Does the electricity marketization resulting from China's power sector reforms reduce wind curtailment?

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Abstract

The rapid growth of wind power is accompanied by a high wind curtailment rate, resulting in substantial economic and environmental losses. With China's power sector reform in 2015, provincial-level electricity market construction and development have been accelerated. This study uses the provincial marketization index as a proxy variable for electricity marketization, examining 31 provinces in China from 2009 to 2021 to focus on the impact of electricity market development on wind curtailment rates. The results show that the development of electricity markets post-2015 has significantly reduced wind power curtailment rates. Further analysis reveals that the marketization effect has gradually strengthened since 2017. Heterogeneity analysis shows that electricity marketization has a more pronounced effect on reducing wind power curtailment rates in the "Three North" regions. This study provides a new perspective on the role of electricity marketization in addressing the issue of wind power curtailment.

Keywords: Wind power curtailment, Power market, Power sector reform, Marketization

JEL Classification: Q48,Q42,L94,O13

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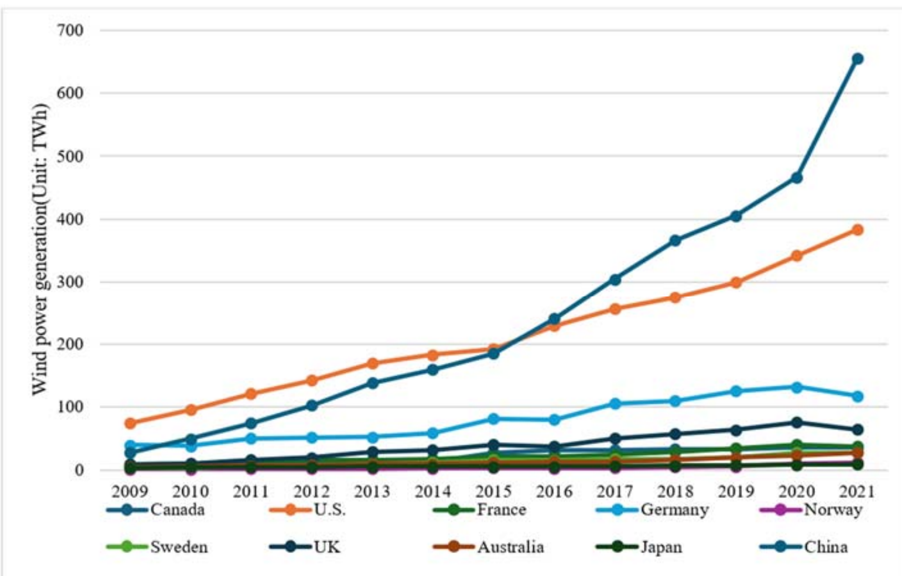
1 Introduction

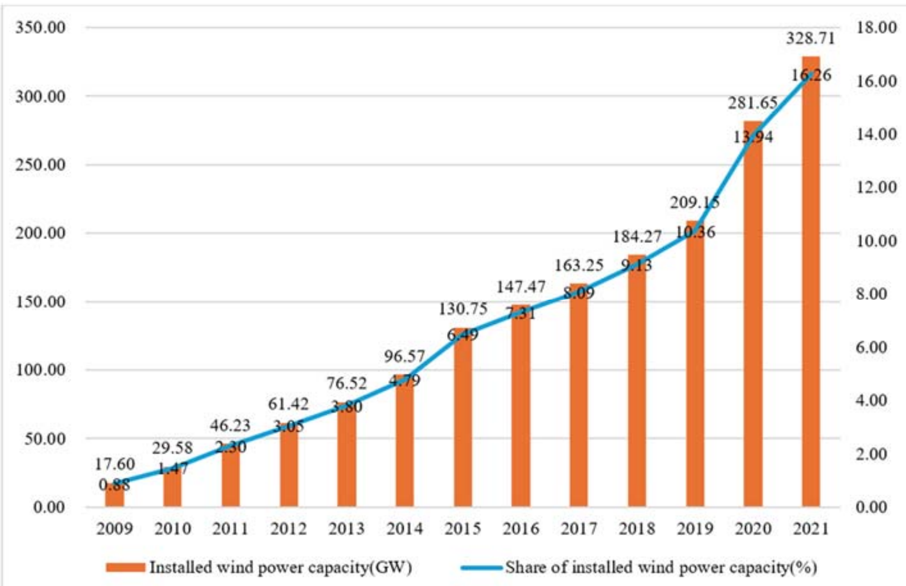
With the promulgation of China's Renewable Energy Law in 2005, wind power generation entered a phase of scaled development (Dai et al., 2018). Newly installed wind power capacity has grown rapidly for several consecutive years and, in 2009, China became the country with the largest scale of newly installed wind power. By the end of 2009, China's cumulative installed wind power capacity reached 17.6 GW, accounting for 2.01% of the total installed capacity. In 2016, as China joined the Paris Agreement, the development of China's wind power industry accelerated and, within that year, it became the world's largest wind power generation country. (**Figure 1**)

