actual carbon emission observations of each region (the impact effect is the difference between the actual observation values and the synthetic values of the region). Then, we got the distribution curves of placebo tests in the control group, and compared them with Guangdong, Jiangsu, and Zhejiang province, respectively. If there was a significant difference in the two kind curves, the exogenous impact significantly affected the real experimental area. Otherwise, further tests are needed.

We had 27 control group areas outside Guangdong, Jiangsu, and Zhejiang provinces. However, if the fitting effect of a certain area is poor (the mean square prediction error MSPE is very large) before the incident, the fitting result is not credible (Abadie et al., 2010). We calculated the MSPE of all areas according to **Eq. 2** in the pre-incident period, in which, y_{1t} is the area treated as an experimental object, $y_{jt,}$ and $w^{\star}$ are control group areas and their weights respectively. Finally, areas whose MSPE twice the experimental area before the incident were excluded. The placebo test results of the remained 21 areas were listed in **Figure 2**.

$$\text{MSPE}_{pre} \equiv \frac{1}{T_0} \sum_{t=1}^{T_0} \left(y_{1t} - \sum_{j=2}^{J+1} w_j^* y_{jt} \right)^2 \qquad (2)$$
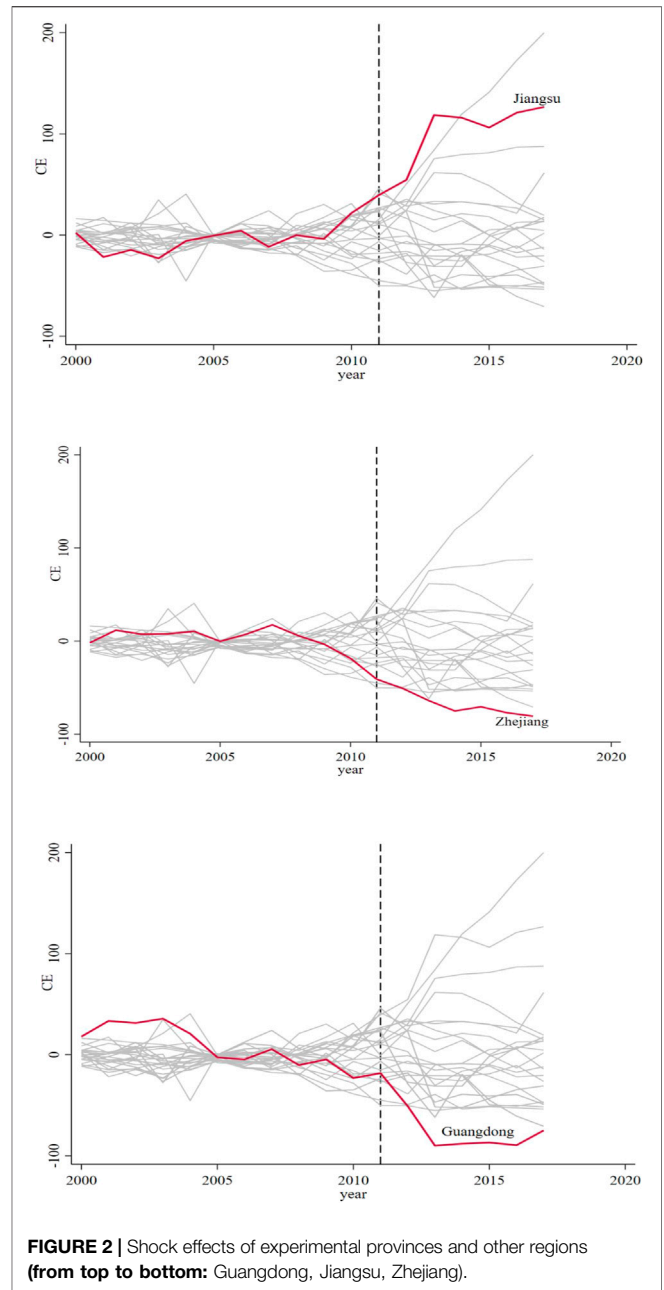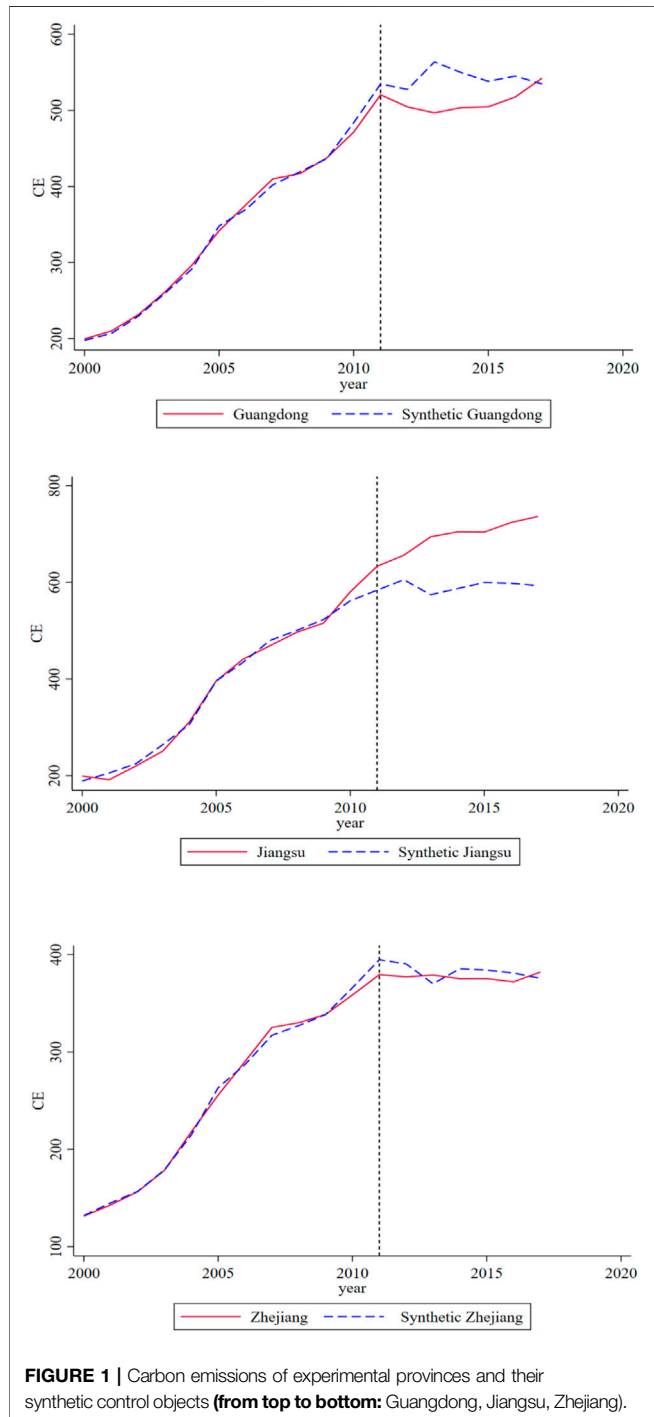
As shown in **Figure 2**, before the impact of the exogenous incident, the difference of the curves between the experimental province and other areas was little. But after 2011, the curves of Guangdong and Zhejiang was outside and different from others. If random disposal is given, only a 4.5% probability

TABLE 3 | RMSPE comparison chart.

Area	Prediction quality of applying composite control method before the exogenous event										
	RMSPE	CE (2000)	CE (2005)	lngdppc	lnpop	lncoal	lnthe	ei	is	open	urb
Real Guangdong	5.6147	199.60	341.80	10.35	9.15	9.23	7.46	0.95	0.51	1.29	0.60
Synthetic Guangdong		197.67	348.12	10.27	8.40	9.43	6.97	1.76	0.50	0.42	0.54
Real Jiangsu	9.9997	199.40	396.10	10.37	8.94	9.65	7.55	0.99	0.54	0.71	0.51
Synthetic Jiangsu		189.09	395.93	10.30	8.61	9.59	7.14	1.50	0.52	0.41	0.52
Real Zhejiang	4.3937	131.40	255.80	10.46	8.53	9.16	7.04	0.99	0.53	0.69	0.56
Synthetic Zhejiang		132.02	263.40	10.37	8.35	9.08	6.85	1.21	0.50	0.55	0.57

TABLE 4 | Weights of synthetic regions of experimental provinces.

