Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

The Low-Carbon Alternative: The Effects of The West-East Gas Pipeline Project On Energy Savings And Emission Reduction — Based On Empirical Research In Hubei Province

Jian Wu (546838437@qq.com)
North China Electric Power University - Beijing Campus: North China Electric Power University
https://orcid.org/0000-0001-6077-9659
Chunying Cui
Wenhua College
Xiaoman Guo
Nanjing Agricultural University

Research Article

Keywords: West-East Gas Pipeline Project, Energy conservation and emissions reduction, Carbon dioxide emission

Posted Date: August 10th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-708855/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Abstract

The extensive use of natural gas has created new opportunities for low-carbon primary energy composition, and has eased the peak value of carbon emissions before the complete transition to clean energy. To explore the impact of natural gas access on energy conservation and emission reduction in inland areas of developing countries, this study examines the policy intervention effects of the West-East Gas Pipeline Project in Hubei Province. In this paper, the causal inference of multi-bandwidth and multi-core analysis is made with breakpoint regression, and then the core conclusion of the counterfactual analysis is proven to be robust by using the synthetic control method. The results show that the transportation of natural gas from west-to-east to Hubei Province can reduce the intensity of carbon emissions, which demonstrates that it is an effective low-carbon energy alternative. The West-East Gas Pipeline Project can meet the demands of a large number of energy shortages caused by the rise of the manufacturing industry and can solve the energy bottleneck in the development process in the central and eastern regions of China. The West-East Gas Pipeline Project has ensured the coordinated development of the western, central and eastern regions in China, has stabilized the economic growth rate, and has achieved high-quality growth. These achievements can serve as a reference for guiding the energy conservation and emission reduction work of a considerable number of gas-importing central provinces.

Introduction

The search for sustainable development in China, a developing country and the single economy with the largest annual carbon emissions, is very important for long-term energy conservation and emission reduction. Both the global total carbon emission load, and the majority of low- and middle-income countries hopes to find a feasible path, aiming to ease the contradiction between their own development and carbon emission reduction, depend on China's energy conservation and emission reduction practices. For a long time, the use of low-carbon energy alternatives based on natural gas has been part of a staged approach towards carbon neutrality, which has been promoted in developed countries for many years. Although natural gas consumption has become a reliable low-carbon energy that contributes to economic growth, it does not achieve zero carbon dioxide emissions like nuclear energy and renewable energy. The increase in the proportion of natural gas consumption in the energy composition will initially reduce carbon dioxide emissions, but the long-term impact on carbon emission reduction is not sustainable, and it is not sufficient to support long-term goals such as peak carbon and carbon neutrality. However, it can serve as a solution as an alternative to high-carbon energy sources at this current stage. In addition to natural gas, the expansion and improvement of renewable and nuclear energy sources are essential to avoid global warming and climate change and to promote economic growth. However, the production cost of these renewable energies is high and requires a significant period of time to undergo the technical changes needed. In developing countries, energy conservation and emission reduction can be achieved while ensuring economic growth, which should be achieved through low-carbon energy alternatives. The development of natural gas industries also creates technical and economic possibilities for low-carbon alternatives in low- and middle-income countries. China's West-East Gas Pipeline Project is an example of a low-carbon replacement process for natural gas. The West-East Gas Pipeline Project, which is a major construction project for China to achieve the large-scale replacement of natural gas as a low-carbon alternative, and to ease the tension of energy consumption and reduce the intensity of carbon emissions, is a significant step for energy construction in Western China to promote the sustainable development of the overall economy (Qiao G, Chen X, Zhang Z, *et al.*, 2010). The West-East Gas Pipeline Project fundamentally alleviates the contradiction between the energy industrial production in Western China and the energy demands for the development of the urban agglomerations in the eastern and central parts of China, provides a domestic pipeline network channel for China's energy import trade, and provides an effective support for China's industrial economic growth.

The nationwide coverage of the natural gas transmission network has created favorable conditions for China to maintain the energy production and supply for economic growth, and is a major impetus for the progress of energy and power technology in the process of industrialization in China. As a low-carbon fossil energy, the unit combustion value of natural gas is higher than that of coal and other traditional energies, and the unit carbon emission is lower than that of high-carbon energy. In that renewable energy technology has not yet been fully replaced, natural gas is a reasonable low-carbon alternative for energy conservation and emission reduction (Azam A, Rafiq M, Shafique M, 2021). The West-East Gas Pipeline Project effectively reduces the proportion of high-carbon energy, such as coal, in China's energy consumption composition, which has an important effect on energy conservation and emission reduction (Peng Xu, Cui Herui, 2016; Li R, Su M, 2017).

As the largest developing country, China's economic development is not balanced. The western region is rich in energy resources, but its economy is lagging behind. The underdeveloped regions need to develop their economy through energy construction. In the eastern region, the large-scale urbanization and industrialization process has led to the continuous increase of energy consumption and carbon emission levels, the gradual increase of environmental carrying pressure, and the gradual relocation of high-carbon emission sectors (Xingping Zhang, Xiaomei Cheng, 2009). A large number of inland provinces in central China have absorbed many of the high-carbon emission industries that have transferred out of the developed coastal areas. In doing so, they need to seek sustainable development under environmental constraints. Therefore, the carbon emissions of primary energy sources and the economy development has become a dilemma in inland areas. In the eastern provinces, environmental policy constraints are significantly higher than those in the central and western regions. The willingness to use natural gas as a low-carbon alternative is firm and the effect is remarkable (Yadong Ning, Boya Zhang, Tao Ding, Ming Zhang, 2016). Hubei is a typical central natural gas importing province that benefits from the West-East Gas Pipeline Project. It is also a province experiencing an influx of industries leaving the eastern provinces. It is located in the central core area of the Yangtze River Economic Belt, where the task of environmental protection is also very serious. As the West-East Gas Pipeline Project winds its way through Hubei, it has transported a large amount of natural gas and has accelerated the switch to low-carbon energy. What role does the pipeline play in the energy conservation and emission reduction of Hubei Province? The answer not only affects the evaluation of China's policies of moving to natural gas as a low-carbon alternative, but also relates to how areas where manufacturing industries move in can work towards this same goal, as well as how to achieve sustainable growth in the inland areas of developing countries.

While there is no convincing empirical research to answer the above question, there has been a significant amount of empirical research on the economic promotion, energy conservation and emission reduction effects of natural gas consumption. Predecessors have fully discussed the above impact mechanisms, as well as the practical results of natural gas consumption and low-carbon consumption in various countries. However, when it comes to the related sub-topics, especially major energy transmission construction projects, there are few studies on the regional energy consumption intensity and the effect on carbon dioxide emissions. The reason may be that it is difficult for other countries and regions to carry out long-term pipeline construction projects like China. At present, only a few studies are related to the implementation of some transnational pipeline projects, including the energy pipelines across North America or from Russia to Western Europe (Sullivan, Sean, 2014; Chen Xiaoqin, 2021). As far as China's West-East Gas Pipeline Project is concerned, the existing research focuses more on the overall impression at the technical and macro- levels. The research objects are mainly for individual countries. There is a lack of empirical evidence concerning the energy conservation and emission reduction effects of the West-East Gas Pipeline Project in inland areas. Causal inference based on the counterfactual method is even scarcer in this field.

This paper intends to compare the energy consumption data of Hubei Province around 2012 at the time of operation of the second West-East Gas Pipeline, and make the main analysis through breakpoint regression with reference to relevant literature, and implement a robustness test combined with the synthetic control method (Wang Jun, Sun Zhijun, 2015; Chen Yi'an, Xu Jiayun, 2019; Jia Nan, 2020). The changes in scale and composition of energy consumption caused by the West-East Gas Pipeline Project in Hubei Province were quantitatively analyzed and observed to identify the impact of the policy implementation on the total energy consumption and energy composition of Hubei Province. The evaluation of the West-East Gas Pipeline Project holds value as a reference point for further energy conservation, emission reduction and high-quality growth in China's inland areas. At the same time, the evaluation may provide important insights for developing countries to reach economic growth and emission reduction goals, and coordinated regional development.

Research Hypothesis

A large number of studies have shown that the overall growth of a local economy has a significant impact on local energy consumption and carbon emissions (Xingping Zhang, Xiaomei Cheng, 2009; Osobajo Oluyomi A., Otitoju Afolabi, Otitoju Martha Ajibola, Oke Adekunle, 2020). The use of fossil-based energy not only increases local GDP, but also causes environmental pollution and reduces the possibility of sustainable development in the future. This is the main reason for China to implement energy conservation and emission reduction policies (Zhang Lei, 2016) .

Since China's 11th Five Year Plan, energy conservation and emission reduction have been considered as main economic growth targets for effective management, aiming to reach the long-term emission reduction targets through low-carbon alternatives. The structural improvement of primary energy sources, not only ensures China's economic growth rate and carbon emission control targets, but also gradually promotes the decoupling of overall economic development from the use carbon (Sheng Pengfei, Li Jun, 2021). Due to the substitution of natural gas consumption introduced by the West-East Gas Pipeline Project, carbon emission efficiency has been significantly improved in the Yangtze River Delta and other economically developed regions (Yadong Ning, Boya Zhang, Tao Ding, Ming Zhang, 2016).

Firstly, the study proposes a two-part hypothesis. Hypothesis 1a: The West-East Gas Pipeline Project can reduce the total amount of carbon emissions; Hypothesis 1b: The West-East Gas Pipeline Project can reduce energy consumption.