Figure 1. Wind power generation by major developed countries from 2009–2021



By the end of 2021, the cumulative installed wind power capacity in China had reached 328.71 GW, accounting for 16.26% of the total installed capacity. (**Figure 2**) There has also been a significant increase in wind power generation: soaring from 27.62 TWh in 2009 to 655.8 TWh in 2021, comprising 7.81% of China's total electricity generation. With the rapid growth of wind power, the issue of wind power curtailment has become prominent. In 2021, China's cumulative wind power curtailment reached 20.61 TWh, with the curtailment rate in some areas reaching as high as 10%. **(Figure 3)**

Figure 2. Installed wind power capacity and share, 2009-2021



High wind power curtailment rates not only result in significant resource waste but also limit the sound development of China's wind power industry (Fan et al., 2015). Luo et al. (2016) indicate that wind curtailment in China is caused by the fluctuating nature of wind power technology. From a macro perspective, the unreasonable structure of power sources and the long-chain grid network are also root causes of the curtailment problem (Pei et al., 2015). To address the issue of wind power curtailment, some scholars have conducted comparative analyzes of the reasons for wind power curtailment and the consumption policies in countries such as the United States and Germany, summarizing international methods for addressing wind power reduction (Bird et al., 2016; Guo et al., 2020). According to F. Song et al. (2021), solving China's wind curtailment problem requires a concerted effort across technical, economic, and institutional dimensions.

Figure 3. Wind power curtailment rates for each province in China in 2021

However, quantitative and empirical studies on China's wind power curtailment rate are still relatively scarce. Yu et al. (2023) found through Tobit model analysis that there is a significant negative correlation between wind power equipment utilization rate and curtailment rate. F. Song et al. (2019) analyzed the impact of external market barriers on provincial wind power curtailment rates before 2016 by constructing an external market barrier index. Xia et al. (2020) used scenario simulation to conclude that an increase in wind power prices would lead to a higher curtailment rate. Nevertheless, research on the economic aspects, especially the impact of market development on wind power curtailment rates, remains lacking.

The reason why the electricity market significantly affects wind power curtailment rates is that it has not fully adapted to organize and manage competitive generation resources in the most efficient manner, leading to resource waste. Specifically, since most renewable generation has no variable cost, they should be first in the merit order and dispatched prior to other traditional generation. Traditional power plants, to avoid the costs associated with frequent shutdowns and startups, may choose to continue operating at negative electricity prices. This process should naturally evolve through market mechanisms, with various power generation assets participating in competition through market bidding. However, in situations where the electricity market is immature or influenced by non-market considerations, such as meeting coal-fired power generation quotas, the market's efficiency-based principles may be compromised, resulting in curtailment of renewable generation while coal or gas plants keep generating.

In March 2015, China's State Council issued the "Opinions on Further Deepening the Reform of the Electric Power System" (Document No. 9), marking the start of a new round of power sector reforms with the construction of the electricity market as a key task (Guo et al., 2020). In November of the same year, the National Development and Reform Commission and the National Energy Administration jointly issued the specific policy document "Implementation Opinions on Promoting the Construction of the Electricity Market," signifying the beginning of the marketization of China's electricity sector.

Before the establishment of the electricity market, the power industry was mainly under direct government control. During this period, the efficiency of the power sector largely depended on national market guidelines, with significant differences in market development levels among provinces and limited degrees of marketization. As reforms progressed and provinces began independently operating their own electricity markets, the impact of provincial marketization on wind power curtailment rates, especially following the 2015 power sector reforms, remains an area requiring further exploration.

