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Impact of China's Energy Internet Development on Carbon Emission Reduction

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Abstract: This paper explores the impact of China's energy Internet development on carbon emission reduction and its internal transmission mechanism, and uses panel data of 30 provinces from 2000 to 2020 to construct comprehensive development indicators of energy Internet through entropy weight method for empirical test. The results show that the development of energy Internet can promote carbon emission reduction, and the increase of renewable energy utilization is an important mechanism for the comprehensive development level of energy Internet to restrain carbon emissions. The heterogeneity analysis shows that, according to the degree of carbon emissions, the energy Internet has obvious effect on carbon emission reduction in regions with low carbon emissions and regions with moderate carbon emissions. According to economic region, the development of energy Internet can significantly curb carbon emissions in the western region. Finally, it is found that in the context of the development of energy Internet, the development of renewable energy can promote the consumption of natural gas and improve the efficiency of energy conversion. In addition, the government's emphasis on regional technological development can bring external reinforcement effect on carbon emission reduction. The research expands the discussion of diversified carbon emission reduction paths, promotes the explanation of the effect and influence mechanism of energy Internet to promote carbon emission reduction, and helps to provide beneficial policy enlightenment for the adjustment of the layout of energy Internet in China to better help achieve the goal of carbon neutrality.

Keywords: energy internet; carbon emission; renewable energy; mediating effect

JEL Classification: O10; O13

1. Introduction

In China, fossil energy, as the dominant energy source, has played an important role in promoting economic and social development. However, this energy mix also brings a lot of carbon emissions. At present, in the context of energy saving and emission reduction as the main melody of economic development and carbon peak and carbon neutralization, our carbon emission reduction situation is not optimistic. At present, China is still the largest developing country and carbon emitter in the world, and there is still a long way to go to promote the process of carbon emission reduction (Li et al., 2022). The root cause of the carbon emission problem is the massive development and use of fossil energy. The solution is to change the mode of energy development and completely get rid of the dependence on fossil energy.

The purpose of building energy Internet is to increase the proportion of renewable energy and the utilization efficiency of traditional fossil energy, fundamentally change the current energy consumption pattern, and then change the decoupling of economic development from the demand for fossil energy and play a role in energy conservation and emission reduction while improving the comprehensive utilization efficiency of energy. The construction of energy Internet is to lead the carbon emission reduction of the whole society with the zero-carbon revolution of the energy system, which plays an overall and leading role in the development strategy of achieving carbon peak and carbon neutrality. Therefore, scientific assessment of the impact of the development of China's energy Internet on carbon emissions and improvement of the development layout of energy Internet to support the progress of carbon emission reduction are urgent problems to be faced and solved.

At present, the research on carbon emission reduction path mainly focuses on three aspects: market mechanism design, digital economy and clean energy. First of all, existing studies believe that the design of market mechanism is conducive to promoting carbon emission reduction (Wang et al., 2019; Wettestad & Jevnaker, 2019; Yu et al., 2020). Secondly, the rapid development of the digital economy can also help reduce carbon emissions (Park, 2018; Moyer & Hughes, 2018; Asongu et al., 2018; Shahbaz et al., 2022). Finally, there are studies on the relationship between clean energy development and carbon emissions. Clean energy development can significantly reduce carbon dioxide emissions (Lu et al., 2013; Dogan & Seker, 2016; Awanet al., 2022). The energy internet is rarely considered in the research of carbon emission reduction effect. Digitalization also inhibits carbon emissions to a certain extent (Yang et al., 2022; Fan, 2022).