There are many studies concerning energy conservation and emission reduction of natural gas in academic circles, mainly focusing on natural gas a stage moving towards renewable energy, energy conservation, and emission reductions. Although renewable energy is an effective solution to help reduce carbon dioxide emissions, natural gas will help policy makers implement energy conservation and emission reduction policies (Li R, Su M, 2017; Azam A, Rafiq M, Shafique M, 2021). However, all countries have been actively introducing the substitution of natural gas in economic practices, so as to achieve the decarbonization of the power sector. The application of substituting natural gas for primary energy sources in energy conservation and emission reduction is a first step in achieving decarbonization targets in the power sector (Shearer C, Bistline J, Inman M, 2014; Wang Caiming, Li Jian, 2017). Empirical analysis from the United States shows that the practical application of natural gas in the power generation industry has greatly reduced the impact of high-carbon emissions of coal-fired power plants (Chang Kai, Song Xiayun, Tong Zhongwen, 2015; Wang D, Li T, 2018). The conclusions mentioned above have been verified by similar empirical studies from BRICs and other MLIC economies. Relevant studies show long-term feedback mechanisms among carbon dioxide emissions, natural gas consumption and renewable energy consumption. A 1% increase in natural gas or renewable energy consumption will reduce carbon dioxide emissions by 0.1641% and 0.2601%, respectively (Dong K, Sun R, Hochman G, 2017). Conversely, policies that impede the practical use of natural gas will hamper the long-term growth of local economies (Shahbaz M, Lean H H, Farooq A, 2013).

Secondly, the study proposes an additional hypothesis, Hypothesis 2: The West-East Gas Pipeline Project can improve the composition of energy consumption through the use of the low-carbon alternative of natural gas.

Although China's natural gas consumption accounts for a small proportion of its total energy consumption, it has grown rapidly in recent years. The consumption potential of natural gas varies greatly in different regions (Wang T, Lin B, 2017). With the implementation of the policy of reducing coal consumption, China's natural gas consumption is expected to increase accordingly, which may have a significant impact on China's energy security and the global natural gas market. There may be a serious shortage of natural gas (Chai J, Liang T, Lai K K, 2018) due to current economic development trends, the implementation of coal reduction policies, the potential of oil and natural gas prices to increase, *etc.* The natural gas market will develop rapidly and natural gas-fueled power generation will be the target of future natural gas market development in resource-limited areas. The Bohai Rim region will be a key area with the potential to experience a surge in natural gas demand (Yang J, 2018). The growth of natural gas consumption is of great significance to China's economic growth and energy composition optimization. The higher the economic level, the greater the marginal effect of natural gas on economic growth will be (Li Z G, Cheng H, Gu T Y, 2019).

The comparative study of natural gas application in different countries shows that the energy consumption intensity and carbon emission intensity will change with the introduction of natural gas. The proportion of natural gas consumption in the primary energy composition in developed countries has been advancing rapidly, which in fact forms the first-mover advantage of the United States and the European Union in the make-up of their low-carbon energy consumption (Ojonugwa Usman, Andrew Adewale Alola, Samuel Asumadu Sarkodie, 2020). In contrast, the consumption of natural gas in developing countries is uneven. Developing countries are faced with the dilemma of choosing a policy priority that focuses on either economic growth or pollution reduction (Awodumi O B, 2020). Firstly, the heavy industrial sector lacks funds and technology for technological transformation, and it is difficult to shift from traditional high-carbon energy to a low-carbon alternative through the introduction of natural gas. Secondly, the urgent need for economic development is unable to support the cost of laying a gas pipeline network on a large scale. Thailand's empirical research shows that high energy consumption caused by rapid economic growth leads to a large amount of carbon dioxide emissions (Phatchapa Boontome, Apichit Therdyothin, Jaruwan Chontanawat, 2017). The evidence from Pakistan shows that countries with slower economic growth have a stable relationship in which carbon dioxide emissions depend on the power generation structure over a long period, and the long-term balance between GDP growth and carbon dioxide emissions is easily affected by international energy prices (Mohiuddin O, Asumadu-Sarkodie S, Obaidullah M, 2016). It is optimistic that with the growth of per capita income in developing countries, natural gas consumption will increase, and the accompanying carbon dioxide emissions will gradually decline. Based on the small-scale data of the Middle East and South Asia, it is found that when the long-term income elasticity of local residents is less than the short-term income elasticity, carbon dioxide emissions decrease with the increase of income (Paresh Kumar Narayan, Seema Narayan, 2010).

Lastly, the study proposes a third, two-part hypothesis. Hypothesis 3a: The West-East Gas Pipeline Project will reduce the intensity of energy consumption; Hypothesis 3b The West-East Gas Pipeline Project will reduce the intensity of carbon emissions.

Methodology

3.1 Study design

Following the example of Flora Alarcon, Gregory Nuel (2019) and Shuai Ruan (2019), the breakpoint regression model is set in Hubei Province. The research logic is as follows: the West-East Gas Pipeline Project is used as the process variable, the total energy consumption as the explained variable, and the GDP and fixed asset investment as the driving variables. In addition, to avoid the bias of quantitative estimation method selection caused by only using the RDD analysis method, a synthetic control method was used to replace the breakpoint regression analysis and a placebo test was carried out. Finally, the model is confirmed and causality inference is carried out for the natural gas transmission policy of the West-East Gas Pipeline Project.

3.1.1 RDD setting

Breakpoint regression design has been applied in many fields since its creation. In this paper, the West-East Gas Pipeline policy is regarded as a policy impact. When the time continuous variable reaches a critical point, the probability of policy intervention on both sides of the point will form a local regression distribution. Because the driving variables, such as economic and social development in the province, are distributed continuously on both sides of the breakpoint, the values of the total energy consumption and carbon emission intensity in Hubei Province will fall into either side of the critical point, which is random. Therefore, as an analysis method closest to a natural experiment, breakpoint regression analysis can be applied in this study. In the evaluation of energy consumption in Hubei Province, if it is observed that there is a change in carbon emissions before and after the introduction of the West-East Gas Pipeline policy, and other factors affecting carbon emissions are continuously changing before and after this, then we have reason to believe that the change in carbon emissions is caused by the West-East Gas Pipeline. It can be inferred that the West-East Gas Pipeline has affected energy conservation and emission reductions in Hubei Province.

Therefore, the formula is established:

$$E=\{\tau_i \mid X_I = x_0\}=\frac{\mu^+-\mu^-}{\rho^+-\rho^-} \quad (1)$$

τ_i is the individual causal effect of the sample, $\tau_i=Y_{1i} - Y_{0i}$, $\mu(x)=(Y_i|X_i = x)$, $Y_i=Y_{oi}+\tau_i D_i$, P is the randomly determined intervention allocation state at the breakpoint, and the value is 0 or 1, which is the jump at the breakpoint. If the event intervention of The West-East Gas Pipeline causes the carbon emissions of Hubei Province to reach a certain critical point, there is a probability of discontinuity, but the potential result is a continuous function of the reference variable x, and the sample individual has no ability to choose the precise control of the reference variable, then it can be considered that the breakpoint is similar to the fully randomized natural experiment, namely quasi-natural experiment. If the above hypothesis is true, the type of adaptive precise breakpoint can be determined, and the corresponding average causal effect is:

$$E=\{\tau_i|X_I = x_0\} = \mu^+ - \mu^- \quad (2)$$

As a model to estimate the intervention Effect near the critical value, the breakpoint regression model is the Local Average Effect (LATE), and the estimation equation of the Local Average Effect at the breakpoint is as follows:

$$y_t=\alpha + \partial D_t+\beta(t_i-c)+\gamma(t_i-c)D_t+\delta X_t+\varepsilon \quad (3)$$

In the above formula, y_t is the result variable, which refers to the total amount of carbon emissions in *t* time; *D* is the processing variable, which is the policy of The West-East Gas Pipeline that has a key impact on carbon emissions in Hubei Province; when *t* is before the operation of the second West-East Gas Pipeline, it is assigned a value of 0; when *t* is after the operation of the second West-East Gas Pipeline, it is assigned a value of 1; c is the critical value, which refers to the operation time of the second West-East Gas Pipeline in 2012. The variable $(t_i\text{-}c)$ is the normalization of the grouping variable t_i, so that the breakpoint of $(t_i\text{-}c)$ is 0; X_t is a control variable and also a covariate, including per capita GDP, total GDP and fixed asset investment; the interaction term $\gamma(t_i-c)D_t$ allows for a different slope on both sides of the breakpoint.

3.2 Variable selection

3.2.1 Outcome variables

In this paper, according to the research methods of Jinwen Zhao, *et al.*, Jinwen Zhao, Jitao Fan (2007) and Huogen Wang and Lisheng Shen (2007), the regional energy consumption status was described on the basis of the total energy consumption. When the level of energy conservation and emission reduction was measured in a region, the total amount of carbon emission, with the characteristics of strong comprehensiveness and high comparability, is usually considered as the best indicator. In the robustness test, we also learn from the research of Guoquan Xu, Zeyuan Liu (2006), Shaozhou Qi, Jinpeng Huang (2017) *et al.*, that the carbon emissions were replaced by the total energy consumption, and we observe whether the policies promote local energy conservation and emission reduction to verify the consistency of the core conclusions.

3.2.2 Treatment variable

In this study, the operation of the second West-East Gas Pipeline Project is taken as the policy variable, and the policy intervention variable is taken as the key explanatory variable. Taking the start of the operation of the second line in 2012 as the boundary, the breakpoint regression model is used to observe the change in this key node, so as to better reflect the energy saving and emission reduction effects of the West-East Gas Pipeline Project in Hubei Province.

3.2.3 Control variables

Because economic and social factors, such as economic development, increases in investment and other policies, have an influence on the outcome variables, the Kuznets hypothesis can confirm the relationship between energy consumption and economic development. In this paper, following the methods used by

Dong K *et al.*, (Dong K, Sun R, Dong x (2018) and Li Z G, Cheng H, Gu TY 2019), GDP is employed to characterize the level of regional economic development ; per capita GDP is used to represent the living standard of residents; fixed assets investment is used to represent the development of regional industry. The common variables mentioned above may affect the total carbon emissions of Hubei Province.

3.3 Data and description of variables

In this paper, the research data are from Hubei Provincial Energy Consumption Survey of National Bureau of Statistics and Hubei Provincial Statistical Yearbook, spanning from 2008 to 2017. Firstly, the total energy consumption, including coal and natural gas, is sorted out. Then, GDP, AGDP and FIX are selected as driving variables. Finally, three important indicators are calculated to measure regional carbon emissions and energy consumption, so as to illustrate the energy savings and emission reduction levels of Hubei Province (Table 1).