This study focuses on the economic problem, discussing the impact of the development of provincial electricity markets on wind power curtailment rates since the launch of provincial electricity market construction in 2015. Since China's provincial electricity markets were gradually established only after the 2015 power sector reform, the evaluation data for provincial electricity marketization are currently difficult to obtain. Therefore, we use the provincial marketization index as a proxy variable for the degree of electricity marketization in each province, this study conducts an empirical analysis of 31 provinces in China from 2009 to 2021. The results indicate that post-2015 electricity marketization has significantly reduced wind power curtailment rates. Furthermore, as the degree of marketization in the electricity sector deepens, the curtailment rate of wind power has significantly decreased. Further analysis shows that the policy effect of electricity marketization is more significant in the "Three North" region, where wind power curtailment is most prevalent.

These findings hold substantial significance for the future development of wind power and other renewable energy sources. First, the study confirms the positive impact of electricity marketization on the efficiency of the power sector. Second, it provides valuable insights for the design of future solar energy and other renewable energy policies. Finally, the results on the impact of electricity marketization on wind power curtailment are also relevant to other countries, offering valuable experiences for the development of the wind power industry globally.

The structure of this paper is as follows: Section 2 reviews the literature, Section 3 presents the methods and data, Section 4 shows the empirical results, and the final section summarizes the conclusions and presents policy recommendations.

2 Literature review

China's wind power industry has experienced several decades of rapid development. High wind power curtailment rates have resulted in significant economic losses. Reducing wind power curtailment would bring the most notable environmental benefits (Cui et al., 2020). There are several reasons for wind power curtailment. Firstly, the technical issues closely related to wind power development cannot be ignored. This includes the problem of turbine model selection, which directly affects the power generation efficiency and stability of wind farms (Huenteler et al., 2018). Further technical issues also encompass possible technological improvements in wind energy integration, such as improved power dispatch, optimization of the overall design of wind farms, and enhancement of wind energy utilization efficiency (Lu et al., 2019; Xiong et al., 2016). Meanwhile, the wind energy curtailment issue that power plants face in meeting ramp rate requirements is also a technical factor in wind power curtailment (Vargas et al., 2015).

Secondly, policy factors play a crucial role in high wind power curtailment rates. Different power generation policies and directive policies have a significant impact on new installed capacity (Y. Song et al., 2021), while differences in pricing policies also affect the installation of wind turbines (Zhao et al., 2016). These policies not only impact onshore wind power but also significantly affect the economic viability of offshore wind power (Xu et al., 2021). All these factors, whether direct or indirect, influence the curtailment rate of wind power.

Thirdly, issues about the power system itself also constitute an aspect that cannot be ignored. Uneven deployment of wind power in the power grid may lead to resource wastage and underutilization (Zhao et al., 2022). The incompatibility between wind energy distribution and supply and local loads (Luo et al., 2018), as well as the potential conflicts between wind power development and electrical power transmission and consumption (Fan et al., 2015), are pivotal factors leading to the persistently high wind power curtailment rates in China.

Before the 2015 power sector reform, China's electricity market was primarily government-controlled. Electricity production, pricing, sales, and distribution were all planned and managed by the government, with electricity prices typically set by the government. The focus of the 2015 power sector reform was to establish a robust electricity market and expand market mechanisms. This included introducing competition in new distribution and retail electricity businesses and gradually liberalizing electricity production and consumption (Xie et al., 2021; Zhao et al., 2023).

To advance the construction of the electricity market, the State Council issued specific implementation opinions targeting the development of the electricity market. The electricity market primarily consists of medium- and long-term markets and spot markets. The Beijing power exchange center and Guangzhou power exchange center facilitate the optimal allocation of resources on a national scale. At the provincial level, the electricity markets mainly conduct intra-provincial medium- and long-term transactions and spot transactions, ensuring that spot markets are not redundantly set up within the same region. Consequently, since the 2015 power sector reform, provincial power exchange centers across China have gradually been established (**Table 1** shows the establishment times of each provincial power exchange center).