Experimental area	Synthetic region (weight)			
Guangdong	Hebei	0.592	Liaoning	0.094
	Shanghai	0.315		
Jiangsu	Liaoning	0.353	Shandong	0.489
	Shanghai	0.158		
Zhejiang	Fujian	0.162	Henan	0.276
	Shandong	0.154	Shanghai	0.408

FIGURE 1 | Carbon emissions of experimental provinces and their synthetic control objects **(from top to bottom:** Guangdong, Jiangsu, Zhejiang).

FIGURE 2 | Shock effects of experimental provinces and other regions **(from top to bottom:** Guangdong, Jiangsu, Zhejiang).

that such an impact effect like Guangdong and Zhejiang will occur in other areas.

In contrast, the carbon emissions in Jiangsu kept growing at a high speed after 2011. Until 2013, the curve was located outside other areas, but after that, the curve fell and was surpassed by another one. It was not until 2 years later that the growth rate of Jiangsu's carbon emission decreased. However, on the whole, the curve of Jiangsu Province was located outside other areas. This impact effect was significant at the 5% level.

PSM-DID Robustness Test
Propensity Score Matching (PSM) can overcome the subjectivity in sample selection. The principle is as follows: for the individuals

TABLE 5 | PSM-DID robustness test.

Carbon emissions	Control group before adjustment	Processing group before adjustment	Difference between processing group and control group before adjustment	Adjusted control group	Adjusted processing group	Difference between process group and control group after adjustment	DID test results
Guangdong, Zhejiang	380.758	281.343	−99.415*** (−3.82)	583.877	377.203	−206.674*** (5.4)	−107.259** (2.32)
Jiangsu	379.389	387.23	7.841 (0.27)	542.01	693.247	151.237*** (4.12)	143.396*** (3.05)

*Note: The total number of control group samples in Guangdong and Zhejiang was 207, Jiangsu was 69, and R2 was 0.37 and 0.63 respectively. There are standard errors in parentheses, and ***, **, * represent significant at the level of 1%, 5%, and 10% respectively.*

in the treatment group, finding individuals with similar characteristics in the control group to match. Then the counterfactual results of the control group are estimated by the results of the control group. We selected variables such as economic development level, population size, and industrial structure as matching variables, constructed a logit model, matched samples following the kernel matching principle, and then carried out DID regression. The test results were shown in **Table 5**. The test results were negative in Guangdong and Zhejiang, and the opposite in Jiangsu, but the number of test samples in Jiangsu was small. It may be due to the particularity of Jiangsu's industrial structure, which makes it difficult to find matching samples. On the whole, the research results of PSM-DID are consistent with the previous studies, which proved the robustness of the above research conclusion.

Controlling Other Policy Impacts

In 2011, China launched carbon emission trading pilot projects in Guangdong, Shenzhen, and other places, which may overlap the impact effect of Fukushima incident in terms of carbon emissions. To avoid this interference, we excluded the sample involved in the project and re-conducts the PSM-DID. The results were shown in **Table 6**, the impact effect of the Fukushima nuclear accident was still significant, indicating that the Fukushima nuclear accident has a robust inhibitory effect on carbon emissions in some nuclear power bases in China.

All these results confirmed the Fukushima nuclear accident is an important factor that led to the decrease of carbon emissions in Guangdong and Zhejiang provinces, and the increase of carbon emissions in Jiangsu Province, rather than an accidental and insignificant factor.

An Analysis of the Influence Mechanism of Nuclear Leakage on China's Carbon Emissions

The results of validity and robustness tests confirmed that the Fukushima nuclear leakage affected China's carbon emissions. Furthermore, we were also concerned about the influence mechanism of nuclear leakage on carbon emissions in Guangdong and Zhejiang provinces.

