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Assessing China's provincial electricity spot market pilot operations: Lessons from Guangdong province

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ABSTRACT

Aiming at improving the efficiency of power generation, China announced its plan to reform the electricity wholesale market. A focal point of the wholesale market reform is to introduce a stable and reliable electricity spot market. Using Guangdong's spot market pilot operations as a case study, this article is the first to use rich *ex-post* market data to assess the efficacy of China's electricity spot market. To investigate the stability of the spot market, we estimate the relationship between prices and demand. We find the electricity supply curve is much steeper when demand approaches the capacity limit, suggesting the need to invest more thermal capacity to stabilize spot market prices (SMPs). To investigate the reliability of the spot market, we first estimate the market distortion caused by a price floor on SMPs, and we then examine whether local market power exists. The price floor on SMPs resulted in a welfare transfer from consumers to producers, the monetary value of which equals to 1.3% of the tradable value of the day-ahead market. We also find evidence of local market power in the east of Guangdong, suggesting the need to invest in more power lines connecting the west to the east.

1. Introduction

Aiming to boost energy efficiency and renewables via a new round of power market reform, the State Council of China launched *Several Opinions on Further Deepening the Reform of the Power System* (referred to as the *No. 9 document*) in 2015. The (still ongoing) reform attempts to regulate transmission and distribution companies and gradually liberalize the wholesale and retail electricity sectors, whose prices used to be set by the government rather than market driven. The reform aims to achieve a more market-based environment and allow for the engagement of private investments in the power sector (Zhang et al., 2018).

Prior to the reform, China employed an equal allocation dispatch system with the same type of power plants operating for (roughly) an equal number of hours regardless of their thermal efficiency and marginal costs (Wetzel and Lin, 2019). Apparently, the previous dispatch system ignored the merit order of the power system, which suggests that those with the lowest marginal costs are supposed to be the first to be brought online to meet demand. This resulted in an inefficient allocation of resources and high costs, precipitating the new round of reform aimed at correcting the distortion and marketizing power generation.

Marketization ensures that prices of electricity are discovered in a marketplace through the interaction between buyers and sellers, which makes firms' residual claimants to cost savings, potentially increasing incentives for efficiency-enhancing efforts (Nickell, 1996). Fabrizio et al. (2007) demonstrated that in the US electricity generation sector, publicly owned plants with owners insulated from marketization reforms in the late 1990s experienced much lesser efficiency gains than investor-owned plants in states that marketized their wholesale electricity markets. Moreover, prices that reflect the marginal cost of electricity generation would make the interregional electricity transaction more efficient, potentially decreasing renewable energy curtailments under the West-East electricity transfer project (Guo et al., 2020).[1]

An important aspect of the reform is to construct a liberalized wholesale market, which will consist of three primary markets that

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[1] Most of China's coal resources are mainly distributed in the western and northern regions, and hydro power resources are mainly concentrated in the southwestern region. Primary energy resources are scarce in the eastern region, whose electricity load is rather concentrated. Therefore, the West-East electricity transfer project aims at concerting the energy in the western region into electricity resources and transmitting them in the eastern coastal areas where electricity is scarce.

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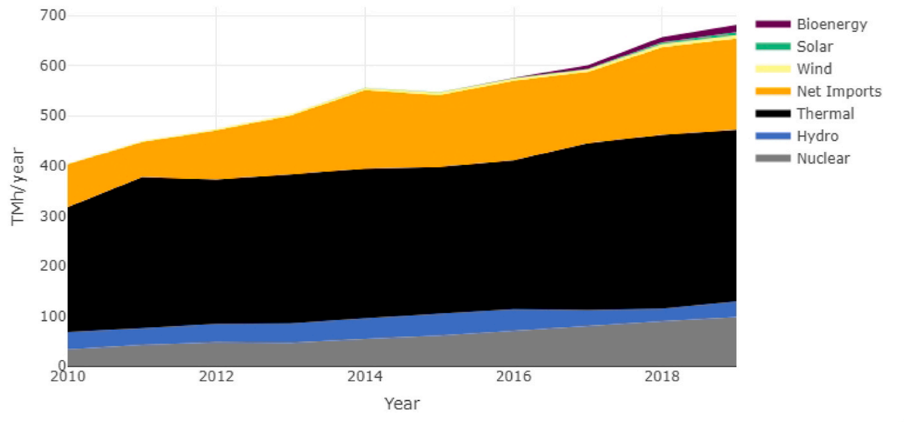