The research on the energy Internet is currently focused on the global level, and most of the literature focuses on the development of the global energy Internet (Liu, 2016; Yang et al., 2019; Laroussi, 2022). There are a few literatures that discuss the development of China's energy Internet, and more focus on its business model, technical architecture and implementation path (Yu et al., 2019; Gqa et al., 2021). There is still a research gap in analysing carbon emission reduction effects from the perspective of energy Internet, especially China's energy Internet. The development of energy Internet and energy reform are closely related to carbon emissions. Therefore, the purpose of this study is to identify the impact of China's energy Internet development on carbon emissions reduction. In order to achieve this, it is necessary to solve the following tasks: (1) Identify the carbon emission reduction effect of China's energy Internet development; (2) Explore the internal transmission mechanism of carbon emission changes caused by the development of China's energy Internet; (3) This paper examines the regional heterogeneity of different factor endowments and the externalities brought by the regional government's emphasis on scientific and technological development. In view of this, the marginal contribution of this paper is: (1) It fills the gap of carbon emission reduction research in China's energy Internet development, broadens the research on diversified carbon emission reduction paths, and provides new ideas for China to achieve the carbon peak before 2030 and carbon neutrality by 2060. (2) The theoretical and practical explanation of the effect and influence mechanism of the development of energy Internet in promoting carbon emission reduction is supplemented, and the heterogeneous results are identified. This not only helps to clarify the work priorities of the construction of energy Internet in each province, but also promotes the adjustment and improvement of the layout of energy Internet. (3) By deepening the research on the emphasis of regional governments on scientific and technological development, the government's role in promoting the development of the energy Internet has been clarified. This will provide reference for the government to adjust its development strategy in promoting the positive relationship between energy Internet and carbon emission reduction.

2. Theoretical Part

In 2004, the Economist magazine published building the energy internet and proposed whether we can learn from the self-healing and plug-and-play digital network of the information internet to build an energy internet, which is the bud of the energy internet. With the development of distributed generation and new electronic technologies, the energy internet has been recognized and developed. Today, the energy internet can be considered as a complex multi-network flow system formed by taking the power system as the core, the internet and other cutting-edge information technology as the basis, and the distributed renewable energy as the main primary energy, and closely coupled with natural gas network, transportation network and other systems (Dong et al., 2014). The construction of energy Internet can reduce information asymmetry, optimize resource allocation, realize cross-regional coordinated utilization of coal, electricity, gas, hydrogen and other energy, and improve the efficiency of energy use. The use of energy Internet can realize joint dual control of energy and carbon emissions, contribute to the detection and traceability of carbon emissions, promote the development of carbon reduction technology, and promote low-carbon and green development. Therefore, this paper proposes the first research hypothesis.

H1: The development of energy Internet can promote carbon emission reduction.

China's coal-based energy system and high-carbon industrial structure make its total carbon emission and carbon intensity present a state of "double high". At present, China's coal consumption still accounts for more than 50%. To solve the problem of carbon emissions, we need to change the mode of energy development, adjust the structure of energy consumption, and increase the proportion of clean energy and renewable energy. The development of energy Internet can promote the diversity of energy supply. Renewable energy such as wind power, solar power and waterpower play a certain role in replacing coal, oil and other energy sources. However, the utilization of these renewable energy sources produces less carbon dioxide than traditional fossil energy sources, which can promote carbon emission reduction. Based on this, this paper proposes a second research hypothesis.

H2: The energy Internet can curb the increase of carbon emissions by promoting the use of renewable energy.

3. Methodology

3.1. Model Design

Benchmark regression model. Based on the above theoretical analysis and research assumptions, this paper constructs the following fixed-effect model of panel data:

$$\mathrm{Y}_{\mathrm{it}} = \alpha_0 + \alpha_1 \mathrm{EDI}_{\mathrm{it}} + \alpha_2 \sum Control_{it} + \xi_t + \varepsilon_{it} \tag{1}$$

where *i* represents the province, *t* represents the year, Y_{it} represents the carbon emissions of province *i* in *t* years, EDI_{it} represents the comprehensive development level of energy Internet of Province *i* in *t* years, $Control_{it}$ represents the control variable affecting carbon emissions, ξ_t represents the fixed effect of year, and ε_{it} represents the random error term.