Table 1. Establishment time of provincial power exchange center

Province	Institution name	Registration time
Beijing	Beijing Power Exchange Center	2016.2.24
Tianjin	Tianjin Power Exchange Center	2016.4.11
Hebei	Hebei Power Exchange Center	2016.5.4
Shanxi	Shanxi Power Exchange Center	2016.5.11
Inner Mongolia	Inner Mongolia Power Exchange Center	2016.4.12
Liaoning	Liaoning Power Exchange Center	2016.4.13
Jilin	Jilin Power Exchange Center	2016.4.13
Heilongjiang	Heilongjiang Power Exchange Center	2016.4.19
Shanghai	Shanghai Power Exchange Center	2016.5.16
Jiangsu	Jiangsu Power Exchange Center	2016.4.15
Zhejiang	Zhejiang Power Exchange Center	2016.5.19
Anhui	Anhui Power Exchange Center	2016.5.4
Fujian	Fujian Power Exchange Center	2016.5.17
Jiangxi	Jiangxi Power Exchange Center	2016.5.23
Shandong	Shandong Power Exchange Center	2016.4.25
Henan	Henan Power Exchange Center	2016.4.29
Hubei	Hubei Power Exchange Center	2016.4.26
Hunan	Hunan Power Exchange Center	2016.6.13
Guangdong	Guangdong Power Exchange Center	2016.5.11
Guangxi	Guangxi Power Exchange Center	2016.12.28
Hainan	Hainan Power Exchange Center	2018.6.1
Chongqing	Chongqing Power Exchange Center	2017.8.17
Sichuan	Sichuan Power Exchange Center	2016.5.26
Guizhou	Guizhou Power Exchange Center	2016.3.28
Yunnan	Yunnan Power Exchange Center	2016.8.24
Tibet	Tibet Power Exchange Center	2016.5.31
Shaanxi	Shaanxi Power Exchange Center	2016.4.21
Gansu	Gansu Power Exchange Center	2016.4.21
Qinghai	Qinghai Power Exchange Center	2016.3.31
Ningxia	Ningxia Power Exchange Center	2016.4.1
Xinjiang	Xinjiang Power Exchange Center	2016.3.21

In 2021, all the power trading centers nationwide cumulatively organized and completed market transaction volumes of 3778.7 TWh, accounting for 45.5% of the total electricity consumption. Among this, the national electricity market accounted for a total of 3040.5 TWh in medium- and long-term direct power transactions.[1] Simultaneously, the number of market participants has been continually increasing. For instance, by the end of 2020,

[1] 2021 China Power Industry Economic Operation Report. http://lwzb.stats.gov.cn/pub/lwzb/tzgg/202205/W020220511403033990320.pdf

there were 4994 registered entities in the Hubei Power Exchange Center.[2] In 2021, the Beijing Power Exchange Center Platform registered 198000 market members, hitting a historic high.[3]

Since the power sector reform in 2015, some scholars have investigated the impacts of this reform. Liu et al. (2022) indicate that the electricity market reform has hindered the growth of wind power installed capacity. Ruhang et al. (2018) review the cost and marketization of renewable energy in China before and after the electricity market reform. Lin et al. (2019) used Guangdong Province as a case study to explore the impact of the 2015 market reform on coal-fired power generation in China. However, to date, the impact of electricity marketization on wind power curtailment rates, particularly the effects following the 2015 power market reform, remains underexplored. This study is of significant reference value for the future development of China's wind power industry.

3 Methods and Data

3.1 Empirical model

This study aims to quantitatively assess the impact of electricity marketization in 2015 on provincial wind power curtailment rates. Given the difficulty of directly measuring the degree of marketization of the provincial electricity sector, the overall provincial marketization index is used as a proxy variable. Firstly, a testable hypothesis is proposed: after the completion of provincial electricity market construction in 2015, provinces with higher levels of electricity marketization will have lower wind power curtailment rates. To test this hypothesis, the following model is applied to panel data from 31 provinces between 2009 and 2021:

$$\boldsymbol{curt_{i,t} = \beta_0 + \beta_1 \cdot market_{i.t} + \beta_2 \cdot market_{i.t} \cdot Post2015 + \beta_3 \cdot X_{i,t} + \lambda_i + \varepsilon_{i,t}} \quad (1)$$

$curt_{i,t}$ represents the wind power curtailment rate of province i in year t.