Table 1
Descriptive statistics of variable observations

Variable meaning	Variable name	Mean	Standard error	Minimum	Maximum
Total energy consumption	TE	17.91848	0.363082	18.99023	17.91848
Coal consumption	Coal	17.91826	0.291124	18.87842	17.91826
Crude oil consumption	Crude	16.02994	0.270599	16.47501	15.55608
Gasoline consumption	Gasoline	15.29941	0.45725	15.82932	14.34124
Diesel consumption	Diesel	15.53884	0.41129	15.97684	14.77601
Fuel consumption	Fuel	13.86035	0.255468	14.21261	13.25339
Natural gas consumption	Gas	20.58075	1.529502	22.3319	18.14624
Electricity consumption	Electric	25.37518	0.438925	25.95384	24.64131
Carbon emission	TCQ	18.8406	0.44487	19.31563	18.04511
Per capita GDP	AGDP	9.923067	0.764433	11.00541	8.747193
Industrial output	Ind	26.83333	0.825866	27.898	25.54616
Population	Pop	9.66427	0.004763	9.6742	9.657971
Trade volume	Trade	23.47475	0.920484	24.55921	21.89354
Investment in fixed assets	FIX	27.21043	1.102862	28.80296	25.62051
Total retail sales of social goods	Rd	27.0263	0.748044	28.18457	25.91032
Gross domestic product	GDP	28.72258	0.748572	29.7816	27.4782
Emission intensity per unit output value	PGCEI	-9.88198	0.328001	-9.43309	-10.476
Energy consumption intensity per unit output value	PGECI	-10.1278	0.404719	-9.52447	-10.8215
Unit energy consumption and emission intensity	PECEI	0.245773	0.09485	0.375963	0.091383
Data source: Hubei Provincial Energy Consumption Survey of National Bureau of Statistics and Hubei Provincial Statistical Yearbook (2008–2017).					

Empirical Results

4.1 Analysis of RDD

In this paper, a nonparametric method is used to calculate the local average effect (LATE) near the breakpoint, so that the assumption of function form can be avoided, and the error occurs on both sides of the breakpoint. According to the study setting, the breakpoint is the processing variable representing the constants 0 and 1, and the grouping rule is that the value is assigned as 0 before the operation of the second West-East Gas Pipeline and 1 after the operation of the second West-East Gas Pipeline. In this paper, the reason for using exact breakpoint regression is that at the breakpoint, the sample is a precise jump of grouping probability from 0 to 1. The best choice of boundary estimation for local linear regression is triangular kernel, so this paper gives priority to the interpretation of triangular kernel analysis. The data of RDD analysis based on triangular kernel shows that the Wald coefficient of the second bandwidth of carbon emission, that is, when the bandwidth is 50, is positive but not significant. The other two bandwidth estimates show that the Wald coefficient is negative and significant when the bandwidth is 100.

Table 2
RDD estimation results of total carbon emissions

TCQ	Coef.	Std. Err.	z	*p*>|z|	[95% Conf.	Interval]
lwald	-0.1079747	0.0112085	-9.63	0	-0.12994	-0.08601
lwald50	0.02038					
lwald200	-0.0298572	0.0434046	-0.69	0.492	-0.11493	0.055214

The local Wald estimate is negative and the *p* value is significant (Table 1), which indicates that The West-East Gas Pipeline Project can effectively reduce carbon emission levels.

4.2 Results with covariates

Economic growth, increased investment, among other reasons will also have an impact on the total carbon emissions. This study considers that the results estimated only by the variables above are unstable, and this variable may include interference from other effects of regional economic growth. Therefore, in this study some covariates were added to verify whether the conclusions are consistent. Table 3 shows the breakpoint regression analysis of carbon emissions after adding GDP and fixed asset investments. By adding the covariates such as GDP and fixed asset investments, this paper further analyzes the energy conservation and emission reduction effects of the West-East Gas Pipeline Project on carbon emissions. After adding covariates, the breakpoint regression analysis results show that the energy conservation and emission reduction effect of the West-East Gas Pipeline is still significant in Hubei Province

Table 3
RDD estimation results of total carbon emissions after adding covariates

TCQ	Coef.	Std. Err.	z	*p*>|z|	[95% Conf.	Interval]
lwald	-0.3190832	0.0582408	-5.48	0	-0.43323	-0.20493
lwald50	0.02038					
lwald200	0.0251438	0.0781297	0.32	0.748	-0.12799	0.178275

With the addition of covariates, Wald's coefficient is negative, and *p* value passes the test (Table 3). Although changing the bandwidth has a certain impact on the LATE estimation, the three estimated values are all negative and still not significant. When bandwidth 100 is added into the covariate GDP and fixed asset investments, the *p* value passes the test, and the estimated value of bandwidth 100 added into the covariate RDD has little dependence on bandwidth (Fig. 2).

4.3 Impacts to total energy consumption

The data of RDD analysis based on triangular kernel shows that the Wald coefficient of the second bandwidth of total energy consumption, that is, when the bandwidth is 50, is positive but not significant. The other two bandwidth estimates show that the Wald coefficient is negative and significant when the bandwidth is 100 (Table 4).

Table 4
RDD estimation results of total energy consumption

TE	Coef.	Std. Err.	z	*p*>|z|	[95% Conf.	Interval]
lwald	-0.0492831	0.0331682	-1.49	0.137	-0.11429	0.015725
lwald50	0.0639801					
lwald200	-0.0602042	0.0487135	-1.24	0.217	-0.15568	0.035273

The obvious downward move can be seen when the bandwidth is 100, which verifies the causal relationship between the West-East Gas Pipeline and total energy consumption under the bandwidth of 100. After the operations of the second West-East Gas Pipeline, a large amount of natural gas began being transported to Hubei Province, thus reducing energy consumption, resulting in a downward drop. However, with the increasing speed of economic development, the production of a large number of energy-consuming products has also caused an increase in energy consumption levels (Fig. 3).

4.4 Impacts to the consumption of three representative energies

The RDD analysis of coal, crude oil and natural gas consumption of the three representative energy sources still adopt the nonparametric precise breakpoint regression method, and Wald's method is used to calculate the local average effect at the breakpoint of the second West-East Gas Pipeline. Descriptive statistical data show that the three representative energy consumption changes before and after the operation of the second West-East Gas Pipeline Project. Breakpoint regression can accurately estimate the extent to which the changes come from the implementation of the West-East Gas Pipeline.

Table 5
LATE analysis results of the three bandwidths of coal, crude oil and natural gas

coal	Coef.	Std. Err.	z	*p*>|z|	[95% Conf.	Interval]
lwald	-0.22506	0.075892	-2.97	0.003	-0.37381	-0.07632
lwald50	-0.00038					
lwald200	-0.15212	0.105172	-1.45	0.148	-0.35826	0.054012
crude						
lwald	-0.08538	0.054875	-1.56	0.12	-0.19294	0.022172
lwald50	-0.07957					
lwald200	-0.05436	0.071276	-0.76	0.446	-0.19406	0.085334
gas						
lwald	0.010476	0.056788	0.18	0.854	-0.10083	0.121779
lwald50	-0.09052	0.024445	-3.7	0	-0.13843	-0.04261
lwald200	-0.29406	0.189637	-1.55	0.121	-0.66574	0.077625

After the operation of the second West-East Gas Pipeline, the coal consumption drops and the Wald coefficient is negative. It passes the significance test at the bandwidth of 100, which is consistent with the assumption that the West-East Gas Pipeline can promote energy conservation and emission reduction in Hubei Province. After the operation of the second line, coal consumption decreases due to the large amount of natural gas being transported to Hubei Province. The use of natural gas reduces the demand for coal among residents, resulting in the reduction of coal consumption. It can be seen from the above figure that the Wald coefficient of crude oil consumption is also negative in the three bandwidths, and the coefficient passes the significance test when the bandwidth is 100 or 200. Crude oil consumption drops as the West-East Gas Pipeline Project passes through Hubei Province to transport a large amount of natural gas. As the substitution of natural gas for heavy polluting energy is more significant, the consumption of crude oil has decreased significantly under the constraints of local governments' energy conservation and emission reduction policies. The Wald coefficient of natural gas consumption is positive and passes the significance test at bandwidth 100. The opening of The West-East Gas Pipeline has transported natural gas from the western region to the eastern provinces, providing clean energy for the economic and social development of the provinces and cities along the route, while increasing the consumption of natural gas (Fig. 4).

4.5 Impacts on the consumption of other energy

The RDD analysis model and steps of the other three types of energy consumption for the West-East Gas Pipeline in this paper are the same as those above. Firstly, it is to determine whether there is an increase in energy consumption when the West-East Gas Pipeline Project is put into operation. Then the Wald Test is used for the local effect of the breakpoint under different bandwidths. According to the local Wald Test of the remaining three sources of energy, the *p* value of the three energy sources is always less than 0.1 under each bandwidth, which means it passes the significance test. This confirms the causal relationship between the West-East Gas Pipeline Project and the change in gasoline consumption. The estimated results are shown in Table 6.

Table 6
LATE results of the three bandwidths of gasoline, diesel and fuel

gasoline	Coef.	Std. Err.	z	*p*>|z|	[95% Conf.	Interval]
lwald	0.046995	0.002915	16.12	0	0.041283	0.052708
lwald50	0.129629					
lwald200	0.25189	0.085848	2.93	0.003	0.083631	0.42015
diesel						
lwald	-0.02405	0.003503	-6.87	0	-0.03091	-0.01718
lwald50	0.047557					
lwald200	0.091765	0.073176	1.25	0.21	-0.05166	0.235187
fuel						
lwald	0.012599	0.000138	91.27	0	0.012328	0.012869
lwald50	0.068966					
lwald200	0.170472	0.059851	2.85	0.004	0.053166	0.287778

The Wald Test analysis of gasoline consumption shows a positive number, and the *p* value under three bandwidths passes the significance test, with an increase. Secondly, through LATE analysis of diesel consumption, Wald's Test results show a negative number under the bandwidth of 100, and the *p* value is less than 0.1 under this bandwidth, which means that it passes the significance test. Finally, Wald's Test results of fuel consumption show a positive number. The *p* values of the three bandwidths all pass the significance test, and there is an increase at the breakpoint (Fig. 5).