Mediation effect model. Based on the analysis of theory and influence mechanism, this paper constructs the following mediation effect model:

$$\ln RE_{it} = \beta_0 + \beta_1 EDI_{it} + \beta_2 \sum \mathrm{Control}_{it} + \xi_t + \varepsilon_{it} \tag{2}$$

$$\mathrm{Y}_{\mathrm{it}} = \lambda_0 + \lambda_1 \mathrm{EDI}_{\mathrm{it}} + \lambda_2 \mathrm{lnRE} + \lambda_3 \sum \mathrm{Control}_{\mathrm{it}} + \xi_t + \varepsilon_{it} \tag{3}$$

In equations (2) and (3), $lnRE_{it}$ represents the renewable energy utilization in t years of I province after logarithm. In this paper, stepwise regression method will be used for identification. Firstly, Equation (1) will be tested. If the coefficient α_1 is significant, subsequent testing steps will be carried out. Then, the regression of equation (2) is carried out. If the coefficient β_1 is significant, continue to the next step. Finally, equation (3) is regression, if the coefficients λ_1 and λ_2 are both significant, it indicates that there is a partial mediating effect. If λ_1 is not significant but λ_2 is significant, it indicates that there is a complete mediating effect.

3.2. Selection of Indicators

Explained variable. The explained variables in this paper are carbon emissions (CE), and carbon emissions per capita (CEPC) and carbon emissions per unit of GDP (CEPUG) are also used in the baseline regression. Carbon emissions per capita are measured by the ratio of carbon emissions to the total population, and carbon emissions per unit of GDP is measured by the ratio of GDP and carbon emissions, and the logarithm of these variables is taken for regression.

Core explanatory variable. The core explanatory variable of this paper is the comprehensive development level of energy Internet. Based on the index construction method proposed by Ge (2019) and Zhang (2018), The comprehensive development level of energy Internet is constructed from three aspects: smart grid development (system1), clean energy development (system2) and coordinated development of energy economy (system3). The specific indicators are shown in Table 1.

Table 1. Index System of Comprehensive Development Level of Energy Internet

First index	Secondary index	Third index	Data sources
Smart grid development index	Infrastructure construction	Ratio of installed capacity of thermal power generation to total installed capacity	China Electric Power Yearbook
		Human capital development (education expenditure/total financial expenditure)	China Statistical Yearbook
	Power grid development	Capacity of power generation equipment	China Electric Power Yearbook
		Generating capacity	China Electric Power Yearbook
	Popularization of electricity	Electricity consumption	China Electric Power Yearbook
		Per capita electricity consumption	China Electric Power Yearbook
	Smart grid importance	The government's emphasis on smart grid (measured by the frequency of smart grid related keywords in the government work report)	Government Work Report
Clean Energy Development Index	Clean energy priority	The government's emphasis on clean and renewable energy (measured by the frequency with which keywords related to clean and renewable energy appear in the Government Work report)	Government Work Report
	Percentage of installed capacity	The proportion of installed capacity of non-fossil energy in total installed capacity	China Electric Power Yearbook
	Power generation ratio	Non-fossil energy power generation capacity accounts for the province's total power generation ratio	China Electric Power Yearbook
Energy Economic Coordination Index	Macroeconomics	GDP per capita	National Bureau of Statistics of China
		GDP growth rate	National Bureau of Statistics of China
	Quality of environment	PM2.5	Atmospheric Composition Analysis Group of Washington University measured the global surface PM2.5 concentration
		Industrial sulfur dioxide emissions	China Environmental Yearbook
		Comprehensive utilization of industrial solid waste	China Environmental Yearbook
	Energy consumption	Total energy consumption	China Energy Statistical Yearbook
	Energy efficiency	Energy efficiency (GDP/ energy consumption)	China Energy Statistical Yearbook

Control variable. In order to control the influence of other factors on carbon emission reduction, the following control variables are selected in this paper according to previous studies: urbanization level (UL), which is measured by the ratio of urban population to total population, and logarithm is taken for this index; Industrial structure (IS), measured by the ratio of the added value of the secondary industry to the gross national product; Technical level (TEC), expressed by the number of patents granted annually; Fiscal decentralization (FD), measured by the ratio of fiscal expenditure to fiscal revenue, logarithm of this index; The level of foreign investment (FDI) is measured by the ratio of total foreign investment to GDP. In addition, industrial sales value (ISV) and Coal consumption of industrial enterprises above designated size are also controlled, and the logarithm of these two indicators is taken.