Fig. 1. Guangdong's yearly electricity supply by fuel type, 2010-2019
Source: *China Energy Statistical Year Book*, 2010–2019.

operate in different timescales, namely the mid-to-long-term (M2L) energy market ranging from annually to multi-daily, the spot market, and the ancillary services market.[2] The M2L market will cover most of the traded electricity, and it takes the role of stabilizing prices and hedging risks in the spot market. As most traded volume is governed under M2L contracts, little revenue risk exists for market participants. The spot market contains a day-ahead and a real-time market, and it ensures market participants respond to later information such as outages and updated load and renewables forecasts. Finally, the ancillary service market helps balance the transmission system as it moves electricity from generating sources to retail consumers.

Among the three primary markets, the spot market is believed to be the most liquid. It is also believed that the introduction of a spot market can improve the efficiency of the final allocation of electricity (Ito and Reguant, 2016), and can help reduce the extent of market power and improve efficiency in an oligopolistic setting (Allaz and Vila, 1993). In 2017, the National Development and Reform Commission (NDRC) and National Energy Administration (NEA) issued the *Notice on Piloting the Spot Power Market Construction*. Eight provinces (and regions) were selected for spot market pilot operations, including Southern China (starting from Guangdong), West Inner Mongolia, Zhejiang, Shanxi, Shandong, Fujian, Sichuan and Gansu. Among these provinces, Guangdong has the highest GDP and consumes the most electricity and hence would potentially be the market with the highest trading volume. In 2020, its total electricity consumption reached 693 TWh, approximately 9.2% of China's total. The province is also at the center of the China Southern Power Grid (CSG), one of the two state-owned electricity utility corporations. Since the release of the *No. 9 document*, Guangdong is leading the reform, becoming the first province to publish bidding rules and market clearing mechanisms for its electricity spot market.[3] As of June 2021, Guangdong had completed five rounds of pilot operations.[4] Issues may arise with pilot operations, and they need to be resolved before the formal operation of the spot market.

1.1. The Guangdong power market

Guangdong is usually considered to be the province leading China's power market reform, as it is more open than other regions in terms of selecting market design forms and processes (Cao et al., 2019). Compared to other regions, Guangdong has a high percentage of supply participating market exchanges and demand opening to retail. It is also the province with the longest functioning spot market pilot, which started in September 2018.

By the end of 2020, the total installed capacity of electricity in Guangdong had reached 141 GW, 65.8% of which was due to fossil fuels and 8.5% of which came from renewable energy (i.e., wind and solar) (GPEC, 2020). Fig. 1 presents the generation by fuel type in Guangdong between 2010 and 2019. Following its rapid economic development, the total electricity supply in Guangdong increased steadily with a nine-year-average annual growth rate of 6%. Despite its share being low, electricity generation from renewables increased twelve folds, with an annual growth rate of 32%. Meanwhile, on average, approximately 24% of Guangdong's electricity was imported, with most being hydro power from the neighbouring Yunnan province.

Prior to the new round of power market reform, electricity generated in China was highly regulated in terms of price and quantity. Specifically, electricity was purchased by the sole grid company via a government-set price and was generated based on a "fair dispatch rule" (Gao and Li, 2010) – an (roughly) equal quota rule that the local government departments followed to allocate a total power generation amount. In Guangdong in 2016, the first year of the reform, less than 8% of the province's electricity supply took place via market exchanges (and the rest was regulated), while the number reached 40% in 2020 (GPEC, 2017, 2020). Because the spot market has not yet been formally operated, all traded wholesale electricity was due to M2L contracts. The operation of the spot market, however, will allow a growing proportion of quantity to take part in the wholesale market, where generators (that participate in the market) submit bids for a specific quantity of electricity that they are willing to supply.

