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# Market segmentation and wind curtailment: An empirical analysis

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ABSTRACT:

China's wind power has experienced explosive growth and reshaped the overall energy mix since 2009. However, increasing investment in the wind power industry has been accompanied by persistent and serious wind curtailment since 2010, leading to significant efficiency loss. This paper argues that the interprovincial market segmentation, which is driven by political motivations, is a key factor contributing to wind curtailment. We first construct an interprovincial electricity market segmentation index. This is then used as an independent variable to explain the variation in wind curtailment rates. A panel dataset of 28 provinces during the 2009–2016 period is used for empirical analysis. The results clearly show that market barriers positively contribute to wind power curtailment. Specifically, a 10% decrease in the market segmentation index will lead to a 4.3–5.3% decrease in wind power curtailment.

## 1. Introduction

Over the past few decades, energy security and environmental concerns have driven the energy supply across the world to transition toward a more sustainable mix consisting of a higher percentage of renewable energy. As the world's largest energy consumer and carbon emitter, China has set ambitious goals to develop renewable energy, including wind power. Between 2008 and 2017, China's installed wind power capacity increased from 8.4 GW to more than 150 GW, with an average annual growth rate of more than 40%. In 2017, wind power supplied 305.7 TWh or 4.8% of the national electricity consumption.

However, accompanying the rapid development of wind power has been a persistent and severe wind curtailment problem, in which capacity is not used. As shown in Fig. 1, the lowest curtailment rate in China between 2011 and 2017 was 8%, and, in most years, the rate was higher than 10%. In contrast, the curtailment rates in other countries with large-scale deployment of wind power were between 0.5% and 3% (Bird et al., 2016). This curtailment causes substantial energy and economic losses. It is estimated that 190 billion kW hours, as much as 15% of overall wind generation, were abandoned between 2009 and 2017. The total energy wasted is equivalent to 61 million tons of coal consumption, or 170 million tons of carbon dioxide and 0.6 million tons of PM2.5,[1] similar to the total emissions of Vietnam in 2017. In addition, the unexpectedly high curtailment rates have substantially increased the cost of carbon mitigation. Lam et al. (2016) estimate that the actual levelized cost of the wind electricity resulting from the Clean Development Mechanism projects is 0.5–2 times higher than expected and, consequently, the cost of carbon mitigation is 4–6 times higher than ex-ante estimates.

The paradox in China's wind power sector is that the country seems eager to make an energy transition in order to reduce dependence on coal and mitigate the associated side effects such as carbon emission and air pollution. Meanwhile, millions of installed wind turbines sit idle and clean energy is curtailed. What factors have caused such high curtailment? This is an important research question and has profound policy implications.

The existing literature explains the issue as follows. First, grid construction has lagged far behind the rapid growth of wind power capacity due to lack of planning and coordination between grid companies and wind farms (Luo et al., 2016). Second, the current coal-dominant electricity system lacks the flexibility to incorporate wind power, which is variable and intermittent (Long et al., 2011; Lu et al., 2016; Pei et al., 2015). A larger share of wind power requires higher grid flexibility to ensure system security, which is a common problem and poses a significant challenge in many countries/regions (Lacerda and van den Bergh, 2016). Third, the demand for electricity has slowed as China's economy has entered a stage of "New Normal," leading to excess generation capacity (Dong et al., 2018). Fourth, there exists a

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[1] http://energy.people.com.cn/n/2014/0324/c71890-24721220.html.

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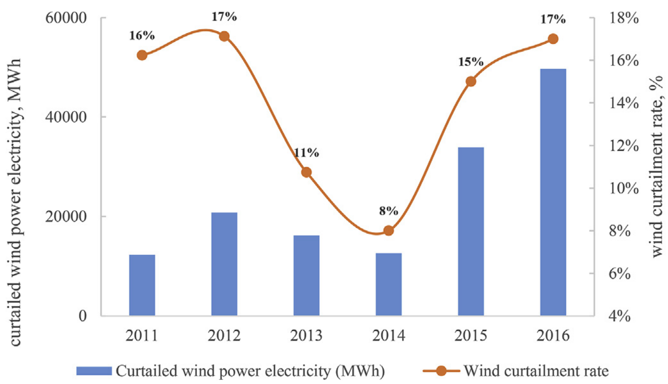


**Fig. 1.** Time trends of curtailed wind power: the level and the rate.

spatial mismatch between wind electricity supply and demand since the majority of wind capacity is concentrated in the "Three North" area,[2] while most load centers are located in the coastal provinces (Xia and Song, 2017; Zhao et al., 2012). Transmission across provinces and regions faces various barriers (Dong et al., 2018; Zhao et al., 2012). Finally, an emerging branch of the literature has tried to identify the relative importance of different factors in determining the unsatisfactory utilization of wind power capacity. A few studies employ decomposition analysis (Lu et al., 2016; Dong et al., 2018), while some engineering studies adopt a production model to simulate the impact of various factors such as grid connection and load size on curtailment at the wind farm level (Shu et al., 2017; Zhang et al., 2016).