Combined with existing research experience, the government's policies for carbon emission reduction mainly start from three aspects: technological upgrading, optimization of regional pollution level, and energy structure. Consequently, three emission reduction effects: industrial structure effect, technological innovation effect, and energy efficiency effect were generated. Referred to the methods of Wang et al. (2020), we used the intermediary effect test procedure to verify the transmission mechanism of the accident impact on emission reduction. The model is shown as **Eqs. 3–5**. Hausman test results showed that the fixed effect model is more suitable than the random effect model.

$$Y_{it} = \alpha_1 \times D_i \times T_t + \beta_m \sum \times C + \mu_i + \nu_t + \varepsilon_{it} \qquad (3)$$

$$M_{it} = \alpha_2 \times D_i \times T_t + \beta_n \sum \times C + \mu_i + \nu_t + \varepsilon_{it} \qquad (4)$$

$$Y_{it} = \alpha_3 \times D_i \times T_t + \alpha_4 \times M_{it} + \beta_0 \sum \times C + \mu_i + \nu_t + \varepsilon_{it} \qquad (5)$$

Where: D_i is a virtual variable. If region i was affected by nuclear leakage, D_i takes 1, otherwise 0; T denotes the time dummy variable, if $t > 2011$, $T = 1$, otherwise 0. M_{it} represents the intermediary variable of the impact of nuclear leakage. C is all kinds of control variables that affect carbon emissions, including economic development level, urbanization level, etc. u, v represent individual and year fixed effects respectively, controlling individual variables and time variables that may be missed, and ε is error term.

Nuclear Leakage Impact and Industrial Structure

Normally, for regional emission reduction, the regional governments will adjust the industrial structure through a series of environmental regulation tools. China's industrial sector is the main source of carbon emissions. Through a series of policies, governments increased the cost of production factors in industries with high energy consumption, forcing enterprises to reduce the elasticity of resource consumption of their products. Consequently, the development of enterprises was restricted. If enterprises want to survive, they must adjust their production methods and processes to increase the green degree of production. At the same time, industries in low-carbon life were encouraged to develop and expand. These factors drove the adjustment of the regional industrial structure, and the regional carbon emissions were reduced. We used the proportion of the added value of the manufacturing industry to GDP as the proxy variable of the industrial structure. The test results were shown in **Table 7**.

TABLE 6 | Robustness test for controlling other policy impacts.

Carbon emissions	Control group before adjustment	Processing group before adjustment	Difference between processing group and control group before adjustment	Adjusted control group	Adjusted processing group	Difference between process group and control group after adjustment	DID test results
Zhejiang	303.421	247.809	−55.612** (−2.39)	524.858	377.203	−147.655*** (4.75)	−92.043 ** (2.37)

The total number of control group samples in Guangdong and Zhejiang was 207, Jiangsu was 69, and R² was 0.37 and 0.63 respectively. There are standard errors in parentheses, and ***, **, * represent significant at the level of 1, 5, and 10% respectively.

TABLE 7 | Intermediary test of industrial structure.

	(1) Lnce	(2) is	(3) Lnce
D × T	−0.0821*** (0.0204)	−0.0133* (0.0073)	−0.0735*** (0.0192)
is			0.6451*** (0.1282)
lnpop	−0.5707*** (0.1396)	−0.2261*** (0.0358)	−0.4248*** (0.1319)
lnthe	0.4533*** (0.0247)	0.0517*** (0.0087)	0.4199*** (0.0259)
open	0.0268 (0.0344)	0.0444*** (0.0128)	−0.0019 (0.0336)
urb	0.2443** (0.1158)	0.0720 (0.0480)	0.1979* (0.1029)
Provincial effect	yes	yes	yes
Time effect	yes	yes	yes
_cons	6.7823*** (1.2157)	2.0786*** (0.3370)	5.4413*** (1.1585)
R²	0.987	0.835	0.988
N	540	540	540
Sobel-Goodman Mediation Tests			
Sobel		−2.641***	0.0083
Goodman-1(Aroian)	−2.621***	0.0088	
Goodman-2		−2.661***	0.0078

There are standard errors in parentheses, Sobel test reports z value and p value respectively, and ***, **, * represent significant at 1, 5, and 10% respectively.

