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Assessing the Effects of Market Power on Electricity Reliability in China: Toward a Green and Reliable Market

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The transition to a low-carbon power system is among the measures to forge green energy transition and carbon neutrality, where grid firms have a crucial role. In this context, this paper uses the provincial data from 2004 to 2017 to evaluate the impact of market power of grid companies on service quality in China. Panel dynamic ordinary least square (DOLS) and fully modified ordinary least square (FMOLS) models are employed. The findings indicate that higher market power has indeed reduced reliability measured by average outage duration. Renewable energy integration also has negative effects and reduces electricity reliability. Finally, the effects are also heterogeneous across the different regions. The results may also provide useful lessons for other developing countries aiming to improve the electricity supply chain.

Keywords: carbon neutrality, electricity transition, supply reliability, grid market power, electricity market reform

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1 INTRODUCTION

China's electricity sector, the largest in the world, accounts for about 45% of energy-related CO_2 emissions and thus the transition to a low-carbon power system is becoming common sense (Abhyankar et al., 2020). Particularly, China promised to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060, which put forward higher requirements for greening electricity supply chain and especially for grid firms. On one hand, the electricity dispatch, transmission, and distribution by power grids act a vital role in the integration of renewable energy. On the other hand, the grid system is an important link that transmits carbon prices from the production side to the consumption side. In this regard, deepening electricity reform and regulations on grid firms are among the measures to forge green energy transition and carbon neutrality.

Like most countries, China has embarked upon a series of reforms toward a competitive, green, and reliable electricity market. The reform process can be seen as the gradual degradation and unbundling, transforming from an absolute to a relative monopoly (Wang and Chen, 2012). The two most influential policies were implemented in 2002 and 2015 (She et al., 2020). In the unbundling reform implemented in 2002, the State Power Corporation was broken down into many companies, including two grid firms to break the monopoly. As for the latest reform in 2015, more effort is tied to introduce competition into power retail side. The most important request for transmission and distribution sector includes that the business operation and revenue income mode will be changed and they are supposed to shoulder the responsibility of demand side management in the future (Zeng et al., 2016).

In China, currently, the grid firms are state owned and the electricity transmission and distribution are operated at the provincial level. The provincial grid firms, working as an important public utility department, are responsible for reliable power supply and economic benefits, which means that they provide public service and pursue more economic profits simultaneously (Xie et al., 2021). Therefore, service quality is an important benchmark to determine the performance of the power grid. Unfortunately, China's unique economic system and regulation framework lead to the grid market power, which raises a question of whether grid market power has negative impacts on service quality (Yu and Fu, 2012; Li and Gao, 2014). The possible reason for this is that stated-owned companies may be less efficient due to problems of the political use, as governments do not aim at profit maximization and operational efficiency (Muller and Rego, 2021). Furthermore, if quality is not contractible and included in regulation standards, a monopolist may deliver a lower service quality (Ter-Martirosyan and Kwoka, 2010).

This paper aims to investigate whether market power of grid companies has an effect on service quality. On one hand, as for the power grid sector, the profit pattern will be replaced by the transmission and distribution tariff under the principle of "cost plus reasonable profits". However, based on the regulatory theory, the firms under a price-cap regime tend to reduce service quality for cost reduction if the service quality and cost are positively related (Spence, 1975; Sheshinski, 1976; Fraser, 1994; Corton et al., 2016). On the other hand, in the context of pursuing net-zero emissions, the power generation that relies heavily on coal will be gradually changed. The development of renewable energy will in turn have a profound effect on sustainability and reliability of the electricity system. In this context, how to improve productive efficiency and regulate the transmission and distribution sector becomes an important issue.

Considering the essential role of power grids in carbon neutrality, the contributions of this paper can be summarized as follows. First, this paper empirically analyzes the impacts of grid market power on service quality and provide some policy recommendations for further improving the transmission and distribution section, as well as achieving the goals of clean electricity transition and carbon neutrality. Second, this research is also an exploration for regulations of China's grid industry from the perspectives of service quality and performance. Finally, building a sustainable and reliable electricity market is an important foundation for ensuring energy transforms. However, due to the instability of clean energy, there may be conflicts between sustainability and reliability. The findings in our paper may also add some insightful reference to deal with this dilemma.