Mediation variables. Renewable energy. Due to the lack of direct data on renewable energy, this paper uses the power generation of renewable energy, mainly including wind power generation, solar power generation and hydropower generation.

3.3. Source of Data

Due to the lack of some data in Tibet, this paper selects panel data from 2000 to 2020 from 30 provinces except Tibet and Hong Kong, Macao and Taiwan. The data of provincial carbon emissions are from China Carbon Accounting Database (CEADs), the data of control variables are from National Bureau of Statistics of China, and the data of intermediary variables are from China Electric Power Yearbook. Descriptive statistics of the main variables are shown in Table 2.

Table 2. Descriptive statistics of main variables

variable	mean	sd	min	max
lnCE	9.858	0.988	4.400	12.17
lnCEPC	0.775	0.792	-1.851	2.552
lnCEPUG	1.693	0.784	-2.074	4.01
EID	0.292	0.133	0.0790	0.752
lnUL	-0.717	0.320	-1.761	-0.110
IS	0.426	0.0810	0.160	0.620
TEC	3.225	6.761	0.00700	70.97
lnFD	0.749	0.384	0.0500	1.909
FDI	0.521	1.441	0.0430	34.02
lnISV	8.969	1.419	5.200	11.96
lnCoal	8.962	0.962	5.208	10.85
lnRE	4.939	2.533	-2.408	15.12

4. Results

4.1. Basic Empirical Results

Table 3 reports the regression results of the influence of energy Internet development on carbon emission reduction. From columns (1) to (3), it can be found that the estimated coefficients of the comprehensive development level of energy Internet on emissions, carbon emissions per capita and carbon emissions per unit of GDP are -0.292, -0.257 and -0.302, respectively, and are significantly negative at the 5% level, indicating that the development level of energy Internet will inhibit the increase of carbon emissions. The higher the development level of energy Internet, the better the effect of carbon emission reduction. Column (4) ~ (6) shows the impact of the three subsystems of the comprehensive development level of energy Internet on carbon emission reduction. It can be found that compared with other subsystems, the development level of clean energy has a greater impact on carbon emission, which is significantly negative at the level of 1%, indicating that the development level of clean energy plays a greater role in the comprehensive development level of energy Internet.

Table 3. Results of baseline regression

	(1)	(2)	(3)	(4)	(5)	(6)
	lnCE	lnCEPC	lnCEPUG	lnCE	lnCE	lnCE
EID	-0.292**	-0.257**	-0.302**			
	(-2.31)	(-2.05)	(-2.44)			
system1				-0.0567		
				(-0.77)		
system2					-0.575***	
					(-5.81)	
system3						0.709***
						(3.24)
Constant	2.749***	-6.541***	-4.355***	2.730***	2.814***	2.883***
	(3.55)	(-8.49)	(-5.75)	(3.51)	(3.74)	(3.74)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
year	Yes	Yes	Yes	Yes	Yes	Yes
N	504	504	504	505	504	505
R^2	0.844	0.830	0.683	0.842	0.853	0.845

Note: Standard errors in parentheses, * $p < 0.1$, ** $p < 0.05$,*** $p < 0.01$

4.2. Influence Mechanism Test

The above analysis analyses the influence of the comprehensive development level of energy Internet on carbon emission reduction from the theoretical level. In order to verify the hypothesis of the influence mechanism, this paper chooses the intermediary effect model for testing, and the regression results are shown in Table 4. On the basis that formula (1) confirms that the comprehensive development level of energy Internet will promote carbon emission reduction, formula (2) verifies whether the comprehensive development level of energy Internet will promote the utilization of renewable energy. The estimated coefficient of the comprehensive development level of energy Internet in column (2) is positive at the level of 5%. It shows that the comprehensive level of energy Internet will promote the use of renewable energy. Finally, the intermediary variable of renewable energy is put back into the regression equation of the influence of the comprehensive development level of energy Internet on carbon emission reduction, and the coefficient value and significance level of the core explanatory variable are observed for judgment: The influence coefficient of the comprehensive development level of energy Internet in column (3) is lower than that in column (1), indicating that the increase of renewable energy utilization is the influence mechanism of energy Internet to promote carbon emission reduction.