Our study focuses on quantifying the effect of market segmentation on wind power curtailment in China by employing a provincial panel regression model. A provincial-level market segmentation index is constructed to measure the level of interprovincial market barriers in China's electricity trade. Then, the curtailment rates of wind power are regressed on the market segmentation index together with a number of other important determinants using a panel dataset of 28 provinces during the 2009–2016 period. The results clearly show that market barriers positively contribute to wind power curtailment. Specifically, a 10% decrease in the market segmentation index will lead to a 4.3–5.3% decrease in wind power curtailment.

This study makes several contributions to the existing literature. First, although China's market segmentation has been measured and its negative effects have been discussed extensively in the literature, this is the first study attempting to construct an index to measure electricity market segmentation and conduct a rigorous and quantitative analysis of its contribution to the wind curtailment problem. Our results highlight the influence of market segmentation on the wind curtailment rate, which could help solve the paradox of China's wind power development. In addition, a better understanding of the effect of market segmentation on wind curtailment could have broader practical implications, since the problem is not unique to China. Second, other forms of renewable energy, such as solar energy, are experiencing rapid growth in China and worldwide. Such energy sources and wind power possess similar features, including randomness, intermittency, and variability. Lessons from wind power development could thus shed light on better policy design for the development of other forms of renewable energy. As pointed out by Lacerda and van den Bergh (2016), renewable energy is a cost-effective way to reduce carbon emissions. Given China's large-scale installed renewable energy capacity and its ambitious targets for the future, understanding and solving the curtailment issue would have global implications.

In the following section, we first introduce some stylized facts about China's wind power development and electricity market segmentation. In section 3, we present our conceptual analysis and proposed hypothesis. In section 4, we conduct a panel regression analysis of the determinants of China's wind power curtailment with a focus on the role of market segmentation. In section 5, we summarize our findings and discuss the policy implications.

[2] This refers to the northwest (Xinjiang and Gansu), northeast (Heilongjiang, Jilin, and Liaoning), and north (Hebei and Inner Mongolia).

## 2. Wind power development and electricity market segmentation in China

### 2.1. *Geographical mismatch between wind power supply and demand*

China has rich wind resources, with the technical potential for wind energy exceeding 5500 GW per year (China Meteorological Administration, 2014), but its regional distribution is unbalanced. Onshore wind resources are mainly concentrated in the "Three North" area. According to the provincial-level assessment of wind power capacity conducted by He and Kammen (2014), eight provinces in the Three North area account for almost 80% of the country's total capacity potential.

This concentration of wind resources encouraged China's early development strategy to focus on these regions. According to the "Medium and Long-Term Development Plan for Renewable Energy" released in 2007 and the "12th Five-Year Plan for Renewable Energy Development" released in 2012, nine large wind power bases of 10 GW capacity were slotted to be built from 2008 to 2015, equivalent to 90% of total planned capacity. Of these nine bases, seven are located in the Three North area. As a result, this resource-based development strategy has led to dramatic regional disparity in wind power development. Although almost all provinces have hosted investments in the wind power industry since 2010, capacity has heavily concentrated in the Three North area. Fig. 2 shows the provincial distribution of electricity consumption and installed wind power capacity in 2016, which clearly indicates the mismatch of demand and supply. Although the installed capacity in the Three North area accounts for over half of all wind power capacity, these wind-rich provinces are economically underdeveloped and have lower electricity demand. The main power load centers in China are found in the eastern coastal regions, where the larger economy and population density lead to higher electricity consumption.

Local grids have difficulty in absorbing all wind power due to a number of factors. For example, the existing electricity system is not flexible enough to be compatible with intermittent wind power, due to dominance in the supply mix of thermal power such as coal, which can be steadily supplied. Transmitting wind power to eastern regions could improve the utilization level, but interprovincial electricity trade is constrained by the strong barriers imposed by China's segmented electricity market.

### 2.2. *Province-based electricity markets*

Knowing the institutional features and history of China's electricity industry is key to understanding China's electricity market segmentation. Since the 1980s, China's electricity industry has undergone several rounds of restructuring but still lags far behind in market-oriented reform compared with other sectors. Several studies have thoroughly reviewed the evolution of China's electricity industry. Two key elements of the sector, the quantity and the price of electricity, vary by province.

#### 2.2.1. *The evolution of the pricing mechanism*

The electricity industry was vertically integrated and essentially under central control until 2002, when the first attempt at market-oriented reform was initiated. The 2002 reform separated the generation plants and the grid companies and tried to establish a market-determined on-grid pricing mechanism by encouraging competition among the generators. However, the attempt failed and instead the