This paper consists of five sections as follows. **Section 2** presents the literature review. **Section 3** briefly introduces the model and data. The empirical result analysis is presented in **Section 4**. Finally, **Section 5** concludes.

2 LITERATURE REVIEW

As the world's largest power market, there is an extensive literature on assessing China's power market reform (such as Guo et al., 2020) and how the reform could affect various aspects of power system operations, such as the integration of renewable energy (Zhang et al., 2018), electricity generation efficiency (Meng et al., 2016), and supply security (Zheng et al., 2021). However, despite many significant achievements, there are still various practical problems that have not been resolved and market power is one of the main concerns (Mozdawar et al., 2022).

Generally, market power could hamper the competition, technology innovation, and service quality (Asgari and Monsef, 2010). For example, Shukla and Thampy (2011) confirm that market power may be part of the reason for an electricity price increase in India. Browne et al. (2015) find that market power in turn results in inefficient dispatch which is exacerbated with large amounts of wind generation. Amountzias et al. (2017) indicate that the wholesale mark-up is significantly and positively influenced by market power of the Big Six in the United Kingdom wholesale industry in the short run. Rostamnia and Rashid (2019) assess the effects of power extent on pricing in the electricity market. Bigerna et al. (2021) discuss the exercise of market power during the COVID-19 lockdown period and find an increase in market power on both supply and demand in the Italian Power Exchange. However, only a few researchers have paid attention to market power of grid companies in China's electricity industry. A recent example is Yao et al. (2019), who prove that market power indeed has significant negative effects on power grid efficiency in China.

Electricity plays a dominant role in the manufacturing sector and daily life. Unreliable power supply will hinder enterprise productivity and create significant constraints (Pless and Fell, 2017; Ayaburi et al., 2020). As such, the underlying causes for poor electricity reliability are complex and especially important for the policy makers. Borenstein et al. (2002) show that the market power plays a crucial role in California's power outages. Fumagalli et al. (2007) suggest that privatization will not lead to quality degradation in the electricity sector. Yu et al. (2009) show that service quality in the distribution networks will be influenced by weather conditions, for example, rain, wind, and temperatures. Pless and Fell (2017) demonstrate that bribes for electricity connection are associated with an increase in electricity reliability. Li and Li (2018) find that the firms tend to reduce the service quality in the utility sector (electricity, water, natural gas, etc.) for consumers when the government cannot cover the deficit caused by subsidizing. Xu et al. (2019) reveals that natural disasters, weak grid power exchange capacity, weak grid support, weak emergency power support, and protection mistakenly moved are the main threats for unsustainable electric power system using Chengdu Electric Bureau as a case. Xie et al. (2021) indicate that the unbundling reform implemented in China has not improved the service quality of the power grid firms. Muller and Rego (2021) prove that private ownership positively influences both quality and financial indicators considering regulatory goals in Brazil.

Although service quality plays an important role in electricity supply, there is only a limited body of literature that has addressed the issue of service quality when studying China's power industry. Although much evidence shows that abuse of market power will result in higher prices and lower service quality, such as David and Wen (2001), will the grid companies abuse the market power and have the market power really brought about a reduction in the service quality? To fill this gap, this study empirically analyzes the effect of market power of grid companies on service quality in China's power sector.

3 DATA AND MODEL SPECIFICATION

3.1 Methodology

To discuss the impacts of market power on reliability from the perspectives of grid companies, we will construct a panel data in this research. The basic panel model is shown in **Equation (1)**.

$$lnoutage_{i,t} = \alpha_i + \beta_1 power_{i,t} + \beta_2 lnallo_{i,t} + \beta_3 clearn_{i,t} + \beta_4 lnscarcity_{i,t} + \beta_5 lncon_{i,t} + \varepsilon_{i,t} \quad (1)$$

where subscripts t and i represent year and province, respectively, and $\varepsilon_{i,t}$ is the error term. In addition, $lnoutage$ represents the explained variable, namely power supply reliability or service quality, measured by the average annual duration of outage. Higher $lnoutage$ always means lower reliability or worse service quality. The power supply reliability indicator for 10 KV user, namely the annual average outage duration of per connected household (AICH1), is utilized (Yu et al., 2009; Hensher et al., 2014). *Power* represents the market power of grid companies. Theoretically, Herfindahl–Hirschman index (HHI), the Residual Supply index (RSI), together with price cost mark-ups (Lerner index) are the conventional measures of market power (Chernenko, 2015). Referring to Yu and Fu (2012) and Yao et al. (2019), this paper uses the Lerner index ($L = (\frac{p-mc}{p})$) to represent the grid market power.