In the table, the coefficient of D × T in the first column is negative, indicating that the loss of the nuclear energy supply, in Guangdong and Zhejiang, failed to increase their carbon emissions, in contrast, their carbon emissions were reduced due to their stricter emission reduction policies. The coefficient of D × T in the second column was also negative, indicating that the industrial structure decreased after the accident. Industrial production is the main source of regional carbon emissions, and industrial governance is the fastest way to reduce carbon emissions. After the Fukushima nuclear accident, to complete the task of reducing emissions, the local governments shifted attention from developing clean energy to changing industrial structure, imposing restrictions on cement, steel, and other industries, forcing these high energy consumption industries to develop in a green way. Owing to Guangdong and Zhejiang provinces had transferred out part high-energy consuming industries, compared with

Jiangsu, the proportion and energy dependence of the manufacturing industry were low. As a result, the two provinces can quickly respond to the accident and issue policies to restrict the development of high-energy consuming enterprises, thus realized regional emission reduction.

In contrast, the main source of GDP in Jiangsu was the manufacturing industry with high energy consumption. Higher energy demand will further increase the share of fossil resources in the energy mix (Alvarez-Herranz et al., 2017). Measures to limit energy consumption and reduce emissions do not play well here and are more likely to fall into a high carbon lock-in effect. Cheap and readily available thermal power was used to meet the needs of industry. Statistics from the *National Bureau of Statistics* show that, started from 2011, in all nuclear power base regions, the ratio of the added value of the manufacturing industry to the GDP in Jiangsu was highest. After the nuclear power construction was restarted in 2015, the speed of new nuclear power construction still cannot meet the energy demand of Jiangsu Province.

In the third column, the coefficients of D × T and is are significant, and the direct effect (α_3) and indirect effect ($\alpha_2 \times \alpha_4$) had the same sign. It is worth noting that $|\alpha_1| > |\alpha_3|$, indicating the nuclear leakage impact played a partial intermediary role in reducing regional carbon emissions. We used the Sobel test to analyze the intermediary effect of industrial structure. The results were listed in **Table 7**, which proved that the research results of this intermediary effect are robust. After calculating, the explanation ratio of reduced industrial structure to emission reduction is 10.45%.

Due to a different industrial structure, the Fukushima nuclear accident had a completely different impact on China's provinces with nuclear power.

Nuclear Leakage Impact and Technological Innovation

Technological innovation is another key factor in carbon emission reduction. Appropriate environmental regulations can promote enterprise innovation and improve competitiveness (Porter and Van der Linde, 1995). If the benefits brought by technological innovation are higher than the costs increased by environmental regulation, enterprises will increase investment in green innovation.

When most enterprises realized green production, the regional carbon emission decreased. In general, local governments will allocate carbon emission quotas to enterprises, or levy carbon taxes on enterprises based on certain standards. Environmental protection enterprises take the lead in completing emission reduction tasks and can sell surplus quotas. To avoid buying more carbon emission quotas or paying more carbon taxes, enterprises with high energy consumption and high emissions will increase green investment, so as to improve production methods and reduce carbon emissions. Based on the research experience of Choi and Choi (2021), we selected the natural logarithm of research and experimental development personnel (R&D) to measure the effect of technological innovation (*lntech*). The estimation was based on **Eqs. 3–5**, and the results were listed in **Table 8**.

Table 8 shows that the coefficient of D × T in the first column is negative, indicating that the emission reduction effect from the accident is significant. Similarly, the coefficient of D × T in the second column was also positive, indicating that the nuclear accident impact increased the investment in innovative resources in the regions. In the third column, the coefficient of D × T was negative, but the coefficient of *lntech* was positive, indicating that technological innovation failed to reduce regional emissions. The coefficients of indirect effect and direct effect were different and $|\alpha_1| < |\alpha_3|$. It indicates that the technological innovation was a masking effect in the emission reduction effect, and weakened the effect. Combined with China's actual situation, this unexpected discrepancy may be explained by the lack of enthusiasm for low-carbon innovation among China's high energy consumption and high emission enterprises.