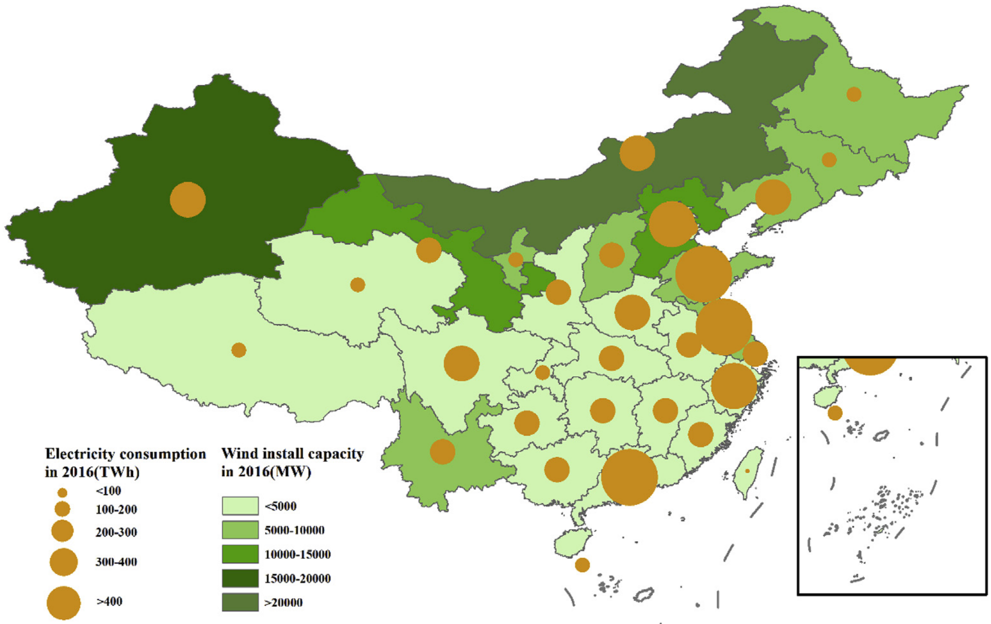


**Fig. 2.** Wind power installed capacity and electricity consumption in China in 2016.

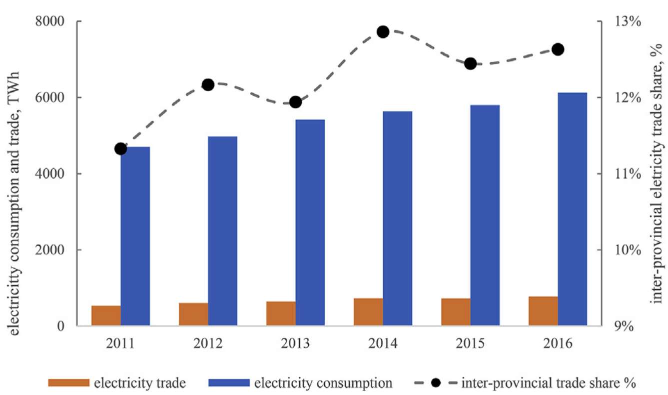


**Fig. 3.** Volume of interprovincial electricity trade and its share in total electricity consumption from 2011 to 2016.

"benchmark on-grid electricity tariff" (*biaogan dianjia*) was introduced for coal-fired power plants coming into operation after 2004. The benchmark on-grid tariffs were based on the average costs of coal power generation, which were province-specific and determined by the performance of advanced generation units in the province.

In 2005, the National Development and Reform Commission (NDRC) established the "Coal and Electricity Prices' Co-Movement" policy, which stipulated that the agency would adjust feed-in and retail tariffs in the event of a change of 5% or more in coal prices within a six-month period. This policy allowed electricity generators to pass up to 70% of increased fuel costs on to the grid companies, which could in turn pass costs on to end consumers (Ma, 2011). However, the policy was not well implemented and, once realized, Liu et al. (2013) found that the adjustment of electricity prices to coal price changes was both sluggish and asymmetric, i.e., the government was reluctant to make upward adjustments to the electricity price.

To encourage the development of renewable energy sources, such as wind, solar, and biomass, a feed-in tariff (FIT) policy was adopted. This policy divides the whole country into different categories based on the geographical distribution of energy resources and project engineering-related factors. Regions with good resources have the lowest rate, reflecting low expected production costs.

### 2.2.2. *The dispatch principle*

More details on China's generation dispatch system can be found in Kahrl et al. (2013), Zhong et al. (2015), Ho et al. (2017), and Wei et al. (2018). Generation dispatch in China can be characterized as equity-based rather than efficiency-based, as opposed to the practices in many Western countries. Due to the fact that insufficient supply was the biggest problem in China's electricity sector until 2011 (Zeng et al., 2013), a long-established principle is that power supply and demand should be kept in balance within a single province. According to this principle, provincial demand was first met by generators within a province and only in the case of a shortage was an outside source sought. As a result, interprovincial trade in electricity was largely administered, directed, and implemented as part of top-level energy strategies, such as the allocation of electricity from major hydroelectric projects (e.g., the Three Gorges Dam) and the west-to-east and north-to-south electricity corridor projects. Although the central government began to encourage interprovincial trade to improve energy efficiency by allocating resources within a larger market starting in 2003, the trade volume remained limited and only accounted for around 10% of total national energy consumption, as shown in Fig. 3.

## 2.3. *Other interregional electricity trade barriers*

Transmission cost is another obstacle for interprovincial electricity trade. Mainland China has six regional grids and, over the years, has been building a significant amount of interregional and interprovincial transmission lines.[3] By the end of 2018, 25 interregional ultra-high voltage (UHV) transmission lines and more than 200 interprovincial lines were in operation in China.[4] All provinces' grids can be physically connected, but due to the vast geography of China, long-distance

[3] Mainland China's six regional grids include the Northeast Grid, Northwest Grid, North China Grid, Central China Grid, East China Grid and South China Grid.