[2] https://news.bjx.com.cn/html/20210220/1137019.shtml
[3] https://news.bjx.com.cn/html/20210219/1136679.shtml

$market_{i.t}$ represents the electricity marketization index, measured by the provincial marketization index of province i in year t. To verify the impact of marketization post-2015, a dummy time variable $Post2015$ is introduced in model (1). This variable reflects the period of electricity marketization for each province, taking the value of 1 after 2015 and 0 otherwise. The coefficient β_2 is the focal point of this study. If the coefficient of β_2 is negative, it indicates that post-2015 electricity marketization has positively contributed to reducing wind power curtailment rates in the provinces. $X_{i,t}$ represents other control variables that may influence the curtailment rates. Referencing the research by F. Song et al. (2019), wind power curtailment rates are influenced by the proportion of wind power installed capacity, with higher installed capacity closely associated with higher curtailment rates. Therefore, this study also includes the share of provincial wind power installed capacity as a fundamental control variable in the model, upon which subsequent analyzes are based. Additionally, the absolute size of the power system is also expected to impact the curtailment rate. Larger systems may be more capable of absorbing the volatility of renewable energy. In model (1), this factor is measured by the logarithmic value of total power generation. Considering the potential impact of technical factors, the model also includes the line loss rate of each province as a control variable. Furthermore, the model also includes various socio-economic development indicators, such as population levels, the proportion of industrial production in GDP, GDP growth rate, and urbanization level. Population levels are measured by the logarithm of population density, while urbanization level is measured by the logarithm of urban area. λ_i denotes province-fixed effects, while $\varepsilon_{i,t}$ represents the random term unrelated to explanatory variables.

To further analyze the impact of the provincial electricity marketization process on wind power curtailment rates, model (1) is modified by interacting the dummy variables for each year post-2015 with the marketization index to observe the time trend of the marketization effect. The specific model is as follows:

$$\begin{aligned} \boldsymbol{curt_{i,t}} = {} & \boldsymbol{\beta_0 + \beta_1 \cdot market_{i.t} + \beta_2 \cdot market_{i.t} \cdot Year2016} \\ & \boldsymbol{+\beta_3 \cdot market_{i.t} \cdot Year2017 + \beta_4 \cdot market_{i.t} \cdot Year2018} \\ & \boldsymbol{+\beta_5 \cdot market_{i.t} \cdot Year2019 + \beta_6 \cdot market_{i.t} \cdot Year2020} \\ & \boldsymbol{+\beta_7 \cdot market_{i.t} \cdot Year2021 + \beta_8 \cdot X_{i,t} + \lambda_i + \varepsilon_{i,t}} \end{aligned} \quad (2)$$

$Year2016$ to $Year2021$ are dummy variables representing years, the other variables are set consistent with model (1).

3.2 Data sources

Data on wind power curtailment rates are from a wide range of sources. For the years 2009 and 2010, Y. Song & Berrah (2013) were used as a reference. The wind power curtailment data from 2011 to 2013 is sourced from the annual wind power development reports published by the National Energy Administration (NEA). From 2014 to 2019, the wind power curtailment data comes from the annual wind power grid operation reports released by the NEA. The wind power curtailment rate data for 2020 and 2021 is obtained from the New Energy Consumption Monitoring and Warning Center, under the guidance of the NEA.

In this study, the marketization of the electricity sector is measured by a marketization index sourced from the National Economic Research Institute (NERI), which includes data for each province.[4] The index database has only released data up to 2019; hence the marketization indices for 2020 and 2021 in this study are constructed by extrapolating based on the growth rate of the data. The Chinese marketization index is a composite index composed of five sub-indices, each capturing different aspects of marketization. These sub-indices encompass five areas: the relationship between government and the market, the development of the non-state economy, the level of development of the product market, the level of development of factor markets, and the development of market intermediary organizations and the legal system environment.

Data on installed wind power capacity ratios, electricity generation and line loss rate were sourced from the China Electricity Statistical Yearbook. Population density and the degree of urbanization were obtained from the China Statistical Yearbook, with the degree of urbanization measured by the logarithm of urban area. Industry ratios and GDP growth rates were obtained from the National Bureau of Statistics. Summary statistics for all variables are listed in **Table 2**.