Compared with investing in green innovation, enterprises are more willing to invest to improve productivity (Yang et al., 2017). The improvement of production efficiency can help enterprises to upgrade to the high end of the value chain, and the corresponding benefits can offset the increased cost caused by environmental regulations. The continuous expansion of energy demand from enterprises led to increasing carbon emissions. Therefore, only when enterprise's innovation investment turns to reduce pollution emissions per unit production, realizing the optimization and upgrading of industrial structure, can technological innovation plays a positive role in reducing carbon emissions.

Nuclear Leakage Impact and Energy Efficiency

To reduce the impact of environmental regulation, enterprises will include the increased environmental costs in the production costs. The internalization of enterprise environmental costs leads to the decline of enterprise profit (Copeland and Taylor, 2004). In the long run, if enterprises do not develop green production technology and improve energy efficiency, they may lose competitiveness and be forced to withdraw from the market. We used the ratio of regional GDP (reduced based on 2000) to regional energy consumption (10,000 tons of standard coal) to measure energy efficiency (*ee*). The estimated results were shown in **Table 9**.

TABLE 8 | Technological innovation intermediary test.

	(1) Lnce	(2) Lntech	(3) Lnce
D × T	−0.0956***	0.5651***	−0.1799***
	(0.0234)	(0.0813)	(0.0262)
lntech			0.1492***
			(0.0267)
lnpop	−0.7748***	0.5916***	−0.8631***
	(0.1975)	(0.1981)	(0.1887)
open	0.0608	0.1496	0.0384
	(0.0608)	(0.1099)	(0.0586)
urb	0.3307	0.6882*	0.2280
	(0.2131)	(0.3744)	(0.1717)
Provincial effect	yes	yes	yes
Time effect	yes	yes	yes
_cons	11.2469***	4.8770***	10.5193***
	(1.7053)	(1.7320)	(1.5373)
R^2	0.975	0.976	0.977
N	540	540	540

There are standard errors in parentheses, and ***, **, * represent significant at 1, 5, and 10%, respectively.

The test results in **Table 9** shows that after the nuclear accident in 2011, the energy efficiency in Guangdong and Zhejiang had further improved. Energy efficiency played a partial intermediary role in the relationship between the accident impact and the reduced carbon emissions. Sobel test results showed that the research results on the intermediary effect of energy efficiency were stable. After calculation, the explanation ratio of energy efficiency to emission reduction is 15.1%. The improvement of energy efficiency can be reflected by the optimization of energy structure. The *China Energy Statistics Yearbook* showed that, after 2011, the thermal power generation in Jiangsu Province maintained high-speed growth. In contrast, the thermal power generation in Zhejiang and Guangdong slowed down, indicating that the two provinces were trying to find alternative energy sources and reduce their dependence on thermal power. All these show that, to cope with the pressure of carbon emission reduction after the lack of nuclear power, governments of Guangdong and Zhejiang issued a series of policies. The production costs of polluting and high-emission enterprises were increased. To reduce environmental costs, these enterprises gradually improved the energy structure or adopted efficient and energy-saving production methods. As a result, the energy efficiency was improved, industries transformed to green development, and carbon emissions were reduced.

On the whole, the carbon emissions of China's nuclear power base provinces showed a downward trend after the Fukushima nuclear accident. However, the development process of China's nuclear power industry has indeed been delayed. According to the statistics of the *World Nuclear Association*, as of February 2020, there were about 45 nuclear power reactors in operation and 12 under construction in the Chinese mainland. The government's long-term goal was to reach 58 GWe capacity by 2020, with 30 GWe under construction. Judging from this data alone,

TABLE 9 | Energy efficiency intermediary test.