[4] The National Development and Reform Commission reported that, by the end of 2013, 15 interregional transmission lines (totaling 12,739 km) and 219 interprovincial lines (43,255 km in total) were in operation (NDRC, 2015). The updated number was obtained from personal communication with State Grid staff.

transmission of electricity is very costly. For example, the transmission cost of UHV electricity between Hami (Xijiang Province) and Zhengzhou (Henan province) is 0.0658 yuan/kWh. The benchmark prices in these two provinces are 0.262 yuan/kWh and 0.355 yuan/kWh, respectively. The cost of transporting electricity from Xinjiang to Henan is at least 0.328 yuan/kWh (which excludes the intraprovincial transmission costs). The expensive transmission cost is also an obstacle to interprovincial or interregional electricity trade.

Interprovincial barriers also arise from local protectionism, which has long been observed in China's domestic market (Naughton, 1999; Poncet, 2003; Wei and Zheng, 2017; Young, 2000; Zhou, 2001). On the supply side, the market is dominated by state-owned coal-fired generators. Provincial governments may be directly involved in investment and planning decisions in order to secure electricity supply, jobs, and tax revenues, for instance. They control and guide the siting of plants, financing through local banks, the allocation of generation hours, and the setting of tariffs (Zhang et al., 2018). In 2012, China's economy entered a stage called the “New Normal,” during which economic growth and electricity consumption have slowed. Against this backdrop, importing wind power means cutting the utilization hours of local generators for the recipient provinces. Provincial governments tend to protect local power generators for tax revenue and employment purposes.

## 2. Empirical model

### 2.1. Quantifying interprovincial market barriers

There are increasing efforts in the literature to empirically quantify the interprovincial market barriers, using several methods. The first method is a production-based approach, which analyzes the difference of output structure among provinces to measure the degree of market segmentation (Young, 2000). The second is a trade-based approach, which evaluates the domestic and international integration of Chinese provinces by computing all-inclusive indicators of trade barriers using provincial trade flow (Naughton, 1999; Poncet, 2003). The third method is based on the “iceberg model” proposed by Samuelson (1964), which essentially employs the price dispersion of similar goods to measure the degree of market segmentation (Parsley and Wei, 1996, 2001). In the present study, we adopt this method and explain how it works as follows.

The law of one price predicts that price differences between different locations create arbitrage opportunities and drive prices to converge. However, due to the arbitrage costs, the prices in two locations may differ at any time and the difference should be bounded by the arbitrage costs. Assuming the prices in location $i$ and $j$ are $P_{i,t}$ and $P_{j,t}$, and the cost of engaging in the arbitrage activities of transporting and selling the good is $C_{ij,t}$, then the arbitrage drives the following inequality to hold:

$$-\ln C_{ij,t} \le ln(P_{i,t}/P_{j,t}) - ln(P_{i,t-1}/P_{j,t-1}) \le lnC_{ij,t} \tag{1}$$

The standard deviation of the price differences can be used to measure the price dispersion. The price dispersion includes many components. For example, it increases with distance or transportation costs. When there is no other transaction cost, arbitrage will drive the variation of prices across provinces to converge to the transportation cost in the long term. However, if there are other types of transaction costs unrelated to distance, such as the trade barriers we discussed in section 2, the distance variable cannot explain all variations in relative price fluctuations and the residue can be used to measure the market segmentation. In our electricity case, let the differences in the changes of prices for province $j$ relative to province $i$ be

$$Q_{ij,t} = |ln(P_{i,t}/P_{j,t}) - ln(P_{i,t-1}/P_{j,t-1})| = |ln(P_{i,t}/P_{i,t-1}) - ln(P_{j,t}/P_{j,t-1})| \tag{2}$$

Following Parsley and Wei (2001) and Lu and Chen (2009), the market segmentation index for province $i$ can be defined as

$$segm_{i,t}\ Var\ (\ )\ for\ all\ j \neq i \tag{3}$$

which defines the market segmentation index as the dispersion of relative changes in electricity price. This measurement has the advantage of removing time–invariant fixed effects such as transportation distance. It can be used as a proxy for the institution-related transaction costs that are independent of spatial distance. The larger the variance is, the greater the market barrier and transaction costs a province will confront. The provincial Fuel and Power Price Index is used to calculate the index.

We speculate that a province may face lower trade barriers with respect to its neighbors or the provinces in the same regional grid, because they have more transmission connections and more coordinated dispatch. Therefore, three types of market segmentation index are constructed: (1) an index for the country-wide market; (2) an index for a province's own regional grid market; and (3) an index for the neighboring provinces' market.

### 2.2. Baseline model

To investigate the role of market segmentation in explaining wind curtailment in China, we propose a testable hypothesis that **the greater the market segmentation/barriers a province confronts, the higher the wind curtailment rate in that province.** The following model is specified:

$$curt_{i,t} = \beta_0 + \beta_1 \cdot Segm_{i,t} + \beta_2 \cdot X + \lambda_i + \varepsilon_{i,t} \tag{4}$$

in which $Curt_{i,t}$ is the wind curtailment rate for wind capacity originating in province $i$ in year $t$. $Segm_{i,t}$ is the market segmentation index, which is used to capture the external market barriers faced by province $i$ in year $t$. The coefficient $\beta_1$ measures the impact of the market segmentation on the curtailment rate. A significant positive $\beta_1$ indicates that greater market segmentation is associated with a higher wind curtailment rate. Vector $X$ contains the control variables to capture other factors that can affect a province's curtailment rate. It is expected that a province's utilization of wind power will be affected by three types of variables: local demand, local supply, and demand from other provinces (external markets). Population (*pop*), income level (*inc*), and economic structure, which is measured by industry and tertiary sector compositions (*ind* and *ter*, respectively), are included to control for local demand factors. To control for local supply-side competition, we use the share of installed wind power capacity (*wind*) in all electricity capacity within province $i$. $\lambda_i$ represents individual fixed effects that do not change over time, while $\varepsilon_{i,t}$ represents a random term independent of the explanatory variable.