Accordingly, *lnallo* is per capita distribution capability to measure the electricity infrastructure. *Clean* is the proportion of clean power generation to take the renewable energy development into consideration. We employ the capacity factor ($lnscarcity = \ln(\frac{GEN^{thermanl}}{CAP^{thermal}})$) to measure electricity scarcity, containing information on electricity generation ($GEN^{thermanl}$), and capacity from thermal power plants ($CAP^{thermal}$) following the study of Fisher-Vanden et al. (2015). *lncon* is the domestic electricity consumption per capita to represent the electricity delivered by grid firms.

The stationarity of time series processes determines the selection of the regression models. If the time series processes are non-stationary and the variables are cointegrated, the conventional OLS estimation methods (such as pooled OLS, fixed effect, and dynamic panel models) will produce inconsistent and biased estimates (Liu and Hao, 2018; Lin and Chen, 2019). Thus, this research utilizes a fully modified OLS (FMOLS) and dynamic OLS (DOLS) as estimation techniques after performing the unit root tests and determining the cointegrating relationship. FMOLS proposed by Phillips and Moon (1999) and Pedroni (2004) and DOLS proposed by Kao and Chiang (2001) provides efficient results for cointegrated variables when the sample is small, which can eliminate the problems of endogeneity and variable serial correlation (Song et al., 2008; Merlin and Chen, 2021). Moreover, FMOLS and DOLS techniques have been applied to estimate long-run parameters by many studies, such as Khan et al. (2019), Merlin and Chen (2021), and Cui et al. (2022). Canonical Cointegrating Regression (CCR) estimation is also applied to verify the result robustness of FMOLS and DOLS.

Technically, the estimation procedure includes the following steps. First, the panel unit root tests are applied to examine the stationarity of the variables. Afterward, the panel cointegration test is further utilized to examine the cointegrating relationship. Finally, the long-run parameters are estimated with FMOLS and DOLS models.

3.1.1 Panel Unit Root Tests

The unit root test of time series based on the large sample is basically a progressive analysis without considering the cross-section factor. However, the panel unit root test is developed in recent years, which improves the problem of small samples and test efficiency. There are many unit root tests proposed in the literature, and in this research LLC (Levin et al., 2002), IPS (Im et al., 2003), and Fisher (Maddala and Wu 1999) unit root tests are chosen due to their estimation power, as well as to avoid the bias caused by a single method.

3.1.2 Panel Cointegration Tests

After identifying the integration order of the variables, the next step is to examine the cointegration relationship. There are a number of cointegration tests suggested in the literature, including Kao (1999), Pedroni (1999), Pedroni (2004), and Westerlund (2005) cointegration tests. In this research, we choose the commonly used panel cointegration test proposed by Pedroni (1999) and Pedroni (2004) to examine the long-term equilibrium relationship between the variables and in the most general case, the formula can be expressed as follows.

$$y_{it} = \alpha_i + \delta_i t + \beta_i X_{it} + \varepsilon_{it} \quad (2)$$

where $t = 1, \cdots, T$, and $i = 1, \cdots, N$ refer to the number of time observations and individual members in the panel. α_i and $\delta_i t$ are individual specific effect and linear trend, respectively. β_i denotes the slope coefficients. The null hypothesis suggests the no cointegration and thus the rejection of the null hypothesis indicates the existence of cointegration. Furthermore, we also report the results of Kao (1999)'s panel cointegration test as a robustness check.

3.1.3 Panel Long-Run Parameter Estimates

After confirming the relationship among the variables, the next step is to estimate the parameters. There are a series of estimation methods including ordinary least squares (OLS), panel dynamic ordinary least square (DOLS), and fully modified ordinary least square (FMOLS) models. As Pedroni (2001) suggested, OLS is associated with the problems of serial correlation and second order asymptotic bias. Therefore, when there is a long-term equilibrium relationship between variables, the ordinary OLS model is no longer effective. To overcome these problems, Stock and Watson (1993) proposed DOLS, and FMOLS was proposed by Phillips and Hansen (1990) and perfected by

Pedroni (2001). Both panel FMOLS and DOLS can effectively address the problems of small sample bias and series correlation challenges attributed to conventional OLS estimator (Sulaiman et al., 2020). Therefore, we apply panel DOLS and FMOLS models to estimate the long-run relationship and **Table 4** shows the baseline regression results.