4.6 Estimation of carbon-emissions

To better explain the effect of West-East Gas Transmission on energy conservation and emission reduction in Hubei Province, this paper selects the key indicators of carbon emissions, GDP and energy consumption for measurement. All three indicators can effectively explain the relationship among economic development, energy consumption and carbon emissions.

4.6.1 Emission intensity per unit output value

The emission intensity per unit output value is actually discussed from the perspective of development. This index refers to the carbon dioxide emissions per unit of GDP growth in the region, which is used to measure the relationship between economic growth and carbon emission growth. The accounting method is as follows: Emission intensity per unit output value = Carbon dioxide emissions/Unit GDP. The LATE results under the three bandwidths are shown in Table 7.

Table 7
LATE results of the three bandwidths of emission intensity per unit output value

PGCEI(TCQ/GDP)	Coef.	Std. Err.	z	*p*>|z|	[95% Conf.	Interval]
lwald	-0.0246417	0.0154227	-1.6	0.11	-0.05487	0.005586
lwald50	-0.0756207					
lwald200	0.0433971	0.0367648	1.18	0.238	-0.02866	0.115455

The Wald Test results of emission intensity per unit output value are negative when the bandwidth is 50 and 100. The *p* value passes the significance test when the bandwidth is 50, and the break point drops, with an even stronger result when the bandwidth is 50. It can be seen from the above figures that the emission intensity continues to decline, and the West-East Gas Pipeline Project causes a decrease at the breakpoint, indicating that natural gas substitution has a significant effect on reducing emissions (Fig. 6).

4.6.2 Energy consumption intensity per unit output value

While it is true that the energy consumption intensity per unit output value can reflect the dependence of economic development on energy consumption, as well as reflect industrial output, and the scale and composition of energy consumption of a region, the index can also indirectly reflect the effects of various energy conservation and emission reduction policies and measures. Therefore, the use of this index can be a good explanation of the effect of The West-East Gas Pipeline Project on energy conservation and emission reduction in Hubei Province. The accounting method is as follows: energy consumption per unit GDP = total energy consumption/GDP. The results of LATE analysis under the three bandwidths are shown in Table 8.

Table 8
LATE results of three bandwidths of energy consumption intensity per unit output values

PGECI(TE/GDP)	Coef.	Std. Err.	z	*p*>|z|	[95% Conf.	Interval]
lwald	0.0213671	0.0449925	0.47	0.635	-0.06682	0.109551
lwald50	-0.0320196					
lwald200	-0.0006605	0.04737	-0.01	0.989	-0.0935	0.092183

The Wald Test results of energy consumption intensity per unit output value is positive when the bandwidth is 100, and the *p* value is greater than 0.1, which does not pass the significance test. This means that it is impossible to prove the causal relationship between the West-East Gas Pipeline Project and energy conservation. The change in energy consumption intensity per unit output value is not observable, which indicates that the overall effect of energy conservation takes place over a long time, but the West-East Gas Pipeline does not affect this process, and the policy impact is invalid. The West-East Gas Pipeline Project is a low-carbon alternative for energy consumption, but energy savings are the result of continued technological progress (Fig. 7).

4.6.3 Emission intensity per unit of energy consumption

Emission intensity per unit of energy consumption can effectively reflect the regional energy composition. To reduce carbon emission intensity, we must start from the optimization of energy consumption composition, which is also the main aspect of developing a low-carbon economy and advocating for energy conservation and emission reductions in China. The accounting method is as follows: unit energy consumption emission intensity = carbon dioxide emissions/total energy consumption. LATE analysis results of the three bandwidths are shown in Table 9.

Table 9
LATE estimation results of three bandwidths of emission intensity per unit energy consumption

PECEI(TCQ/TE)	Coef.	Std. Err.	z	*p*>|z|	[95% Conf.	Interval]
lwald	-0.0785995	0.0410884	-1.91	0.056	-0.15913	0.001932
lwald50	-0.0436013					
lwald200	0.0004927	0.0539871	0.01	0.993	-0.10532	0.106306

The Wald Test results of energy consumption intensity per unit output value are negative when the bandwidth is 100 and 50, and *p* values are less than 0.1. This means they pass the significance test. When the bandwidth is 100, the breakpoint drops down significantly. The energy consumption emission per unit shows the carbon emission levels caused by energy consumption without considering economic output. After eliminating the price effect of natural gas, the net value of the effect of low-carbon energy technology demonstrates a downward breakpoint drop in the short-term, indicating that it is effective (Fig. 8).

Robustness Test

5.1 Test of kernel estimation change

In the RDD analysis, in order to ensure the robustness of the results, local linear regression of triangular kernel and rectangular kernel were carried out in this paper. Triangular kernel and rectangular kernel are separately used for RDD analysis, and the conclusions of the core interpretation remain unchanged (Fig. 9).

5.3 Covariate continuity test

A conditional density continuity test, including covariates, was performed. The above mentioned three stability tests were passed, and the conditional density continuity at the breakpoint of the covariable needed to be tested. This shows that the conditional density of covariates at the breakpoint of the second West-East Gas Pipeline in 2012 is continuous. This indicates that the conditional density of the covariable at the breakpoint of the operation of the second West-East Gas Pipeline in 2012 is continuous (Table 10).

Table 10
LATE analysis results of the three bandwidths of covariables

Energy	Coef.	Std. Err.	z	*p*>|z|	[95% Conf.	Interval]
GDP	-0.0721	0.009455	-7.63	0	-0.09063	-0.05357
AGDP	-0.06596	0.016737	-3.94	0	-0.09876	-0.03316
FIX	-0.03822	0.044368	-0.86	0.389	-0.12518	0.04874

Note: The smaller the $p > | Z |$ is, the more significant the parameter estimation is. Generally, it is considered to be statistically insignificant when $p > 0.1$.

5.4 Test of synthetic control method

To avoid the selection error of only using RDD analysis for measurement analysis, the synthetic control method (SCM), proposed by Abadie and Gardeazabal (2003), was used to replace breakpoint regression analysis and carry out a placebo test. SCM is a data-driven empirical measurement method, which can accurately identify the starting point of policy and observe the gap between the counterfactual value and the actual value. The model of this study is as follows:

$$P_{ij} = P_{ij}^{N} + C_{ij}\alpha_{ij} \quad (4)$$

In the above model, P_{ij}^{N} is the carbon emission status of the provincial administrative region that the West-East Gas Pipeline Project does not pass through, C_{ij} and expresses that if the West-East Gas Pipeline Project has passed through region *i* in *j* period, the variable is 1, otherwise it is 0. There are 31 provinces in China. The first West-East Gas Pipeline Project passes through Anhui, Shanghai and other provinces. The second line of the project passes through 9 provinces including Xinjiang and Gansu. We selected 12 provinces from the remaining 18 provinces to implement the placebo test. SCM was applied to 12 cities in turn, and the comparison results of policy effects were obtained (Fig.10). It can be seen from the figure that after the operation of the second West-East Gas Pipeline begin in 2012, the growth of synthetic carbon emissions is significantly higher than the original growth. The carbon emissions in Hubei Province show a continuous decline, which effectively indicates that the West–East Gas Pipeline had a significant effect on energy conservation and emission reduction in Hubei Province, thus proving that the results of this study are reliable. Overall, SCM also tests the exclusiveness of policy time points and the robustness of empirical conclusions.

Discussion

6.1 Analysis on the driving factors for the use of low-carbon alternatives

Through empirical analysis of Hubei Province, we find that the West-East Gas Pipeline Project has brought cheap and low-emission natural gas to a large number of importing provinces, which not only solves the bottleneck of energy demand in terms of total amount, but also solves the severe problems of high-carbon emissions and environmental constraints in terms of its composition. In this paper, the following three factors constitute the driving factors for the use of low-carbon natural gas as an alternative:

Firstly, the West-East Gas Pipeline Project can meet the rising energy shortage demands of the manufacturing industries in the central and eastern regions. After joining the WTO, the manufacturing industries of central and eastern China have grown rapidly, leading to an energy shortage due to this development. To solve the energy bottleneck in the central and eastern regions, the state plans to carry out energy distribution policies. In this way, a large amount of natural gas and renewable energy can be transported to the central and eastern regions through the West-East Gas Pipeline Project to meet this energy demand.

Secondly, as the price of renewable energy is expensive, low-carbon energy sources, such as combustible ice and natural gas, should be adopted. Compared to coal, these energy sources have lower carbon dioxide emissions, higher combustion values, better combustion effects, and higher thermal efficiency. Therefore, people prefer to use natural gas without considering emissions. Natural gas is not only cheap, but also has a high energy value and reduces carbon emissions. The West-East Gas Pipeline Project mainly transports natural gas to the central and eastern regions, which has a positive impact on the economy. These conclusions are more important for developing countries than for developed countries.

Finally, the provinces in the central and eastern regions are rapidly replacing other primary energy sources with natural gas. China attaches great importance to the West-East Gas Pipeline Project, which was implemented as an important energy construction project, having been continuously worked on for 17 years. During these past 17 years, the construction of the Phase I and Phase II extension lines have been continuously promoted to ensure that natural gas reaches most provinces in China. At the same time, pipeline nodes have been under construction in most counties. The West-East Gas Pipeline Project mainly solves the following problems: first, it solves the problem of making up the energy gap in the process of economic development in central and eastern China; the second is to solve the problem of low-carbon energy substitution in the process of high-quality growth.

6.2 Impact mechanism of energy consumption and carbon emission

Many previous studies have investigated the impact mechanism of natural gas pipeline transportation on energy consumption and carbon emissions. This research will explore the mechanism in the following four aspects.

Firstly, we must promote the coordinated development of the western, central and eastern regions. To fuel the economic growth and spur the development of the energy industry in western provinces, it is necessary to make full use of the West-East Gas Pipeline Project. There are large reserves of natural gas resources in western China, while there is a large demand for natural gas in eastern China. The West-East Gas Pipeline is the most convenient and effective channel for energy consumption, transfer, and distribution.