	(1) Lnce	(2) ee	(3) Lnce
D × T	−0.1053***	0.0669***	−0.0894***
	(0.0121)	(0.0207)	(0.0135)
ee			−0.2376**
			(0.1176)
lngdp	0.0916***	0.5277***	0.2170***
	(0.0352)	(0.0324)	(0.0699)
lnthe	0.2140***	0.0543***	0.2269***
	(0.0270)	(0.0208)	(0.0252)
lncoal	0.3714***	−0.4154***	0.2727***
	(0.0319)	(0.0265)	(0.0549)
lnpop	−0.1002	−0.0026	−0.1008
	(0.0784)	(0.0932)	(0.0735)
open	0.0137	−0.0311	0.0063
	(0.0249)	(0.0296)	(0.0243)
urb	0.1090	−0.1374	0.0763
	(0.0915)	(0.0952)	(0.0765)
Provincial effect	yes	yes	yes
Time effect	yes	yes	yes
_cons	0.2769	−0.1534	0.2405
	(0.7817)	(0.9360)	(0.7312)
R^2	0.993	0.942	0.993
N	540	540	540
Sobel-Goodman Mediation Tests			
Sobel		−1.662*	0.0964
Goodman-1(Aroian)	−1.632	0.1027	
Goodman-2		−1.695*	0.0901

There are standard errors in parentheses, Sobel test reports z value and p value respectively, and ***, **, * represent significant at 1, 5, and 10% respectively.

China's nuclear power development process has not reached the expected target. As an important part of clean energy, the lagging development of the nuclear power industry will affect the realization of China's carbon neutrality in 2060.

However, the impact of Fukushima nuclear leakage on China's carbon neutrality target goes far beyond these direct impacts. China's central and western regions have a large population and are in urgent need of nuclear power for development. The large energy demand has led to great pressure on carbon emission reduction in Shanxi, Inner Mongolia, Shaanxi, Ningxia, and other central and western regions (Li et al., 2021). The stranding of nuclear power construction projects in the central and western regions, which was caused by the Fukushima nuclear leakage, has not only become an energy bottleneck restricting the development of inland cities, but also hindered the early realization of China's carbon neutrality goal.

Conclusion and Policy Enlightenments

We treated the Fukushima nuclear accident as an exogenous shock, utilized the data of 30 provinces and cities in China from 2000 to 2017, and used the SCM to study the impact of the accident on carbon emissions in nuclear power base provinces. Furthermore, we examined the mediating effect of nuclear leakage on regional carbon emissions reduction from three aspects: industrial structure, technological progress, and energy efficiency. The conclusion of this paper are as follows: 1) After the Fukushima nuclear accident, the nuclear power plants in China's nuclear power-owning provinces (Guangdong, Jiangsu, Zhejiang) were suspended, and the nuclear power gap was filled by thermal power. However, under the pressure of national carbon emission reduction and doubts about nuclear power prospects, these provinces carried out endogenous changes, such as formulating stricter emission reduction policies and a new energy strategy, to reduce carbon emissions. On the whole, the carbon emissions in the three provinces did not rise but fall. However, considering the stranding of inland nuclear power projects, the potential impact of Fukushima nuclear leakage on China's carbon emission reduction may far exceed the direct impact already revealed. 2) Due to heterogeneous industrial structures, the impact of Fukushima nuclear leakage on provinces is different. Jiangsu Province, which had a high industrial structure, increased its demand for thermal power after losing the supply of nuclear power. Contrary to Guangdong and Zhejiang, carbon emissions in Jiangsu increased rapidly after 2011. 3) The emission reduction effect of nuclear leakage, in Guangdong and Zhejiang, was mainly realized through promoting the upgrading of industrial structure and improving energy efficiency, with explanation ratios of 10.45 and 15.1%, respectively. 4) The effect of technological progress on carbon emission reduction is a masking effect. It indicates the innovation driving force of China's green development is insufficient, and enterprises are more willing to put innovation investment into improving enterprise productivity, and make up for the increased environmental costs with the benefits brought by productivity improvement.