In the FMOLS model, a non-parametric correction term is used to solve the problems of long-run correlation and endogeneity (Liu and Hao, 2018), and the panel FMOLS estimator and t-statistic can be written as follows.

$$\hat{\beta}_{FMOLS} = N^{-1}\sum_{i=1}^{N}\hat{\beta}_{FMOLS,i} \tag{3}$$

$$t_{\hat{\beta}_{FMOLS}} = N^{-1/2}\sum_{i=1}^{N}t_{\hat{\beta}_{FMOLS,i}} \tag{4}$$

Further, since the cointegrating equation with the lead and lagged differences of the regressor are augmented, the panel DOLS model can be built as follows.

$$\begin{aligned} lnoutage_{i,t} = {} & \alpha_i + \beta_{1i}power_{i,t} + \beta_{2i}lnallo_{i,t} + \beta_{3i}clean_{i,t} \\ & + \beta_{4i}lnscarcity_{i,t} + \beta_{5i}lncon_{i,t} \\ & + \sum_{k=-K_i}^{K_i}\lambda_{1ik}\Delta power_{i,t-k} \\ & + \sum_{k=-K_i}^{K_i}\lambda_{2ik}\Delta lnallo_{i,t-k} \\ & + \sum_{k=-K_i}^{K_i}\lambda_{3ik}\Delta clean_{i,t-k} \\ & + \sum_{k=-K_i}^{K_i}\lambda_{4ik}\Delta lnscarcity_{i,t-k} \\ & + \sum_{k=-K_i}^{K_i}\lambda_{5ik}\Delta lncon_{i,t-k}\varepsilon_{i,t} \end{aligned} \tag{5}$$

The associated panel DOLS estimator and t-statistic can be given in **Equations (6)** and **(7)**.

$$\hat{\beta}_{DOLS} = N^{-1}\sum_{i=1}^{N}\hat{\beta}_{DOLS,i} \tag{6}$$

$$t_{\hat{\beta}_{DOLS}} = N^{-1/2}\sum_{i=1}^{N}t_{\hat{\beta}_{DOLS,i}} \tag{7}$$

3.2 Data and Measures of Grid Market Power

The panel data studied in this paper cover 27 provinces from 2004 to 2017 in China. Due to availability, Shanghai, Hainan, Xinjiang, Tibet, Hong Kong, Macau, and Taiwan are not part of the sample. Data for measuring control variables are collected from the compilation of statistics of the power industry, as well as the China Electricity Yearbook. The data of power supply reliability come from the compilation of statistics of the power industry, the official website of the China Electricity Council, and the National Energy Administration's Power Reliability Management Center.

Usually, market power can be defined as the ability to affect market prices. As for grid market power measured by the Lerner index, the difficulties lie in the estimation of price (*p*) and marginal cost (*mc*). In Chinese reality, the "Promotion Tournament Game" Pattern is one of the most powerful incentives for economic growth (Que et al., 2019). Under this incentive mechanism, local officials are promoted mainly based on their contribution to local economic development (Jia, 2017). The system of "province as an entity" leads to market segmentation and different power structures. To maintain the competitiveness of local larger industries for improving political performance, local government tends to give relatively lower prices to large industries and acquiesce gird enterprises in charging higher prices by small and medium-sized consumer for compensation. This "win-win exchange" regulation failure can be seen as a sign of grid market power. Thus, the phenomenon of cross-subsidy is very serious, not only industry subsidizing residents, but also small and medium-sized consumer subsidizing large industry (Jiang et al., 2015). To some extent, the electricity retailing price for large enterprises can be taken as marginal cost (*mc*) and the price for general industrial and commercial users could be taken as the price (*p*). More theoretical analysis and justification can be found in Yu and Fu (2012).