Secondly, like many other countries, China's economic modernization relies on urbanization, but urbanization itself has a significant role in promoting energy consumption and carbon emissions (Qiang Wang, Shidai Wu, Yue-e Zeng et al, 2016) [32]. Cross-national studies from 78 countries show that urbanization is characterized by low energy efficiency, high energy consumption and high emissions (Pengfei Sheng, Yaping He, Xiaohui Guo, 2017) [33]. The urbanization process directly results in the increase of populations living in urban areas, which leads to the surge of energy consumption of urban households (Hongtao Liu, Juanjuan Lei, 2018) [34]. In fact, China's economic boom is the result of the coordinated development of the central, eastern and western regions. In the central and eastern regions, the export sector is the main manufacturing industry, requiring a large amount of energy to be imported, while the western region relies on the production of resources and energy as the main economic pillar. Therefore, if the central and eastern regions want to drive economic growth in the western region, they must implement the rapid development of the energy industry in the western region through the bridge and lever of the West-East Gas Pipeline, so as to drive the coordinated development of the entire Chinese economic structure.

Thirdly, the industrial structure of coastal areas has begun to be optimized, upgraded and transformed, and a large number of manufacturing industries are transferring to the central region. As the coastal areas pursue more high-end manufacturing industries, medium-end manufacturing industries are being transferred to the central region, which must absorb a large number of industrial transfers from coastal areas. This process is the result of supply-side structural reform. While undergoing this process, Hubei Province, a major energy importing province, can use The West-East Gas Pipeline to ensure local economic development, energy conservation, and emission reductions, all of which are common problems in the development of the six central provinces of China.

Fourthly, there is still a problem between growth and environmental protection in the developing countries and regions around the world, that is, how developing regions can maintain their own economic growth rate and effectively control energy consumption and carbon emissions after industry shifts from more developed regions to developing regions, to achieve the goal of high-quality economic growth. Because natural gas has excellent power generation efficiency and lower carbon dioxide emissions per unit of electricity than coal, abundant natural gas resources will reduce the use of coal and renewable energy technologies. The practice of using low-carbon alternatives in the U.S. power sector shows that only climate policy can effectively curb future overall electricity consumption and carbon dioxide emissions (Ojonugwa Usman, Andrew Adewale Alola, Samuel Asumadu Sarkodie, 2020). Without strict restrictions on greenhouse gas emissions or explicit policies to encourage renewable energies, abundant natural gas may actually slow the process of decarbonization, mainly by delaying the deployment of renewable energy technologies. The Chinese government is scaling back coal-fired power plants across the country and replacing them largely with natural gas. Because the total installed capacity of power generation in China has been increasing, the energy structure of power generation has been adjusted to reduce the carbon emissions.

Conclusions And Implications

Using the breakpoint regression model, this paper takes the West-East Gas Pipeline Project as the policy variable, total energy consumption as the explanatory variable, GDP and fixed asset investment as driving variables. We constructed a quasi-natural experiment of The West-East Gas Pipeline on energy consumption in Hubei Province. In view of the continuous distribution of relevant reference variables in the vicinity of the second West-East Gas Pipeline, the variable breakpoint increase observed in 2012 at the start of operations can be used to show the causal effect caused by the implementation of the West-East Gas Pipeline policies. Based on this, the paper studies the energy savings and emission reduction effects of The West-East Gas Pipeline Project in Hubei Province. The results are as follows:

(1) Natural gas consumption brought by the West-East Gas Pipeline Project has helped regulate total energy consumption.

(2) The West-East Gas Pipeline Project is an effective low-carbon alternative and reduces carbon emission levels. A substantial amount of natural gas was transferred to Hubei Province through the West-East Gas Pipeline Project, thus the use of other energy sources, such as coal, was reduced, reducing the intensity of carbon emissions.

(3) The West-East Gas Pipeline Project can change the composition of primary energy consumption and optimize the proportion of low-carbon energy, so as to optimize energy consumption intensity and reduce carbon emission intensity under the existing technical conditions.

Through the above analysis conclusions, we put forward the following suggestions:

1) The governments of developing countries can popularize the use of natural gas through the construction of pipelines to implement the structural substitution of low-carbon energy and complete energy conservation and emission reduction in stages. The Chinese government puts great emphasis on the West-East Gas Pipeline Project and takes it as an important energy source, which has ensured the success of the construction of the pipeline

2) Energy conservation and emission reduction need to be implemented in stages to achieve even further substitution from low-carbon to zero-carbon. It is difficult for developing countries to engage in the large-scale replacement of clean energy at a high cost. Before technological advancement effectively popularizes the low-cost green energy production, the energy conservation and emission reduction need long-term overall planning. Solutions for low-carbon energy should be gradually found, after which effective and cheap solutions for clean energy should be sought.

3) For low- and middle-income countries, economic growth is constrained by high energy costs. Therefore, the price of natural gas consumption is cheaper than that of other renewable energies, which can better realize the tolerance mechanism of energy consumption in the process of growth. However, the price mechanism of natural gas still needs to be sorted out. Only low-carbon energy consumption with long-term cost advantages can promote the implementation of energy conservation and emission reduction in low- and middle-income countries.

4) The long-term nature and high economic and social costs of natural gas pipeline construction require developing countries to have a stable domestic political environment and an inclusive environmentalist mentality. The emerging economies represented by China still have abundant economic strength to carry out long-term construction projects. For less-developed countries and regions, external economic assistance and domestic social and political identity are indispensable factors for long-term energy construction projects.

Declarations

Data availability statement The research data are from Hubei Provincial Energy Consumption Survey of National Bureau of Statistics and Hubei Provincial Statistical Yearbook, spanning from 2008 to 2017.

Declarations This study was purely registry based, as no human participants were recruited or included in experiments.

Ethical approval Ethics approval is not required for this paper.

Consent to participate Not applicable.

Consent for publication Not applicable.

Authors' Contributions WU and CUI developed the idea of the study; WU participated in its design and coordination and helped to draft the manuscript. GUO contributed to the acquisition and interpretation of data. WU and CUI provided critical review and substantially revised the manuscript. All authors read and approved the final manuscript.

Declaration of competing interests: The authors declare no competing interests.

Funding This paper is supported by the science and technology research project of Hubei Provincial Department of education "Research on the impact mechanism of energy consumption and export trade in Hubei Province" (No. B2019305).

References

1. Abadie A, Gardeazabal J (2003) The economic costs of conflict: A case study of the Basque Country. American economic review 93(1):113–132
2. Awodumi OB, Adewuyi AO (2020) The role of non-renewable energy consumption in economic growth and carbon emission: Evidence from oil producing economies in Africa. Energy Strategy Reviews 27:100434
3. Azam A, Rafiq M, Shafique M et al (2021) Analyzing the effect of natural gas, nuclear energy and renewable energy on GDP and carbon emissions: A multi-variate panel data analysis. Energy 219:119592
4. Chai J, Liang T, Lai KK et al (2018) The future natural gas consumption in China: Based on the LMDI-STIRPAT-PLSR framework and scenario analysis. Energy Policy 119:215–225
5. Chang Kai S, Xiayun TZ (2015) Chinese Energy Consumption and Carbon Emission Intensity on EKC Effects under the Constraint of Energy-saving and Emission-reduction. Science Technology Management Research 35(14):206–209
6. Chen X (2021) Analysis of Russia’s Asia-Pacific Energy Strategy: From the Perspective of the Far East Oil and Gas Pipeline Project. Northeast Asia Forum 30(02):100–112 + 128
7. Chen Yi’an, Xu Jiayun. Talent misplacement and innovation: the empirical evidence from China. World Economic Paper, 2019 (06): 71–87
8. Dong K, Sun R, Dong X (2018) CO2 emissions, natural gas and renewables, economic growth: assessing the evidence from China. Sci Total Environ 640:293–302
9. Dong K, Sun R, Hochman G (2017) Do natural gas and renewable energy consumption lead to less CO_2 emission? Empirical evidence from a panel of BRICS countries. Energy 141:1466–1478
10. Alarcon F, Gregory Nuel. Detecting latent exposure in genome-wide association studies using a breakpoint model for logistic regression. Statistical Methods in Medical Research, 2019, 28 (6)
11. Hongtao, Liu, Juanjuan Lei. The impacts of urbanization on Chinese households' energy consumption: An energy input-output analysis. Journal of Renewable and Sustainable Energy, 2018, 10 (1)
12. Jia Nan (2020) The Impact of Retirement on Urban Household Financial Assets Selection in the Aging Context—Based on Fuzzy Regression Discontinuity Design. Statistical Research 37(04):46–58

13. Li R, Su M (2017) The role of natural gas and renewable energy in curbing carbon emission: case study of the United States. Sustainability 9(4):600
14. Li ZG, Cheng H, Gu TY (2019) Research on dynamic relationship between natural gas consumption and economic growth in China. Struct Change Econ Dyn 49:334–339
15. Mohiuddin O, Asumadu-Sarkodie S, Obaidullah M (2016) The relationship between carbon dioxide emissions, energy consumption, and GDP: A recent evidence from Pakistan. Cogent Engineering 3(1):1210491
16. Ojonugwa Usman AA, Alola, Samuel Asumadu Sarkodie (2020) Assessment of the role of renewable energy consumption and trade policy on environmental degradation using innovation accounting: Evidence from the US. Open Access Renewable Energy 150:266–277
17. Osobajo Oluyomi A, Afolabi O, Ajibola OM, Oke Adekunle. The Impact of Energy Consumption and Economic Growth on Carbon Dioxide Emissions. Sustainability, 2020, 12(19)
18. Narayan PK, Narayan S (2010) Carbon dioxide emissions and economic growth: Panel data evidence from developing countries. Energy Policy 38(1):661–666
19. Xu P, Herui C (2016) Research on the Effects of Energy Structure Adjustment in China on Carbon Intensity. Journal of Dalian University of Technology (Social Sciences) 37(1):11–16
20. Pengfei Sheng Y, He X, Guo. The impact of urbanization on energy consumption and efficiency. Energy and Environment, 2017, 28(7)
21. Phatchapa Boontome A, Therdyothin J, Chontanawat (2017) Investigating the causal relationship between non-renewable and renewable energy consumption, CO2 emissions and economic growth in Thailand. Energy Procedia 138:925–930
22. Qi Shaozhou H, Jinpeng. The Impact of Total Carbon Emission Control on Economic Development in the 13th Five Year Plan Period: a case study of Hubei Province. Hubei Social Sciences, 2017 (05): 70–75
23. Qiang Wang S, Wu Yue-e, Zeng et al. Exploring the relationship between urbanization, energy consumption, and CO 2 emissions in different provinces of China. Renewable and Sustainable Energy Reviews, 2016, 54
24. Qiao G, Chen X, Zhang Z et al. Mechanical properties of high-Nb X80 steel weld pipes for the second west-to-east gas transmission pipeline project. Advances in Materials Science and Engineering, 2017, 2017
25. Shahbaz M, Lean HH, Farooq A (2013) Natural gas consumption and economic growth in Pakistan. Renew Sustain Energy Rev 18:87–94
26. Shearer C, Bistline J, Inman M et al (2014) The effect of natural gas supply on US renewable energy and CO2 emissions. Environmental Research Letters 9(9):094008
27. Sheng Pengfei L, Jun Z, Mengxin et al. Economic growth efficiency and carbon reduction efficiency in China: Coupling or decoupling. Energy Reports, 2021, 7