### 2.3. Heterogeneous effects

It is also interesting to further investigate the heterogeneous effects of market barriers on wind curtailment. Specifically, we set up an econometric model on the basis of model (1) as follows:

$$Curt_{i,t} = \gamma_0 + \gamma_1 \cdot Segm_{i,t} + \gamma_2 \cdot Segm_{i,t} \cdot Z_{i,t} + \gamma_3 \cdot Z_{i,t} + \gamma_4 \cdot X + \lambda_i + \varepsilon_{i,t} \tag{5}$$

where vector $Z$ represents the candidate terms that may alter the effect of market segmentation on wind curtailment. Three potential heterogeneity effects are explored. First, if a province faces an external market that has interest groups that can compete with wind power, the province is expected to face more barriers, i.e., the external market will tend to reject the importation of wind power. Second, if a province faces an external market that has good institutional quality, the province may be less affected by local interest groups because such an external market would receive more guidance from the central government and would thus be less likely to erect market barriers. Third, if a province faces an external market that has more concern about environmental quality, fewer trade barriers may be imposed since the trade partner may have a higher incentive to purchase more renewable energy and replace traditional thermal power.

We introduce several variables and their interaction terms into the market segmentation index to examine this heterogeneity. Three types of local interest groups who may compete with wind power are identified and represented by the share of thermal power installed capacity (*H1_coal*), share of hydropower installed capacity (*H1_hydro*), and share of State-Owned Enterprises (*H1_SOE*). Chinese Marketization Indexes (*H2_a*) are introduced to represent the institutional quality at the province level (Wang et al., 2017). This is a comprehensive, survey-based evaluation indicator, covering 31 provinces and spanning 1990 to 2016, which is widely used in the literature (He et al., 2018; Li et al., 2018a, 2018b; Wang, 2016; Wei and Zheng, 2017; Yi et al., 2017; Zhang et al., 2019). Specifically, we use the overall indicator and its four sub-indicators: government-market relationship score (H2_*b*), commodity market development score (*H2_c*), factor market development score (*H2_d*), and the law and institution index (*H2_e*). $SO_2$ emission per $km^2$ (*H3_env*) is included to represent the local government's environmental regulation efforts.

If province *i*'s external market is the rest of the country, consisting of all the other provinces besides itself, then these variables are taken as the mean of the provinces other than province *i* and are included as variables of vector *Z* in model (2). The partial effect of market segmentation on wind curtailment rate can be derived as $d(\boldsymbol{C})/d(\boldsymbol{Segm}) = \gamma_1 + \gamma_2 Z$. This shows that the interprovincial barriers' impact on local wind power development will be partially determined by the hypothesized *Z* variables. The coefficient $\gamma_2$ is our major focus in examining whether heterogeneous effects exist. If the positive effect of market segmentation on wind curtailment is confirmed ($\gamma_1 > 0$) and the interaction term ($\gamma_2$) is positive and statistically significant, this will indicate that the change of variable *Z* will exacerbate the impact of market segmentation on the wind curtailment rate. Otherwise, if $\gamma_1 > 0$ and $\gamma_2 < 0$, it means the change of variable *Z* may weaken the negative effect of interprovincial barriers on wind power integration.

### 2.4. Data sources

The National Energy Administration (NEA) has released annual reports of wind power development in China since 2011, which include annual wind curtailment rates at the provincial level. The statistics for 2009 and 2010 are obtained from Song and Berrah (2013). The data on installed power capacity come from the annual yearbook of the China Electricity Council (CEC). The energy-related data and economic data come from the *China Energy Statistical Yearbook* and *China Statistical Yearbook* series, respectively. All monetary variables (such as GDP and per capita GDP) are deflated at the 2005 constant price. The data on the Fuel and Power Price Index that were used to estimate the market segmentation index come from the *China Statistical Yearbook* series. The statistical summary of all variables is listed in Table 1.

## 3. Results and discussion

### 3.1. Baseline model results

The regression results for equation (4) are presented in Table 2. The first column (model s0) only includes the share of installed wind capacity, which is the most influential factor. The high $R^2$ value (0.689) suggests that the variable can explain the majority of variance in wind curtailment rates. The significant positive coefficient also indicates that the higher percentage of wind installed capacity is strongly associated with a higher wind curtailment rate. On the basis of s0, the second column (model s1) further controls for the provincial fixed effect. It yields greater explanatory power with $R^2 = 0.827$, indicating that some unobserved individual effects matter and can contribute to the change of the wind curtailment rate. Taking model s1 as a benchmark, s2–s5 add various explanatory variables in turn. We find that the per capita GDP is significant at the 10% level, and its sign is consistent with expectations. Greater local demand, represented by a higher income level, will reduce the wind curtailment rate.