[4] China market index database. https://cmi.ssap.com.cn/

Table 2. Dependent and independent variables and their summary statistics

Variable	Variable description	Obs	Mean	SD	Min	Max
curt	Curtailment rate	403	3.306	7.170	0.000	43.000
market	Marketization index	403	7.685	2.202	-0.161	12.390
post2015	Dummy variable	403	3.803	4.338	0.000	12.390
ricw	Ratio of installed wind power capacity	403	7.228	7.474	0.000	28.040
ge	Ln (total power generation)	403	4.914	0.998	0.588	6.429
llrate	Line loss rate	403	6.340	1.990	2.230	15.640
ind	Industry share	403	33.461	9.351	7.047	57.378
gdpgrow	GDP growth rate	403	10.667	5.664	-5.337	28.229
urban	Ln (urban area)	403	8.354	0.925	5.687	10.084
pop	Ln (population density)	403	7.865	0.431	6.244	8.669

4 Results and Discussion

4.1 Empirical results

The regression results of model (1) are shown in **Table 3**. According to the study by F. Song et al. (2019), there is a strong correlation between wind power installed capacity and wind curtailment rate. Therefore, results (1-2) first analyze the relationship between the wind power installed capacity ratio and the wind curtailment rate. The results indicate that the higher the wind power installed capacity, the higher the wind curtailment rate.

On this basis, the impact of electricity marketization on the wind curtailment rate was further analyzed, incorporating provincial fixed effects. Results (3) show that electricity marketization has a significant negative impact on the wind curtailment rate. Considering the development of China's electricity market since the power sector reforms in 2015, a time dummy variable was added to the model for further analysis, as shown in results (4). The results indicate that provincial electricity marketization has reduced the wind curtailment rate since 2015. After adding other control variables in results (5), even after including other control variables, electricity marketization still significantly reduces the wind power curtailment rate at the 99% confidence level. Specifically, after 2015, each point increase in the degree of marketization reduces the wind power curtailment rate by 0.252 to 0.299 percentage points. This indicates that after the power sector reforms, there is a significant negative correlation between electricity marketization and wind power curtailment rates, suggesting that increased market orientation significantly reduces the incidence of wind power curtailment.

Table 3. Results of marketization on wind power curtailment rate

Variable	Dependent variable: curt				
	(1)	(2)	(3)	(4)	(5)
ricw	0.448***	0.241***	0.380***	0.456***	0.495***
	(0.046)	(0.054)	(0.070)	(0.073)	(0.082)
market			-1.121***	-0.484	-0.940**
			(0.366)	(0.401)	(0.440)
market·post2015				-0.252***	-0.299***
				(0.070)	(0.095)
ge					-2.543*
					(1.439)
llrate					-0.057
					(0.240)
ind					-0.011
					(0.096)
gdpgrow					-0.063
					(0.048)
urban					7.752**
					(2.997)
pop					3.365
					(2.794)
FE-province	No	Yes	Yes	Yes	Yes
Observations	403	403	403	403	403
R-squared	0.050	0.050	0.074	0.105	0.155
Number of province	31	31	31	31	31

Note: The standard error is reported in the parentheses. * Significant at the 10% level; ** significant at the 5% level; *** significant at the 1% level. The following table is the same.

As the marketization process deepened, the impact of electricity marketization on the wind power curtailment rate gradually increased. In the year when the provincial electricity trading centers were established, the effect was not significant. However, as the provincial electricity markets began to take shape, starting from 2017, the influence of electricity marketization on the wind power curtailment rate became increasingly significant (**Table 4**).

Table 4. The impact of the electricity marketization process on the wind power curtailment rate

Variable	Dependent variable: curt		
	(1)	(2)	(3)
market	-0.028	0.204	-0.263
	(0.124)	(0.397)	(0.440)
market16	0.037	0.104	-0.020
	(0.116)	(0.103)	(0.113)
market17	-0.175	-0.111	-0.217*
	(0.112)	(0.103)	(0.117)
market18	-0.431***	-0.362***	-0.493***
	(0.111)	(0.104)	(0.123)
market19	-0.579***	-0.490***	-0.659***
	(0.111)	(0.104)	(0.128)
market20	-0.688***	-0.562***	-0.758***
	(0.110)	(0.109)	(0.131)
market21	-0.766***	-0.623***	-0.770***
	(0.109)	(0.113)	(0.141)
ricw	0.740***	0.517***	0.521***
	(0.034)	(0.070)	(0.079)
ge			-2.177
			(1.365)
llrate			-0.560**
			(0.241)
ind			-0.077
			(0.092)
gdpgrow			-0.023
			(0.051)
urban			8.248***
			(2.842)
pop			4.871*
			(2.659)
FE-province	No	Yes	Yes
Observations	403	403	403
R-squared	0.577	0.202	0.253

Note: "market16" represents the coefficient of the interaction term "market · Year2016" in model (2). Similarly, "market17" represents the coefficient of the interaction term "market · Year2017", and so on.