28. Shuai Ruan. Early Warning Effect of “Wearing Cap” and “Catching Cap” on the Company’s Risk Structure —Empirical Research Based on Breakpoint Regression Design. Modern Economy, 2019, 10 (3)
29. Sullivan SSNL, Energy: Pipelines Aim for Chicago as North American Market Adjusts to Marcellus. Pipeline & Gas Journal, 2014, 241(12)
30. Wang D, Li T (2018) Carbon emission performance of independent oil and natural gas producers in the United States. Sustainability 10(1):110
31. Wang T, Lin B (2017) China's natural gas consumption peak and factors analysis: a regional perspective. J Clean Prod 142:548–564

Figures

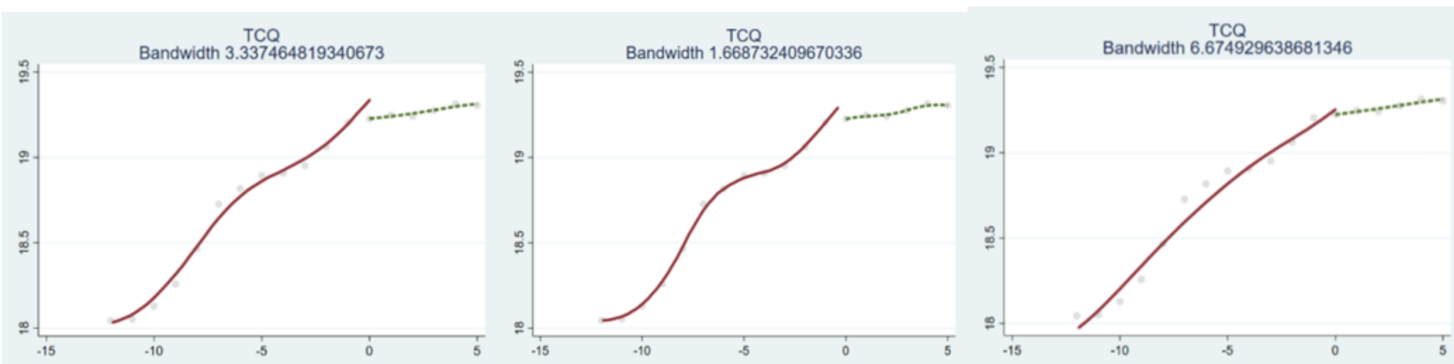
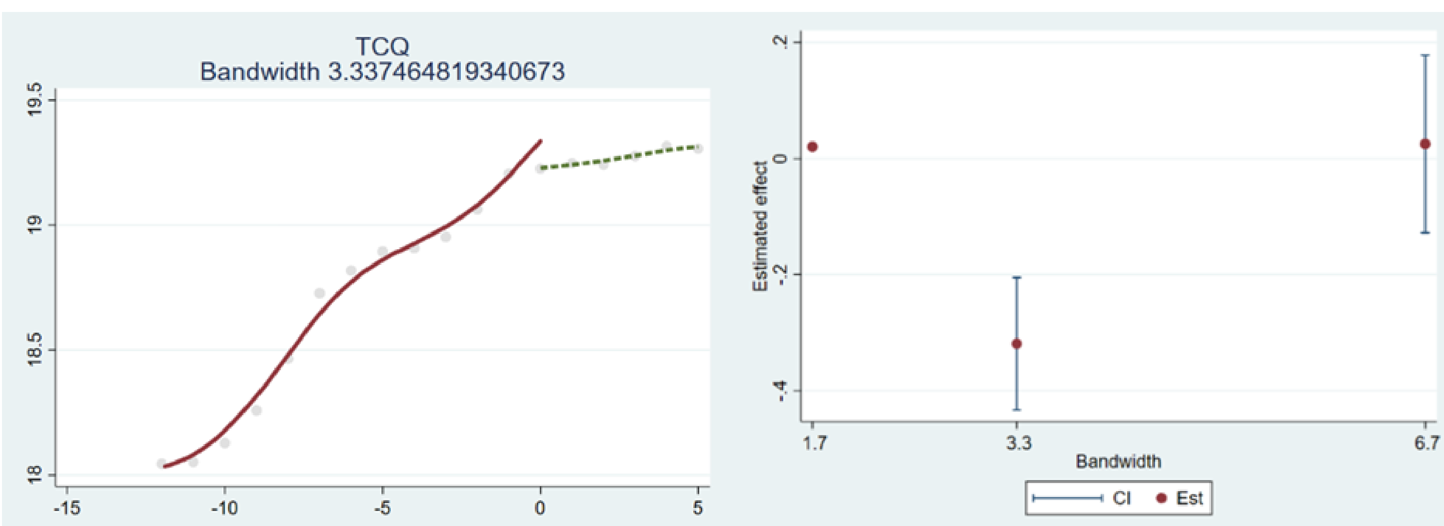


Figure 1

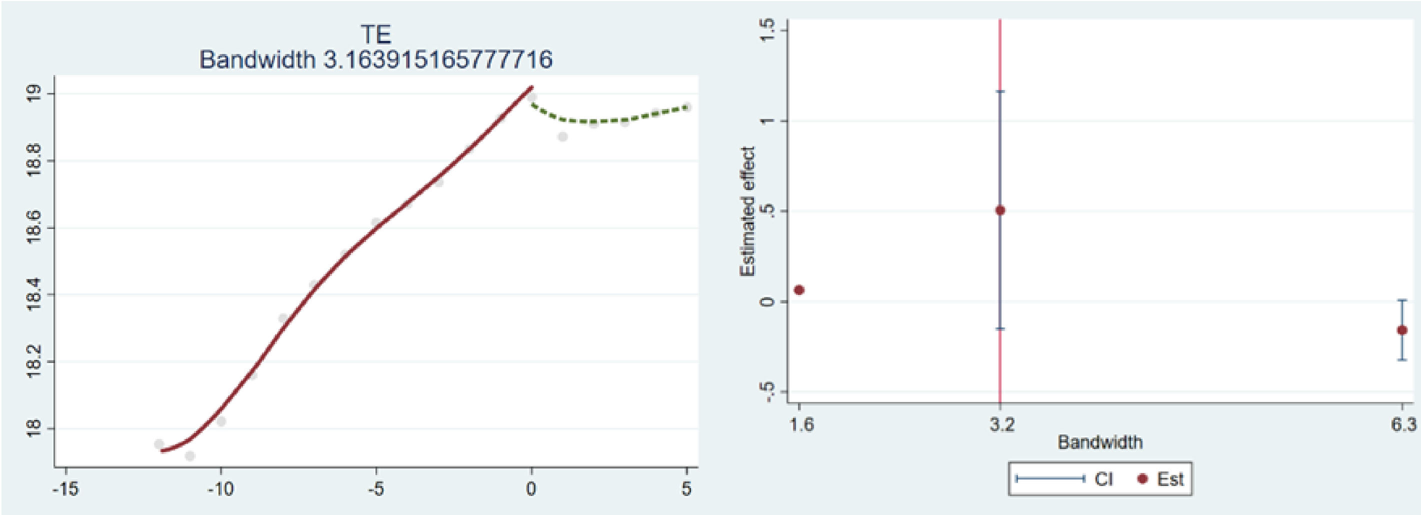
RDD diagram of three bandwidths of total carbon emissions