We further introduce the market segmentation index in models s5 and s6 and present the results in columns 7 and 8. The significant positive coefficient of variable *segm* indicates the interprovincial market barrier will exacerbate the wind curtailment rate. After controlling for the market barrier, the per capita GDP is still negative but is not significant.

After pooling all variables together in the last column (model s7), the sign still holds for all variables. This suggests that, in terms of magnitude and significance, local supply (the share of wind installed capacity) is the major contributor to the wind curtailment rate. This is consistent with the literature, which argues that the rapid, large-scale development of wind power capacity is the main reason for the excess capacity and subsequent contraction in China's wind power development (Dong et al., 2018; Zhao et al., 2012). The signs for per capita GDP, industry share, and tertiary share are negative but not significant, suggesting that local demand may help to balance over-supplied wind power to some extent, but its effects are not significant. More importantly, we find empirical evidence to support our hypothesis. Our results show that, when controlling for various local variables, a 1% increase in the interprovincial market barrier is associated with a 0.43–0.48 percentage increase in wind curtailment. To put this in context, if the market segmentation index of Gansu, which has the highest wind curtailment rates (an average of 22.8% during our sample period), decreases to the mean level of all provinces, its wind curtailment would drop by 6.6–7.5%.

**Table 1**
Dependent and independent variables and their summary statistics.

| Category | | Variable | Obs | Mean | S D | Min | Max |
|---|---|---|---|---|---|---|---|
| Dependent variable: curtailment rate | | *curt* | 248 | 3.70 | 7.85 | 0.00 | 43.00 |
| Local demand | Ln(population) | *pop* | 248 | 8.11 | 0.85 | 5.69 | 9.31 |
| | Ln(per capita GDP) | *inc* | 248 | 1.12 | 0.51 | −0.09 | 2.33 |
| | Industry share | *ind* | 248 | 46.12 | 8.21 | 19.30 | 58.60 |
| | Tertiary share | *ter* | 248 | 43.43 | 9.19 | 30.60 | 80.20 |
| Local supply | Share of wind installed capacity | *wind* | 231 | 0.57 | 0.68 | 0.00 | 2.60 |
| Market segmentation | Ln(market segmentation index) | *Segm* | 248 | −7.73 | 1.26 | −9.85 | −5.39 |
| Local interest group | Share of thermal installed capacity | *H1_coal* | 248 | 68.39 | 22.84 | 15.22 | 98.46 |
| | Share of hydropower installed capacity | *H1_hydro* | 248 | 23.43 | 23.62 | 0.00 | 75.66 |
| | Share of SOE in industry sector | *H1_SOE* | 248 | 24.64 | 11.61 | 6.79 | 52.52 |
| Institutional quality | Overall market index | *H2_a* | 186 | 5.88 | 1.93 | 0.16 | 9.44 |
| | Government-market relationship | *H2_b* | 186 | 5.85 | 2.40 | −4.95 | 8.95 |
| | Commodity market index | *H2_c* | 186 | 7.62 | 1.35 | 3.48 | 9.79 |
| | Factor market index | *H2_d* | 186 | 4.73 | 2.11 | −0.95 | 10.69 |
| | Law and institution index | *H2_e* | 186 | 4.78 | 3.46 | −0.06 | 14.15 |
| Environmental concern | Ln(SO2 emission density) | *H3_env* | 248 | 0.94 | 1.60 | −5.90 | 3.39 |

**Table 2**
Regression results: the effect of market segmentation on wind curtailment.

| Variables | S0 | S1 | S2 | S3 | S4 | S5 | S6 | S7 |
|---|---|---|---|---|---|---|---|---|
| *wind* | 9.84*** | 7.89*** | 7.97*** | 9.19*** | 8.21*** | 8.42*** | 9.18*** | 9.17*** |
| | (0.44) | (0.74) | (0.80) | (1.03) | (0.82) | (0.76) | (1.02) | (1.07) |
| *pop* | | | −2.67 | | | | | 9.72 |
| | | | (9.48) | | | | | (11.06) |
| *inc* | | | | −3.19* | | | −2.07 | −2.25 |
| | | | | (1.75) | | | (1.83) | (3.18) |
| *ind* | | | | | −0.26 | | | −0.03 |
| | | | | | (0.30) | | | (0.35) |
| *ter* | | | | | −0.29 | | | −0.07 |
| | | | | | (0.29) | | | (0.38) |
| ***segm*** | | | | | | 0.50** | 0.43** | 0.48* |
| | | | | | | (0.20) | (0.22) | (0.25) |
| Fixed effect | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 231 | 231 | 231 | 231 | 231 | 231 | 231 | 231 |
| *Adj* $R^2$ | 0.689 | 0.827 | 0.827 | 0.830 | 0.828 | 0.832 | 0.833 | 0.834 |