The results in **Table 4** further validate and reaffirm the negative correlation between electricity marketization and wind power curtailment rates. We found that from 2017 to 2018, the reduction in the wind power curtailment rate nearly doubled. This is because the Chinese government actively addressed the wind power curtailment issue by issuing the "Action

Plan for Clean Energy Consumption (2018-2020)." This policy once again emphasized the promotion of provincial electricity market development. The document states that, while ensuring the safe and stable operation of the grid, priority should be given to the consumption of clean energy power and the execution of trading contracts. It encourages clean energy generation to participate in the spot market, and provincial auxiliary service markets were also piloted in provinces such as Shanxi and Ningxia. This reflects the accelerated development and improvement of provincial electricity markets.

4.2 Robustness test

Two robustness tests were conducted for model (1). The first method involved removing samples after 2019. Since the provincial marketization index only contains data published up to 2019, the data for 2020 and 2021 were calculated based on the growth rates of the five sub-indices that constitute the marketization index. The original data were used to perform the regression for model (1) to observe if there were significant errors in the results. The findings indicate that the results from the original dataset are largely consistent with the basic regression results. After 2016, provincial electricity marketization has a significant negative impact on the wind power curtailment rate, suggesting that the estimates are robust (**Table 5**).

Table 5. Robustness check-1

Variable	Dependent variable: curt		
	(1)	(2)	(3)
market·post2015	-0.344***	-0.242***	-0.261***
	(0.070)	(0.069)	(0.094)
market	-0.119	-0.323	-0.672
	(0.131)	(0.415)	(0.473)
ricw	0.861***	0.660***	0.656***
	(0.038)	(0.082)	(0.100)
ge			-0.815
			(1.648)
llrate			0.074
			(0.255)
ind			-0.026
			(0.102)
gdpgrow			-0.040

			(0.053)
urban			4.000
			(3.311)
pop			-0.408
			(2.985)
FE-province	No	Yes	Yes
Observations	341	341	341
R-squared	0.623	0.190	0.225

The second method is a regression analysis on a sub-sample, focusing on provinces that still have wind curtailment rates in 2021. The results, shown in **Table 6**, reveal that the regression results for the sub-sample remain significant at the 99% level. Furthermore, for regions with persistent wind power curtailment rates, the establishment of electricity markets has a more pronounced effect on reducing the curtailment rate in those provinces. These findings indicate that the previous regression results are fundamentally robust.

Table 6. Robustness check-2

Variable	Dependent variable: curt		
	(1)	(2)	(3)
market·post2015	-0.880***	-0.721***	-0.659***
	(0.158)	(0.178)	(0.218)
market	-0.256	-0.300	-1.226
	(0.348)	(0.819)	(0.909)
ricw	0.856***	0.686***	0.825***
	(0.066)	(0.121)	(0.160)
ge			-4.937*
			(2.745)
llrate			-0.139
			(0.552)
ind			-0.068
			(0.155)
gdpgrow			-0.066
			(0.085)
urban			7.497
			(7.231)
pop			0.947
			(7.580)
FE-province	No	Yes	Yes
Observations	195	195	195
R-squared	0.479	0.175	0.257

4.3 Discussion

There is heterogeneity in wind power development strategies. Wind power curtailment mainly occurs in the Northeast, North, and Northwest regions of China, collectively known as the "Three North" regions (North: Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia; Northeast: Liaoning, Jilin, Heilongjiang; Northwest: Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang) (Luo et al., 2016). This is because these regions are rich in renewable energy resources. To study the impact of electricity marketization on the wind power curtailment rate in these key areas, a grouped analysis of the "Three North" regions and the "Non-three North" regions was conducted. After performing regional group regression, directly comparing the coefficients could introduce biases. Therefore, after using the Chow test to determine that there are significant differences in the coefficients between the "Three North" regions and the "Non-three North" regions, a heterogeneity analysis