A) TCQ 100 after adding covariable; B) Bandwidth dependence detection

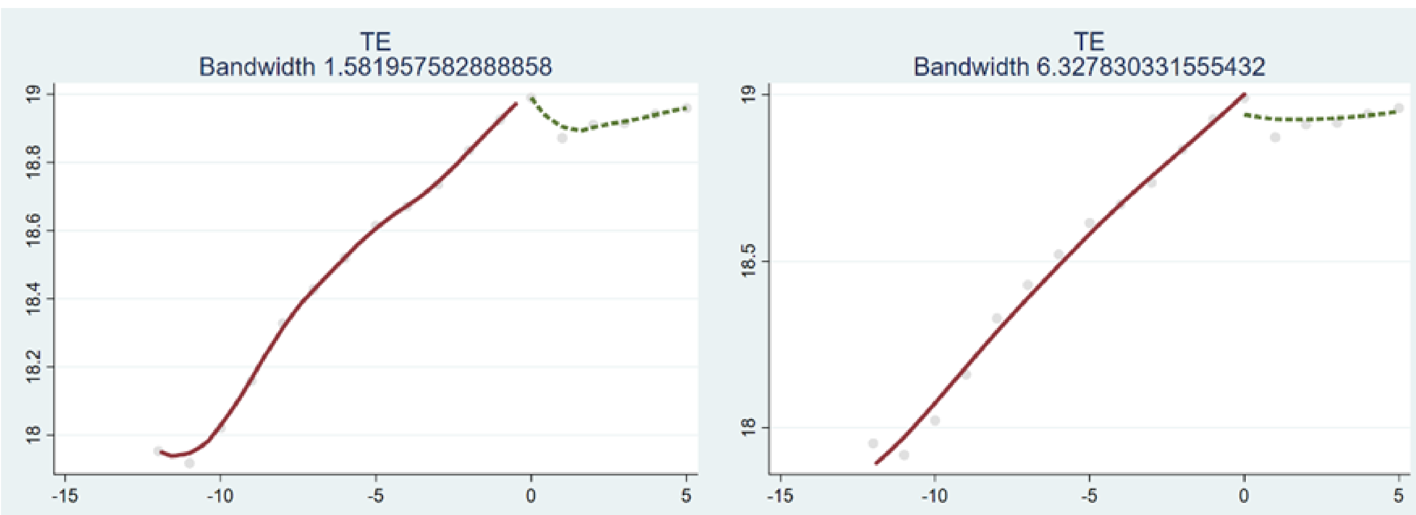
Figure 2

RDD diagram of bandwidth 100 and dependency test of total carbon emission



a) TE100

b) TE sensitivity test

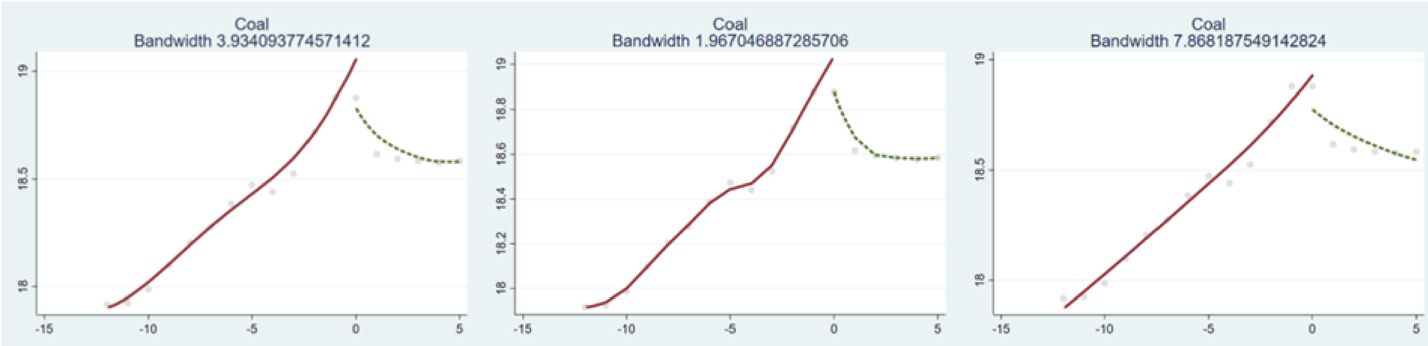


c) TE50

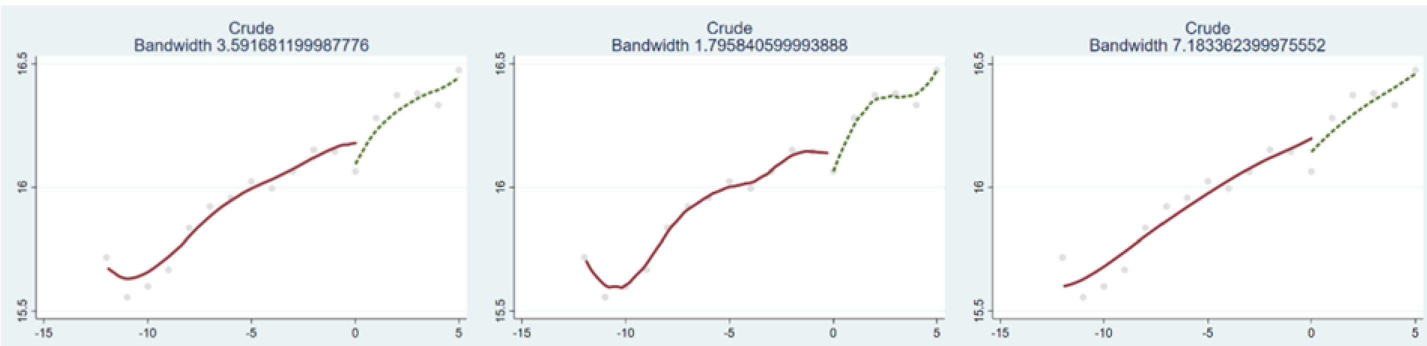
d) TE200

Figure 3

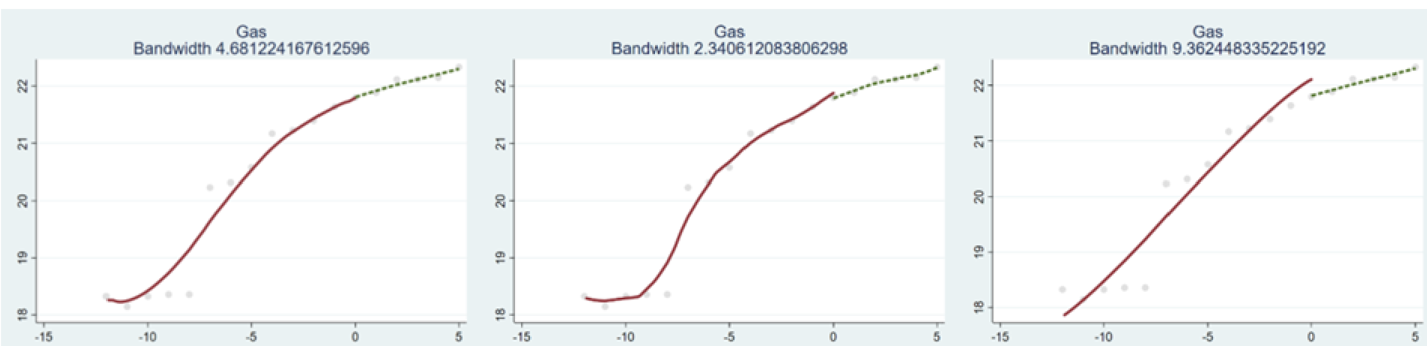
RDD diagrams of three kinds of bandwidth and a sensitivity test of total energy consumption