**Table 3**
Robustness check models: introducing a one-year lag term of the wind curtailment rate.

| Variables | S5 | S5_lag | S6 | S6_lag | S7 | S7_lag |
|---|---|---|---|---|---|---|
| *Lag1.curt* | | 0.42*** | | 0.42*** | | 0.41*** |
| | | (0.07) | | (0.07) | | (0.07) |
| *wind* | 8.42*** | 6.92*** | 9.18*** | 8.28*** | 9.17*** | 8.46*** |
| | (0.76) | (0.92) | (1.02) | (1.18) | (1.07) | (1.25) |
| *pop* | | | | | 9.72 | 15.21 |
| | | | | | (11.06) | (11.83) |
| *inc* | | | −2.07 | −3.45* | −2.25 | −5.13 |
| | | | (1.83) | (1.89) | (3.18) | (3.53) |
| *ind* | | | | | −0.03 | 0.12 |
| | | | | | (0.35) | (0.35) |
| *ter* | | | | | −0.07 | 0.11 |
| | | | | | (0.38) | (0.38) |
| ***segm*** | 0.50** | 0.53*** | 0.43** | 0.47** | 0.48* | 0.47** |
| | (0.20) | (0.20) | (0.22) | (0.20) | (0.25) | (0.23) |
| Fixed effect | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 231 | 208 | 231 | 208 | 231 | 208 |
| *Adj* $R^2$ | 0.832 | 0.875 | 0.833 | 0.877 | 0.834 | 0.879 |

For a robustness check, we introduce the one-year lag term of the wind curtailment rate as an independent variable and present the results in Table 3. When controlling for the lag term of the wind curtailment rate, a 1% increase in the market segmentation index is associated with a 0.47–0.53 percentage increase in the wind curtailment rate. The market segmentation index (*segm*) in the lagged model is consistent with the base model results in terms of coefficient magnitude and significance level, indicating our estimation results are robust.

As we discuss above, provinces may face smaller trade barriers from provinces in the same grid or adjacent since they have more physical transmission connectivity or more coordinated dispatch. Table 4 present the means of the market segmentation index constructed using (1) all provinces; (2) the provinces in the same grid; and (3) the provinces that share borders. Consistent with our expectation, we find that the indices in cases (2) and (3) are smaller than case (1). In addition, the market segmentation does not show statistically significantly effect on wind curtailment for provinces in the same grid or sharing borders. These results suggest that the regional grid may help ease the negative effect of market segmentation and break down provincial protectionism. The inter-regional trade barriers may play a more important role in explaining the curtailment.

**Table 4**
Comparing the effects of market segmentation within the same regional grid and neighboring provinces.

| $segm_{i,t}$ | sample mean | coefficient of $segm_{i,t}$ |
|---|---|---|
| All provinces | 0.00093 | 0.48* (0.25) |
| Provinces in the same grid region | 0.00091 | 0.16 (0.20) |
| Physically adjacent provinces | 0.00072 | 0.18 (0.20) |

### 3.2. Heterogeneous effects

Table 5 reports the estimation results of equation (5), which examines the heterogeneous effects. They are obtained by introducing the three types of representative variables into the baseline model. Due to space limits, only the coefficients of market segmentation, its interaction terms, and its marginal effects are presented. The coefficients of other control variables are consistent with the baseline model results in terms of magnitude and significance.

First, different candidate variables representing local interest groups are used to examine whether these interest groups aggravate the effect of market segmentation. The marginal effects of thermal power and SOE are positive and statistically significant at 10%. This suggests that,

**Table 5**
Estimated coefficients and marginal effects of various heterogeneous effects.

| Category | | Variable | $\gamma_1$ | $\gamma_2$ | Marginal Effect $\gamma_1+\gamma_2{\cdot}Z$ |
|---|---|---|---|---|---|
| Local interest groups | Share of thermal installed capacity | *H1_coal* | 0.334 (0.767) | 0.002 (0.010) | 0.471* (0.255) |
| | Share of hydropower installed capacity | *H1_hydro* | 0.754** (0.315) | −0.016 (0.010) | 0.408 (0.251) |
| | Share of SOE in industry sector | *H1_SOE* | −0.441 (0.495) | 0.037** (0.017) | 0.457* (0.250) |
| Institutional quality | Overall market index | *H2_ai* | −1.462* (0.821) | 0.152 (0.108) | −0.541 (0.362) |
| | Government-market relationship | *H2_bI* | −1.230 (0.806) | 0.123 (0.107) | −0.475 (0.362) |
| | Commodity market index | *H2_c* | −1.654 (1.175) | 0.156 (0.140) | −0.448 (0.358) |
| | Factor market index | *H2_d* | −0.985 (0.647) | 0.101 (0.096) | −0.492 (0.359) |
| | Law and institution index | *H2_e* | −0.735 (0.514) | 0.048 (0.057) | −0.498 (0.367) |
| Environmental concern | Ln(SO2 emission density) | *H3_env* | 0.532* (0.312) | −0.096 (0.165) | 0.430 (0.262) |

holding other things constant, if a province's external market has a higher share of thermal power or SOE, it will face a larger trade barrier and thus suffer higher wind power curtailment.

Next, to examine the effect of institutional quality, we add five institutional quality variables and their interaction terms with the market segmentation index into the baseline model. Although the sign of all interaction terms is positive, none of them is significant at the 10% level. This suggests that the market barriers' effect on wind power is independent of institutional quality.

Finally, the interaction term and the marginal effect after including the environmental concern variable are not statistically significant, which indicates that the segmented market's impact on wind power development is not correlated with local environmental quality or governance.