More specifically, the retailing price is jointly decided by the local government and grid enterprise and then submitted to the central government for approval. Finally, a table of electricity sale price will be publicly issued and the regional grid companies charge an electricity fee according to the table. Particularly, electricity prices differ in provinces in China. Generally speaking, electricity consumers can be divided into resident users, industrial and commercial users, large industrial users, and agricultural users. The catalogue price is set different for different customers. Moreover, as for the same kind category of users, the electricity price will also differ in various voltage levels. With different prices for various voltage levels, this paper utilizes the average value under different voltage levels for calculation. If peak and valley pricing is involved, the price in the flat period is used. The data to estimate market power come from the official website of the Development and Reform Commission, price bureaus, and the official website of the municipal power company of each province. Descriptive statistics of variables are shown in **Table 1**.

In addition, **Figure 1** also shows the average values of market power of grid companies of different regions, which are basically consistent with the calculation by Yu and Fu (2012). The average value of grid market power in China reaches 0.3176, indicating unbalance among regions. Some economically developed regions, such as Beijing, Guangdong, Fujian, Jiangsu, and Zhejiang, have relatively small grid market power, while Liaoning and Jilin with a high proportion of heavy industry have larger values.

4 MAIN RESULTS

The panel data are from 2004 to 2017. Before the regression, the stationary test is required. If the data are non-stationary, the

TABLE 1 | Description of variables

Variables	Definitions	Obs	Mean	Std	Min	Max
Power	Grid market power	378	0.318	0.081	0.154	0.511
Clean	The proportion of clean power generation	378	0.234	0.235	0	0.919
Lnoutage	Power service quality measured by annual average outage time Supply interruption (hours/household)	378	1.930	0.821	0	4.684
Lnscarcity	Electricity scarcity	378	8.426	0.326	3.943	10.73
Lnallo	Per capita transformer capacity	378	5.558	0.632	3.912	7.226
Lncon	Domestic electricity consumption per capita	378	3.421	0.566	2.114	4.966

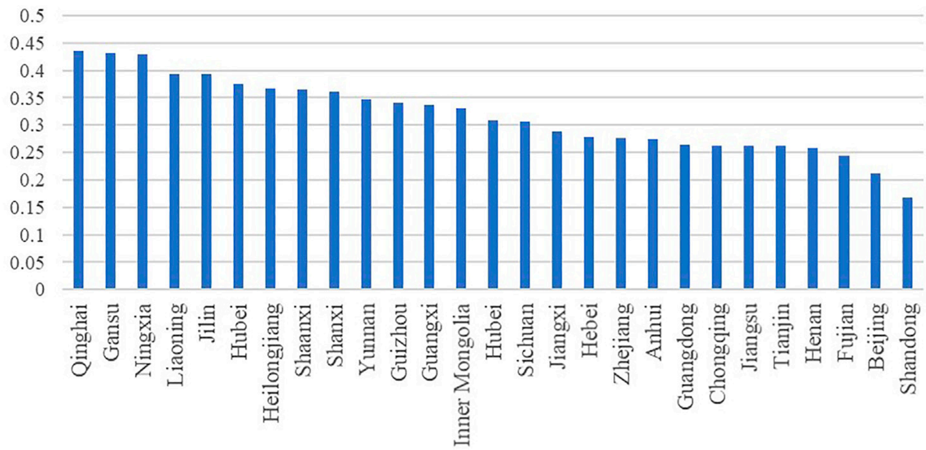

FIGURE 1 | Average values of grid market power.

TABLE 2 | Results of unit root test

	Variable	LLC	IPS	ADF	PP
Level	Lnoutage	−9.5317	−5.2829***	64.3671	155.5678***
	Power	−13.1836***	−3.7541***	73.8088**	58.1278
	Lnallo	−10.5686***	−4.2064***	43.3816	137.9354***
	Clean	−8.3518*	−2.3808***	47.3569	112.3395***
	Lnscarcity	−12.7789***	−4.3155***	58.9321	82.5269***
	Lncon	−9.3760***	1.9535	28.8626	19.4358
First difference	Lnoutage	−18.7971***	−8.7508***	144.6019***	696.5453***
	Power	−16.6096***	−9.0777***	116.9647***	322.0972***
	Llnallo	−20.6196***	−10.2069***	170.3041***	562.8418***
	Clean	−14.9111***	−9.2613***	129.0157***	480.9550***
	Lnscarcity	−18.0750***	−8.1355***	123.0074***	274.6257***
	Lncon	−21.2804***	−7.2630***	164.8791***	157.5607***

*Note: ***, **, and * indicate significant levels at 1, 5, and 10%, respectively.*

ordinary regression method based on stationary panel may lead to the estimation bias, namely the phenomenon of spurious regression.