Table 4. Influence mechanism

	(1)	(2)	(3)	(4)
	lnCE	lnRE	lnCE	lnCE
EID	-0.292**	2.321**	-0.232**	-0.225*
	(-2.31)	(2.15)	(-1.99)	(-1.86)
lnRE			-0.0105**	-0.0128**
			(-2.13)	(-2.43)
Constant	2.749***	-1.017	1.217***	0.840*
	(3.55)	(-0.42)	(4.34)	(1.94)
Control variable	Yes	Yes	Yes	Yes
Year	No	No	No	No
Code	No	No	No	Yes
N	504	493	493	493
R2	0.844	0.133	0.833	0.834

Note: Standard errors in parentheses, * p < 0.1, ** p < 0.05, *** p < 0.01

5. Discussion

5.1. Test of Heterogeneity

The comprehensive development level of energy Internet may have different impacts on regions with different levels of carbon emissions. Therefore, this paper divides 30 provinces and cities into low emission zones, medium emission zones and high emission zones according to the carbon emissions. The regression results are shown in Table 5. From columns (1) to (3), it can be seen that the comprehensive development level of energy Internet has a better effect on carbon emission suppression in low emission areas and medium emission areas, especially medium emission areas, but it has no obvious effect on carbon emission reduction in high emission areas. In addition, dummy variables are also set according to the situation of power grid science and technology information management in each province. The provinces with power grid science and technology information planning are marked with 1, while those without are marked with 0. From columns (4) to (5), it can be seen that the situation of power grid science and technology information management in each province does not affect the effect of comprehensive development level of energy Internet on carbon emission reduction.

Table 5. Heterogeneity effects of carbon emission and power grid planning

	(1)	(2)	(3)	(4)	(5)
	low	medium	high	have grid planning	without grid planning
	lnCE	lnCE	lnCE	lnCE	lnCE
EID	-0.568**	-0.236***	0.223	-0.271*	-0.395*
	(-2.11)	(-2.66)	(1.43)	(-1.90)	(-1.77)
Constant	-3.177*	4.354***	7.294***	-0.0507	1.167
	(-1.82)	(6.12)	(5.76)	(-0.05)	(0.87)
Control variable	Yes	Yes	Yes	Yes	Yes
year	Yes	Yes	Yes	Yes	Yes
N	166	169	169	369	135
R2	0.821	0.973	0.915	0.817	0.936

Note: Standard errors in parentheses, * p < 0.1, ** p < 0.05, *** p < 0.01

Different provinces have different influences due to differences in politics, economy, culture, resources and other factors. In this paper, the 30 provinces are divided into four regions: Eastern region, central region, western region and Northeast region. The eastern region includes Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong and Hainan, and the central region includes Shanxi, Anhui, Jiangxi, Henan, Hubei and Hunan. The western region covers Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Xinjiang and Ningxia, while the northeastern region covers Heilongjiang, Jilin and Liaoning. It can be seen from Table 6 that the comprehensive development level of energy Internet can significantly promote carbon emission reduction in the western region, while the effect of carbon emission reduction in other regions is not significant. This may be because the western region is rich in clean energy such as wind and solar energy, which can better replace traditional energy.

Table 6. Regression by region

	(1)	(2)	(3)	(4)
	east	middle	west	northeast
	lnCE	lnCE	lnCE	lnCE
EDI	-0.117	-0.183	-1.009***	0.111
	(-0.78)	(-0.74)	(-3.58)	(0.82)
Constant	2.253**	6.682**	-2.631*	6.164***
	(2.05)	(2.00)	(-1.69)	(2.93)
Control variable	Yes	Yes	Yes	Yes
year	Yes	Yes	Yes	Yes
N	168	101	184	51
R2	0.912	0.916	0.860	0.993