Based on these research conclusions of this paper, the following policy suggestions were put forward:

First of all, breaking the NIMBY effect and promoting coastal and inland nuclear power construction. The eastern nuclear power bases need to conduct a dynamic assessment of the safety of nuclear power development and publish the results promptly to improve public acceptance. For the central region in urgent need of nuclear power, the *National Development and Reform Commission* and local governments need to establish inland nuclear power pilot and advance areas after assessing the environment, population distribution, and public acceptance of each region, then promote nuclear power construction inland.

Secondly, realizing a rational industrial layout in China based on regional heterogeneity. Manufacturing costs in the eastern region remain high and the restrictions on resources and the environment are increasingly obvious. So, some industries in the eastern region began to shift to the central and western regions. Guangdong, Zhejiang, and other places have taken the lead. Compared to them, Jiangsu relies much on the manufacturing industry, most of which are labor-intensive and energy-intensive. This development path is unsustainable, so Jiangsu, and other areas similar to it, need to consider industrial transfer and realizing an advanced and green industrial structure. On the other hand, the cost of labor and land factors in central China is low, so under the

premise of ecology is not destroyed, they can undertake the transferred high energy consumption enterprises.

Thirdly, adopting appropriate policy tools. Environmental regulation tools, such as environmental standards and emission limits have strong control, in contrast, carbon emission trading and environmental subsidies provide continuous incentives for low-carbon innovation of enterprises. According to the research, environmental regulation can reduce carbon emissions in Guangdong and Zhejiang provinces by improving industrial structure and energy efficiency. However, when it comes to the whole country, it is necessary to consider the regional economic heterogeneity and adopt differentiated environmental regulation. In the eastern developed areas, such as Guangdong and Zhejiang, people have higher demands for green development, so it is suitable to adopt stricter environmental policies like environmental standards and emission limits. For the central and western regions with many resource-intensive industries, the adoption of strict policy may directly curb the lifeblood of regional development. Therefore, incentive policy tools, such as carbon emission trading and environmental subsidies, are suitable choices.

Finally, paying more attention to green innovation. Green innovation technology is an important factor to achieve high-quality development of the regional economy. Ignoring green innovation and focusing only on improving productivity will eventually bring a vicious impact on the environment. The reason for this situation may be that, the short-term income of green investment is not high, and external constraints are not enough to force enterprises to realize low-carbon transformation. Compared with traditional industries, the new energy industry has positive externalities, such as energy security and environmental friendliness, but it also faces the risk of insufficient competitiveness. Therefore, while the government continues to strengthen the environmental regulation on high energy consumption and high emission enterprises, it also needs to subsidize low-carbon development enterprises to enhance their competitiveness. Similarly, to avoid the transformation difficulties caused by high costs, the government needs to use financial tools to help high-energy-consuming enterprises transform into green production.

This paper presents a preliminary analysis of the potential impact of the Fukushima nuclear accident on carbon neutrality in China, but there are shortcomings. The study data in this paper are provincial, but the service area of a nuclear power plant is limited, so a larger study scale may bias the estimation of the impact level. In addition, the impact of the nuclear accident on carbon emissions in inland areas could not be analyzed quantitatively due to limitations in research data and research methods. Finally, now that Japan has decided to discharge its nuclear wastewater into the ocean, the potential impact of a nuclear accident on China goes beyond the nuclear power industry, other industries, such as fishing and mariculture, are likely to be affected by nuclear wastewater. Therefore, future research can be conducted in three aspects. First, based on this study, the scale of studies can be narrowed down to further analyze the impact of nuclear accidents on cities where nuclear power is located, and second, inland areas can be included in the study to explore the heterogeneity of the impact of nuclear accidents on coastal and inland cities. Third, scholars can analyze the impact of the Fukushima nuclear accident on China from multiple perspectives and industries, not just limited to the energy and environmental fields.

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

CL: Conceptualization, Resources, Methodology, Software, Validation, Formal analysis, XY: Writing—original draft, Methodology, Visualization. BL: Investigation, Data curation, ZY: Software, Validation, Writing—review and; editing. LZ: Conceptualization, Project administration, Supervision.

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