a) coal 100 b) coal 50 c) coal 200



d) crude 100 e) crude 50 f) crude 200



g) gas 100 h) gas 50 i) gas 200

Figure 4

RDD diagram of coal, crude oil and natural gas

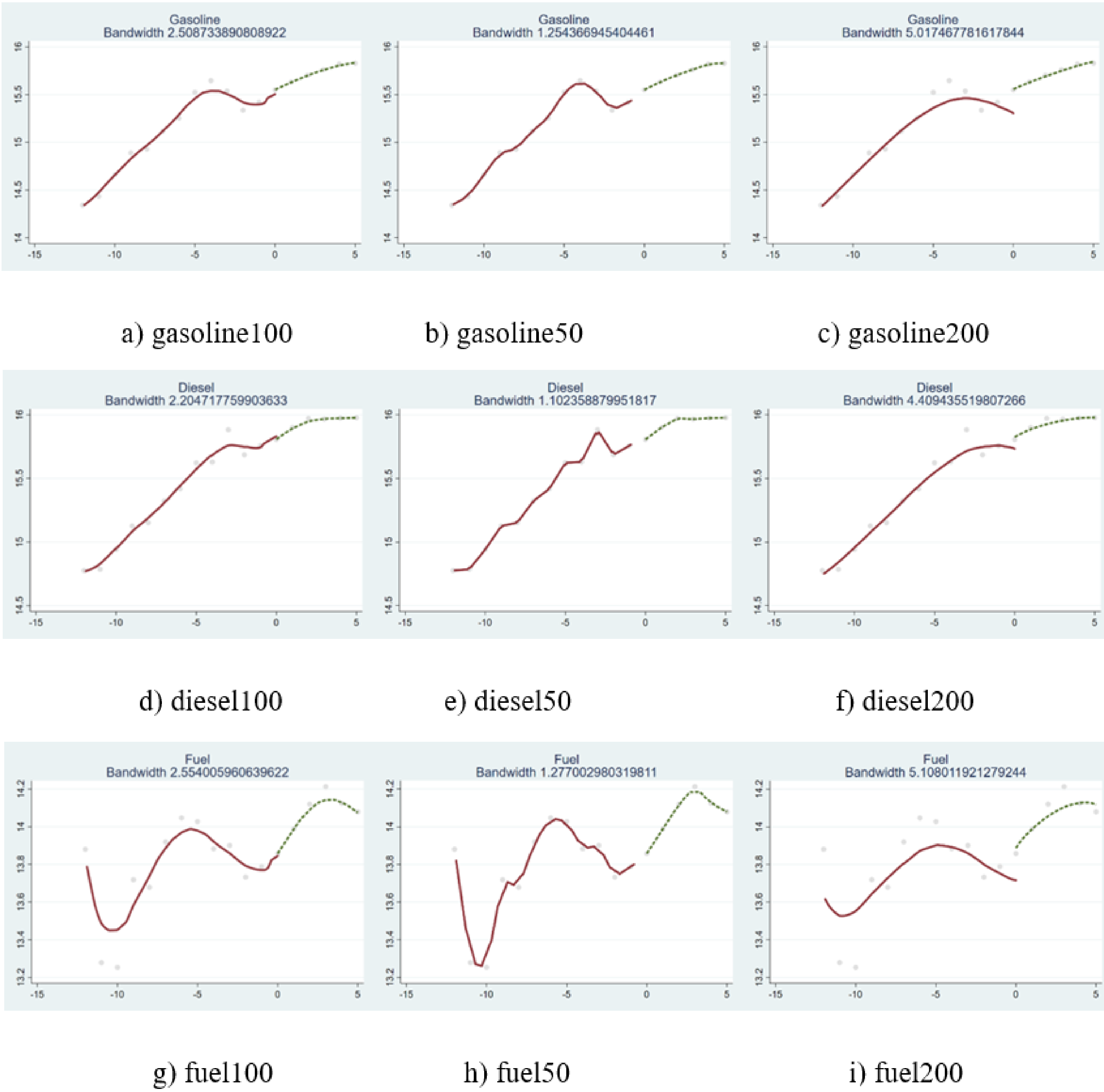


Figure 5

RDD diagram of gasoline, diesel and fuel

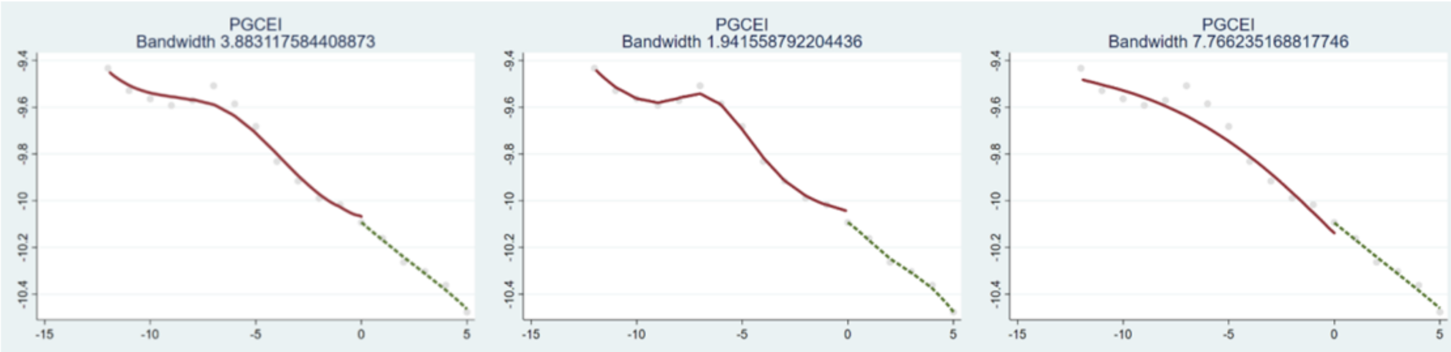
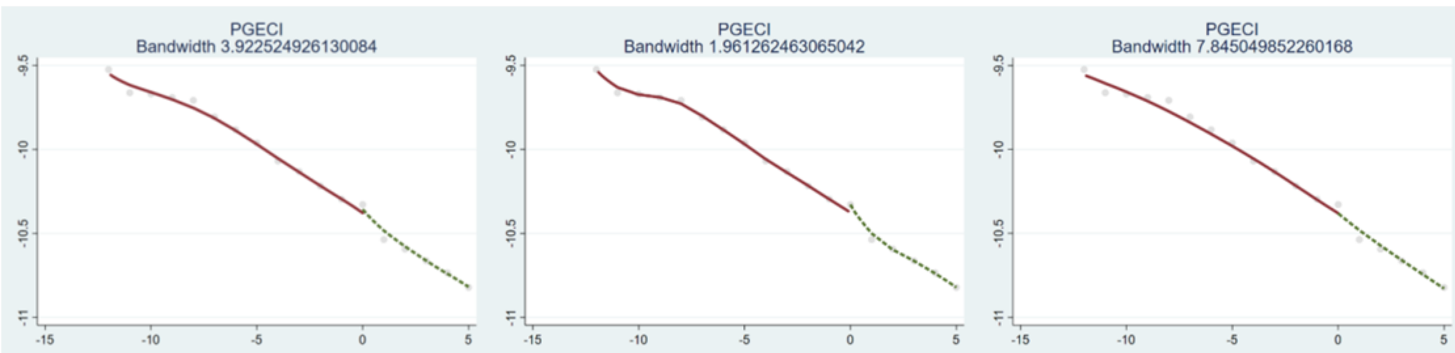


Figure 6

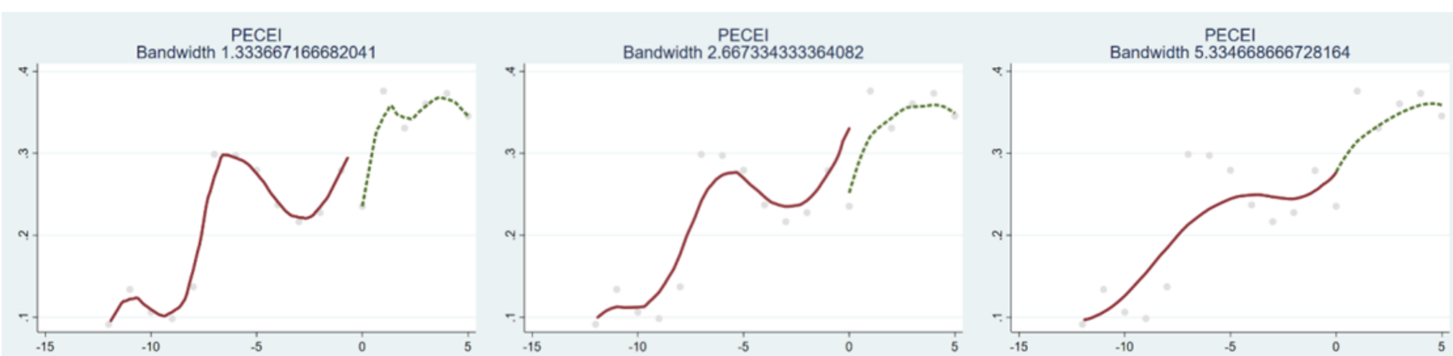
RDD diagram of three bandwidth emission intensity per unit output values



a) PGECI 100 b) PGECI 50 c) PGECI 200

Figure 7

RDD diagram of three bandwidths for energy intensity per unit output value



a) PECEI 100 b) PECEI 50 c) PECEI 200

Figure 8

RDD diagram of three bandwidths for emission intensity per unit of energy consumption

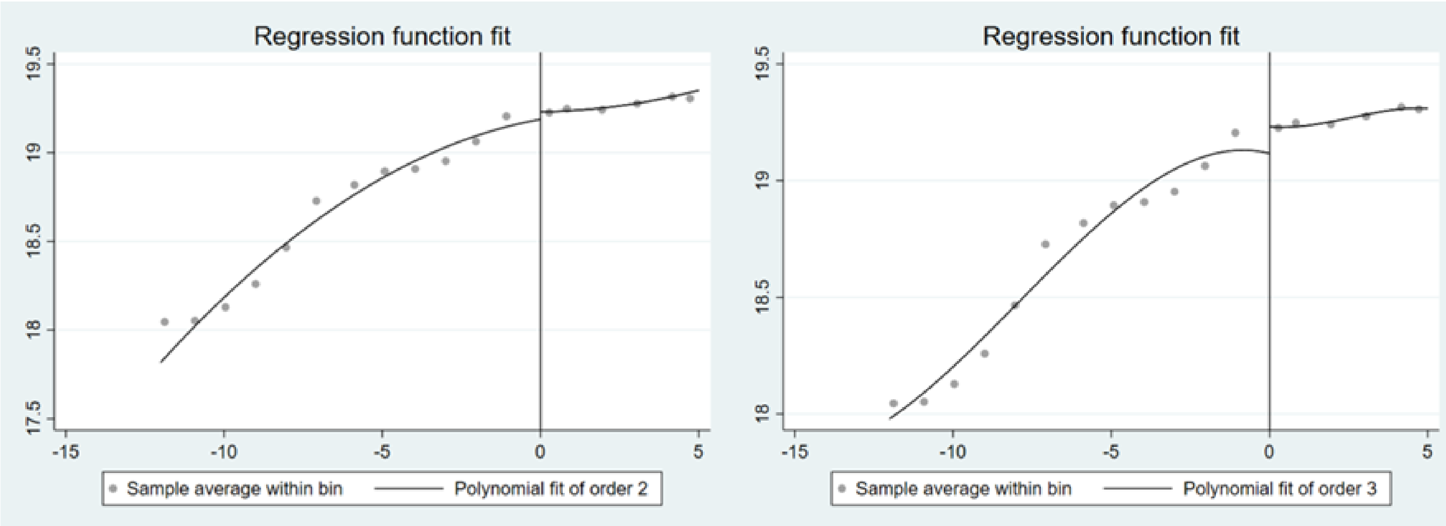


Figure 9

Local linear regression RDD diagram of triangle kernel and matrix kernel of carbon emission a) Second order polynomial of default bandwidth of triangle kernel for carbon emissions; b) Second order polynomial of default bandwidth for rectangular core of carbon emissions

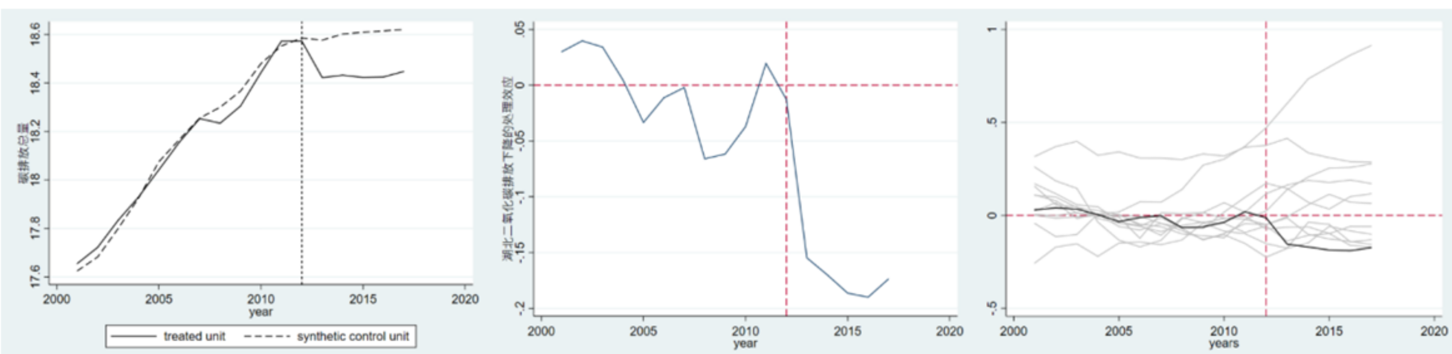


Figure 10

SCM test a) Comparison of total carbon emissions; b) Treatment effect of carbon emission reduction; c) Placebo test in 12 provinces