4.1 Results of Panel Unit Root Tests

As mentioned, to select regression techniques and ensure estimation validity, the unit root tests of LLC, IPS, ADF-Fisher, and PP-Fisher are performed before estimating the parameters. According to the results shown in **Table 2**, at level, not all the variables are stationary. At the first difference, all the statistics are significant at 1% or 5% level, confirming the stationarity of all the variables. It can draw the conclusion that all the variables are integrated of order 1.

4.2 Panel Co-Integration Estimation Results

Since we have confirmed the stationary of variables, the panel co-integration estimation is conducted. The results can be found in **Table 3**. The null hypothesis of no co-integration is significantly rejected by both Pedroni test and Kao test, and the co-integration test results confirm the existence of long

TABLE 3 | Results of panel co-integration test

Method		Statistics
Pedroni test	Modified Phillips-Perron t	6.8747***
	Phillips-Perron t	−8.9544***
	Augmented Dickey-Fuller t	−6.5655***
Kao test	Modified Dickey-Fuller t	−3.7270***
	Dickey-Fuller t	−5.0556***
	Augmented Dickey-Fuller t	−1.9254**
	Unadjusted modified Dickey-Fuller t	−6.7827***
	Unadjusted Dickey-Fuller t	−6.2877***

*Note: The null hypothesis is no co-integration relationship. *** indicates significant levels at 1%.*

TABLE 4 | Baseline results

Variables	Lnoutage	Lnoutage
	DOLS	FMOLS
Power	2.531***	3.179***
	(0.524)	(0.655)
Lnallo	−1.762***	−1.497***
	(0.316)	(0.265)
Clean	0.685***	0.570**
	(0.170)	(0.256)
Lnscarcity	−0.0285	0.00375
	(0.289)	(0.148)
Lncon	1.648***	1.321***
	(0.310)	(0.288)

*Note: ***, **, and * indicate significant levels at 1, 5, and 10%, respectively. The standard error is reported in the parentheses.*

run effects. Therefore, we conclude that the variables have a long-run relationship.

4.3 Panel Parameter Estimates of the Long-Run Effects

4.3.1 The Effects of Grid Market Power on Power Quality

After confirming the long-term relationship among variables, the next step is to estimate the long-run model. As mentioned, we apply panel DOLS and FMOLS models to estimate the long-run relationship and **Table 4** shows the baseline regression results. We can see that the coefficients of the grid market power estimated by DOLS and FMOLS are both significant at 1% level, which indicates higher grid market power will lead to longer duration of outage, or worse service quality. As mentioned, the characteristics of natural and regional monopoly lead to the grid market power, which may be harmful to the public eventually. The power industry is undergoing a profound transformation, where reform in 2015 will have far-reaching impacts on the power industry. However, it is believable that grid enterprises and power generation companies are still the principal participants for retailing in the short run, and the profit pattern of grid companies will remain not changed immediately due to information asymmetry and stickiness. The signal effect of price is rather limited and government control remains strong after the 2015 reform. In reality, various enterprises have taken part in the establishment of electricity sales companies, with few of them actually participating in the operation. Although the direction and intention of the reform are significantly important, what really plays a decisive role is the policies to guarantee the reform in accordance with our expectation.

The proportion of clean energy yields positive and significant effect on outage. This indicates that an increase in integration of renewable energy will have a negative effect and reduce service quality. The power service quality in China is in its rapid development. However, the marginal cost will increase by this improvement, that is, higher service quality or lower outage duration is accompanied by a higher cost. Subject to global warming and the environment, developing renewable energy becomes the strategic goal of many countries, including China. By increasing the renewable sources, the power grids are facing more complicated problems and challenges than ever. The state-owned grid firms, working as an important public utility department, act a crucial role in renewable energy integration, and regulation measures are required for grid firms to balance the relationship between economic benefits and service efficiency.