Table 7. Heterogeneity for the Three North regions and Non-three North regions

Variable	Dependent variable: curt			
	Three North regions		Non-three North regions	
market·post2015	-0.597***	-0.565**	-0.013	-0.024
	(0.177)	(0.220)	(0.014)	(0.021)
market	-0.749	-1.582	-0.126	-0.194**
	(0.959)	(0.994)	(0.078)	(0.092)
ricw	0.661***	0.791***	0.089***	0.089***
	(0.134)	(0.172)	(0.021)	(0.023)
ge		-3.915		-0.621
		(2.953)		(0.402)
llrate		0.004		-0.012
		(0.587)		(0.048)
ind		-0.037		0.004
		(0.170)		(0.029)
gdpgrow		-0.093		-0.007
		(0.095)		(0.011)
urban		8.316		1.693*
		(5.958)		(0.868)
pop		0.464		1.326*
		(5.841)		(0.764)
FE-province	Yes	Yes	Yes	Yes
Observations	169	169	234	234
R-squared	0.161	0.233	0.084	0.105

was conducted. The results in **Table 7** indicate that in the "Three North" regions, the marketization of the power sector after 2015 significantly reduced the wind power curtailment rate. Furthermore, in areas where wind power curtailment was more severe, the development of marketization proved to be more effective in reducing the curtailment rate.

5 Conclusion and Policy implications

This study utilizes data on wind power curtailment rates from 31 provinces in China from 2009 to 2021 to examine the relationship between provincial electricity marketization and wind power curtailment rates after 2015. The results show that the development of electricity marketization in provinces after 2015 has played a significant role in reducing wind power curtailment rates. Specifically, after 2015, each point increase in the degree of marketization reduces the wind power curtailment rate by 0.252 to 0.299 percentage points. Moreover, as marketization advances further, its effect on reducing wind power curtailment rates becomes even more pronounced. In the "Three North" regions, electricity marketization has had a more positive impact on reducing wind power curtailment rates.

The results highlight the importance of electricity marketization in addressing the issue of wind power curtailment. Further advancing electricity marketization will help effectively utilize wind power resources, especially considering the near-zero marginal cost advantage of wind power. Although provincial electricity markets have initially been established in China, there are still areas that require further improvement:

1. Accelerate the Construction of Provincial Spot Markets: Based on the specific characteristics of provincial electricity markets, the construction of provincial spot markets should be accelerated. Although in August 2017, the National Development and Reform Commission and the National Energy Administration jointly issued the "Notice on Carrying Out Pilot Work for the Construction of Electricity Spot Markets," selecting eight regions, including Shanxi, as the first batch of pilot provinces to accelerate the construction of spot markets, most provinces currently still focus on medium and long-term transactions. Therefore, the scope of spot market construction should be further expanded, while the construction of provincial spot markets should

be improved.

2. Promote the Formation of Regional Electricity Markets: Break down inter-provincial barriers and promote cross-provincial and regional electricity market transactions. Specifically, strengthen the construction of a unified national electricity market and establish inter-provincial electricity markets. Further, liberalize inter-provincial transaction plans, reduce administrative intervention, and allow users the choice of inter-provincial transactions. Additionally, enhance the construction of transmission channels and improve their utilization rates to strengthen the interconnection capabilities of regional and inter-provincial grids, thereby increasing the efficiency of high-voltage grid operations.

3. Improve the Integration of the Green Certificate Market with the Renewable Energy Consumption Mechanism: Integrate the renewable energy consumption guarantee mechanism with the green certificate subscription mechanism. As of the end of 2021, China's green electricity certificate market had only sold 75,338 wind power certificates, indicating that the market scale is still limited and the types of renewable energy power are relatively few. Accelerating the development of a tradable green certificate market for renewable energy is crucial for enhancing the economic viability and market competitiveness of wind power projects, thereby reducing wind power curtailment.

4. Strengthen Regulation and Incentive Mechanisms within the Electricity Market: It is imperative to establish a comprehensive regulatory framework to ensure effective supervision and regulation of market participants, preventing market manipulation and unethical behavior. Furthermore, consider implementing practical incentive mechanisms, such as preferential policies and reward programs, aimed at encouraging wind power companies to improve generation efficiency and minimize curtailment.

In conclusion, electricity marketization has played a significant role in reducing the wind power curtailment rate. Further development of the electricity market and the acceleration of the marketization process are crucial for mitigating the losses caused by wind power curtailment. However, as the development of China's electricity market is still ongoing, the changes that future developments in the electricity market may bring to the wind power industry still require further research.

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