In short, we propose and examine a basic hypothesis based on our literature discussion and empirical observations. Our results show the following: (1) the concentration of wind power capacity measured by the share of wind power capacity in a province is the major reason for wind power curtailment; (2) the interprovincial market barrier further exacerbates the curtailment of wind power; (3) the regional grid may help ease the negative effect of market segmentation and break down provincial protectionism while the inter-regional trade barriers may play a more important role in explaining the curtailment; and (4) coal power competes with wind power, which can amplify the external market barrier and results in a higher wind power curtailment rate. Finally, state-owned enterprises increase electricity trade barriers, which we believe is due to their bargaining power in resisting competition.

## 4. Conclusions and policy implications

The causes of wind power curtailment in China are manifold. As far as we are aware, this is the first study to quantitatively examine the role of market segmentation in explaining the wind curtailment problem in China. By constructing a provincial market segmentation index and estimating its partial effect on the wind curtailment rate using a panel model, we find that a 1% increase in the market segmentation index will lead to a 0.43–0.53% increase in the wind curtailment rate. This result is significant both statistically and practically, highlighting the importance of market segmentation in contributing to the waste of wind resources.

Our study has several policy implications. The results highlight the importance of removing interprovincial trade barriers in order to increase the penetration of renewable energy into China's energy supply mix. If the problem of market segmentation cannot be solved, wind curtailment could continue to bring about great economic losses. From 2010 to 2016, the total loss due to wind power curtailment was nearly 145 TWh, equivalent to the total annual electricity power generation of the Three Gorges and Gezhouba hydropower stations in 2015. The associated direct economic losses caused by wind curtailment totaled about 75 billion yuan in this period. In order to achieve the development goal of increasing the share of renewable energy to 15% in 2020 and 20% in 2030, it is expected that wind and solar power installed capacity will increase to 360–400 GW in 2020 and then further increase to 1000 GW (NDRC and NEA, 2016). This implies that significantly increasing the volume of interprovincial power trade is inevitable since most renewable energy resources—including wind, solar, and hydropower—are located in northern and western China, far from the load centers located in the eastern and southern parts of the country (Fan et al., 2015).

Interprovincial trade barriers are rooted in China's governance structure and the political economy of the relationships among the central government, provincial governments, and state-owned enterprises. Agencies at the provincial level, in particular, have substantial autonomy and power to regulate the economy, including the power sector. Each province wants to protect its generators in order to maintain employment and tax revenues, and there is often resistance to centralized efforts to rationalize the national system (Ho et al., 2017).

China initiated a new round of market-oriented electricity reforms in 2015, aiming to gradually establish an electric power market, with medium- and long-term trading at its core to avoid risks and with spot trading as a supplement to price discovery. However, partially due to previous lessons, this round of reform encouraged provincial governments to take the lead in implementation. A key element of the reform is to establish spot markets to reveal the real market price of electricity and to allocate resources based on price signals, which can help mitigate wind power waste since it has cost advantages with near-zero marginal costs. Currently, most of the spot market efforts in China are proceeding province by province, although the central government has asked the five provinces in the Southern Grid region to eventually implement a regional market.[5] The spot market is being piloted with individual provincial markets. As a result, the interprovincial trade barriers seem to impede interprovincial and inter-regional electricity trading and prevent the integration of provincial markets into regional/national markets. Zhang et al. (2018) have provided a detailed discussion on how the reform can facilitate an increase in the generation of renewable energy, including strengthening top-level design and supervision, building up electricity spot markets, pushing forward regional electricity markets, and facilitating the establishment of a renewable energy quota system.

A mandatory renewable energy quota system, which would impose minimum consumption targets for each province, is currently being discussed as a policy instrument for increasing the level of renewable energy penetration. We argue that the quota system may not be as effective as expected since an efficient allocation of renewable electricity resources requires free trade. If the trade barriers still exist, the provinces may choose to meet the quota requirement by building renewable electricity generation capacity instead of purchasing from outside of the province. The inefficiency resulting from segmented markets cannot be fundamentally resolved without addressing these barriers.

To remove the interprovincial barriers, the central government should play a greater role in electricity reform by strengthening top-level design and supervision. The spot market is particularly critical because of its real-time transactions, which can make the electricity power market more competitive and optimize power resource allocation. Although the current model of provincial-based spot markets led by provincial governments is easy to implement, it may intensify interprovincial barriers in the long run. The central government should play a central role in market design and push forward regional/national electricity markets.

As far as we know, our analysis is the first application of the market segmentation method to study the electricity market. A potential caveat arises from the fact that electricity is a network good, which has clear physical constraints on where electricity flows. In addition, electricity faces congestion – essentially an infinite cost of arbitrage – which occurs at times even between connected regions. A potential problem is that the segmentation index may also capture the transmission constraint. As our analysis shows, adjacent provinces and provinces within the same grid have a smaller market segmentation index, which promotes absorption of wind capacity. Unfortunately, whether this effect comes from more physical connectivity or less local protectionism is unclear and is worth further investigation.[6]

[5] In August 2017, the NDRC and NEA of China issued a policy to start spot market pilots in China, choosing eight districts for the first pilot: the South (starting in Guangdong province), Western Inner Mongolia, Zhejiang, Shanxi, Shandong, Fujian, Sichuan, and Gansu.

[6] We appreciate an anonymous reviewer for raising this point.

## Conflicts of interest

The authors declare that they have no conflict of interest.

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