The coefficient of per capita domestic electricity consumption is also significantly positive at 1% level, which implies that the power supply becomes more prone to failure with the increase in electricity delivering and consumption. The coefficient of power distribution capacity is significantly negative. That is, higher power distribution capacity helps to reduce the duration time of power outage, resulting in better service quality. Surprisingly, the coefficient of electricity scarcity is not significant. As emphasized by Fisher-Vanden et al. (2015), electricity scarcity will influence the reliability of the power supply and even can be seen as a decent indicator for the potential electric power shortage within the region. The main reason for insignificant coefficient lies in that power shortages are not serious in China with the improvement of the electricity infrastructure.

4.3.2 Heterogeneity Tests

China is a vast country, and the economic and social differences between each district presents out gradually. Therefore, to assess the impact of grid power on service quality based on regional disparity, we divide the sample into eastern and mid-western regions. As shown in **Table 5**, the grid market power has significant positive impacts on outage time in the eastern region, while the coefficient is not significant in the mid-western regions. In addition, due to the uneven distribution of energy resources, there are significant spatial differences between power production and consumption. This article divides the sample into electricity exporter and electricity importer provinces according to the power flow[1]. It can be found that the influence of the grid market power in regions of exporting electricity is not significant.

[1]Electricity import regions include Shanxi, Inner Mongolia, Heilongjiang, Anhui, Fujian, Hubei, Sichuan, Guizhou, Shannxi, Gansu, Qinghai, and Xinjaing.

TABLE 5 | Heterogeneity test

Variables	Lnoutage (Eastern)		Lnoutage (Mid-west)		Lnoutage (Exporter)		Lnoutage (Importer)	
	DOLS	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS	FMOLS
Power	5.062***	3.178***	0.00737	1.523*	−0.104	1.646*	3.807***	4.030***
	(0.915)	(1.029)	(0.798)	(0.909)	(0.792)	(0.964)	(0.962)	(1.196)
Lnallo	−3.304***	−2.160***	−2.061***	−1.535***	−3.252***	−1.844***	−1.405***	−0.830*
	(0.665)	(0.506)	(0.463)	(0.309)	(0.568)	(0.305)	(0.419)	(0.433)
Clean	−0.936	0.793	0.710***	0.558**	0.465**	0.422	0.671**	0.855
	(0.656)	(0.618)	(0.193)	(0.264)	(0.199)	(0.278)	(0.334)	(0.656)
Lnscarcity	−0.376	0.142	0.356	0.110	0.296	0.0722	0.968	0.233
	(0.580)	(0.266)	(0.278)	(0.163)	(0.287)	(0.152)	(0.589)	(0.302)
Lncon	2.884***	1.492**	1.969***	1.521***	2.927***	1.795***	0.983**	0.403
	(0.741)	(0.629)	(0.423)	(0.330)	(0.497)	(0.322)	(0.481)	(0.481)

*Note: ***, **, and * denote significant levels at 1, 5, and 10%, respectively. The standard error is reported in the parentheses.*

TABLE 6 | Robustness tests (using the CCR model)

Variables	(1) Lnoutage
Power	3.250***
	(0.775)
Lnallo	−1.822***
	(0.326)
Clean	0.443*
	(0.248)
Lnscarcity	0.236
	(0.216)
Lncon	1.591***
	(0.352)
Constant	3.497
	(2.131)

*Note: ***, **, and * denote significant levels at 1, 5, and 10%, respectively. The standard error is reported in the parentheses.*

TABLE 7 | Robustness tests (under changing dependent variable)

Variables	Lnroutage		Lnaoutage	
	DOLS	FMOLS	DOLS	FMOLS
Power	3.828***	2.152**	3.673***	2.533***
	(1.052)	(0.924)	(1.026)	(0.935)
Lnallo	−1.607***	0.0203	−1.678***	−0.230
	(0.612)	(0.396)	(0.596)	(0.401)
Clean	0.818***	0.737**	0.803***	0.711**
	(0.311)	(0.307)	(0.303)	(0.310)
Lnscarcity	0.407	−0.0831	0.269	−0.0282
	(0.360)	(0.150)	(0.351)	(0.152)
Lncon	1.636***	0.118	1.781***	0.391
	(0.615)	(0.393)	(0.600)	(0.397)

*Note: ***, **, and * denote significant levels at 1, 5, and 10%, respectively. The standard error is reported in the parentheses.*

4.3.3 Robustness Tests

To verify the consistency, this study utilized the Canonical Cointegrating Regression (CCR) model to check the estimation robustness (Merlin and Chen, 2021). The results estimated by the CCR model, which are shown in **Table 6**, are consistent with the previous estimation by FMOLS and DOLS models. The findings indicate that the results from FMOLS and DOLS are robust.