Note: Standard errors in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

5.2 Further Analysis

Energy consumption and energy conversion efficiency under the development of Energy Internet. In order to further explore the impact of the development of renewable energy on energy consumption and energy conversion efficiency under the background of the development of energy Internet, this paper constructs the interaction term of the comprehensive development level of renewable energy and energy Internet as the explanatory variable. The explained variables were the consumption of natural gas and the energy conversion efficiency. The energy conversion efficiency of each province was calculated by multiplying the provincial education expenditure to the national education expenditure as the weight and multiplying the national energy conversion efficiency. The regression results are shown in Table 7. Columns (1) and (2) show that the development of renewable energy can promote the consumption of natural gas, natural gas plays a certain role in replacing oil, coal and other energy sources, and natural gas, as a kind of clean energy, can effectively reduce carbon emissions. Column (3) and (4) indicate that the development of renewable energy can promote the improvement of energy conversion efficiency. The higher the energy conversion efficiency, the more thorough the utilization of energy.

Table 7. The impact of renewable energy on energy consumption and energy conversion efficiency

	(1) natural gas	(2) natural gas	(3) energy conversion efficiency	(4) energy conversion efficiency
EDI*lnRE	0.291**	0.257***	0.0179*	0.0180**
	(2.11)	(3.01)	(1.78)	(2.00)
Constant	-0.441	17.54***	0.662***	-0.529
	(-1.16)	(6.04)	(31.45)	(-0.98)
Control variable	No	Yes	No	Yes
year	Yes	Yes	Yes	Yes
N	588	493	389	298
R2	0.481	0.630	0.0398	0.388

Note: Standard errors in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 8. Externalities

	(1) lnCE	(2) lnCE	(3) lnCE	(4) lnCE
EDI	-14.81***			
	(-3.13)			
system1		-4.824		
		(-1.52)		
system2			-21.37***	
			(-4.57)	
system3				-7.528*
				(-1.91)
Constant	3.027***	3.024***	3.045***	2.682***
	(3.76)	(3.73)	(3.83)	(3.27)
Control variable	Yes	Yes	Yes	Yes
year	Yes	Yes	Yes	Yes
N	493	494	493	494
R2	0.846	0.843	0.850	0.844

Note: Standard errors in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Externality of the degree of emphasis on regional technology development. Local development cannot be achieved without the support of the government, and the development of energy Internet needs the support of technology. This paper further studies whether the government's emphasis on regional technology development can bring external reinforcement effect on carbon emission reduction. The importance the government attaches to regional technology development is measured by the proportion of local science and technology expenditure in local general budget expenditure, and an interaction term is constructed with the comprehensive development level of energy Internet and the three subsystems as explanatory variables. The regression results are shown in Table 8. The comparison between the results in column (1) and the baseline regression shows that the government's emphasis on regional technology development can promote carbon emission reduction. It can be seen from column (3) and (4) that, for the two subsystems of clean energy development level and coordinated development level of energy economy, the government's attention can also promote carbon emission reduction. However, the interaction coefficient between the development level of smart grid and the government's emphasis on regional technology development is not significant. The government should strengthen the construction of smart grid.

6. Conclusions

This paper establishes the comprehensive development level index of energy Internet and studies the influence of the development of energy Internet on carbon emission reduction. Through the empirical test, it is found that the development of energy Internet can effectively promote carbon emission reduction, but the development level of smart grid and the coordination level of energy economy cannot promote carbon emission reduction. The analysis of influence mechanism shows that the comprehensive development level of energy Internet can restrain the increase of carbon emissions mainly by promoting the utilization of renewable energy. Heterogeneity analysis shows that the development of energy Internet has a more significant effect on carbon emission reduction in low and medium emission zones. In the four regions, the comprehensive development level of energy Internet in the western region can significantly restrain carbon emissions. Finally, through further research, this paper finds that in the context of the development of energy Internet, the development of renewable energy can promote the consumption of natural gas and improve the efficiency of energy conversion. In addition, the government's emphasis on regional technological development can bring external strengthening effect on carbon emission reduction. The higher the emphasis, the better the effect of carbon emission reduction.

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