TABLE 8 | Robustness tests (under considering electricity reform and large-scale power shortages)

Variables	Lnoutage (Deleting 2004 and 2011)		Lnoutage (2004–2014)	
	DOLS	FMOLS	DOLS	FMOLS
Power	2.597***	3.636***	2.479***	2.884***
	(0.542)	(0.634)	(0.684)	(0.661)
Lnallo	−1.596***	−1.552***	−1.233***	−1.752***
	(0.332)	(0.253)	(0.413)	(0.287)
Clean	0.565***	0.392	0.796***	0.824***
	(0.176)	(0.243)	(0.223)	(0.261)
Lnscarcity	−0.265	0.0593	−0.0359	0.0684
	(0.273)	(0.134)	(0.378)	(0.139)
Lncon	1.563***	1.333***	1.158***	1.411***
	(0.326)	(0.273)	(0.403)	(0.301)

*Note: ***, **, and *denote significant levels at 1, 5, and 10%, respectively. The standard error is reported in the parentheses.*

To further check the robustness of results, this paper replaced annual average outage time for city users by the indicator of annual average outage time for rural users and all users. The annual average outage time for rural users is represented by *lnroutage* and the indicator for all users is expressed by *lnaoutage*. As shown in **Table 7**, we can find that the coefficient of grid market power is still significantly positive, indicating that our regression results are robust.

There were two large-scale power shortages in 2004 and 2011, causing enormous losses. Mandatory power cuts were imposed in many provinces, which may also have a certain impact on the estimation results. In view of this, we delete the data in 2004 and 2011. The sign and significance are basically not changed as shown in **Table 8**. In 2015, China has begun a new round of electricity reform and the prices for industry and commerce are reduced much after. To avoid the influence by the new electricity reform, we take the regression with the sample from 2004 to 2014. The results show that the grid market power still has significant positive effects on outages. Therefore, it is reasonable to assume that the results are robust, and thus, we have the conclusion that higher market power has indeed reduced supply reliability measured by duration of outage per household.

5 CONCLUSION AND SUGGESTIONS

The transition to a low-carbon power system is among the measures to forge green energy transition and decarbonize the electricity supply, where grid firms act a crucial role. In view of this, we empirically analyze how grid market power influences service quality by applying panel DOLS and FMOLS models with panel data from 2004 to 2017 in China. The empirical results show that there is a long-term cointegration relationship between market power of grid firms and service quality measured by the average duration of outages per connected customer. That is, grid market power indeed has negative effects on service quality. In addition, the improvement in power distribution capacity can significantly reduce the average time of power outages. As expected, renewable energy integration will have a certain negative impact on power service quality. Results are also heterogenous across different regions.

According to the above discussion and conclusion, we further point out the following suggestions.

First, it is essential to deepen the market-oriented electricity price reform. The market-oriented price mechanism will certainly contribute to the weakening of market power of grid firms, thus improving service quality and efficiency. Especially, competitive electricity pricing will also serve the purpose of passing through from carbon price to electricity price, which is beneficial to energy conservation, and pollution reduction from the demand side. Furthermore, as for the monopolistic grid firms, the mechanism for setting transmission and distribution prices should be further improved, so as to substantially reduce the electricity price for customers.

Second, with the deepening of reforms, it is also important to establish explicit reward and punishment mechanisms related to the operational efficiency and service quality of grid firms. As state-owned companies, Southern Power Grid and State Grid are supervised by the State-owned Assets Supervision and Administration Commission of the State Council (SASAC). At present, supervision standards are mainly profit and power consumption. While taking service quality into an incentive regulation system will contribute to encourage grid firms to actively strengthen their business environments and improve their service efficiency.

However, it is also important to consider the limitation of this research, such as the trade-off between power quality and cost. Higher power quality often means higher costs or electricity prices to some extent, and over-pursuing service quality, while ignoring the costs may lead to over construction and lower efficiency.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization, methodology, and writing-original draft, ML; software and data curation, CJ; conceptualization, methodology, writing-review and editing, and supervision, RH All authors have read and agreed to the published version of the article.

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