1.2. The Guangdong spot market pilot

Guangdong's pilot electricity spot market adopted a "gross pool" model, with all (participating) generation dispatched through a common pool, considering demand as given to the pool and all generators who bid into the pool bidding at their marginal cost. It is worth mentioning that not all generators participated in the market, such as renewables, which were taken as a regulatory must-take. Imports (and exports) were

[2] This is covered in the supplementary materials of the No.9 document, see in Chinese http://www.gov.cn/xinwen/2015-11/30/5018221/files/87556b7e1f4f4aaab86ac7c99f5acf3f.pdf. See also *Guiding Opinions on Accelerating the Construction of a National Unified Electricity Market System* launched by the National Development and Reform Commission (NDRC) and National Energy Administration (NEA) in 2022 in Chinese http://www.gov.cn/zhengce/zhengceku/2022-01/30/content_5671296.htm.

[3] See, in Chinese, http://www.gdei.gov.cn/gzhd/wsdc/myzj/201811/t20181102_130784.htm.

[4] Since November 2021, Guangdong has started a new round of uninterrupting spot market pilot operation. Till now (February 2022), the pilot is still under operation and we shall investigate the most recent round of pilot operation in due course.

Table 1
Characteristics of each round of Guangdong's spot market pilot operations.

Time	Characteristics and Improvements
1st round: 15–16 May 2019	190 generation units, 123 retail companies, and 3 large electricity consumers participated. M2L CfDs were moved to a forward price contract, whose price equals the thermal benchmark price plus the contracted price differences of each market entity. Due to the different on-grid tariffs approved by various types of units, the power grid company fully bore profits and losses from the M2L conversion. The retail contract signed by the retail company and its agent users remained unchanged. The unbalanced cashflow in the market generated by the pilot settlement would temporarily be paid upfront by the current medium and long-term settlement balance funds. With the spot market, M2L contracts must be decomposed to formulate the "decomposition curve". The responsibility was entirely borne by the market operating agency that determines the decomposition method. The variable cost compensation was borne by the grid company.
2nd round: 20–23 June 2019	Market entities were allowed to negotiate and adjust the decomposition curve independently. (The rest is the same as the first round).
3rd round: 21–27 October 2019	192 generation units, 128 retail companies, and 3 large electricity consumers participated. M2L CfDs were converted into absolute price contracts. The formation of electricity tariffs was based on the wholesale prices plus the Transmission and Distribution (T&D) price. M2L power exchange was organized and operated while the spot market was in operation (between 21–27 October). The M2L contracts were decomposed based on the historical consumption of electricity users. When a consensus was reached, market entities were allowed to adjust the decomposition curve, and the decomposition adjustment could be achieved through M2L transactions (while the spot market was in operation). The variable cost compensation was borne by the grid company.
4th round: 1–31 August 2020	The market settlement was based on the monthly CfD, monthly trading, spot market power exchange, and electricity contract transfers. 99 generation units, 136 retail companies, and 1 large electricity consumers participated. The day-ahead market clearing results and daily settlement bills (T+5) were published daily. The scale of electricity generation was determined according to market users' power consumption. Variable cost compensation was borne evenly by all industrial and commercial consumers.
5th round: 1–31 May 2021	The market settlement was based on the monthly CfD and electricity contract transfers. 209 generation units, 159 retail companies, and 2 large electricity consumers participated. Day-ahead market clearing results and daily settlement bills (T+5) were published daily. Practical capacity compensation was attempted, though no actual collection or payment was made. A market-oriented demand response was applied, though consumers were reluctant to participate. Variable cost compensation was borne evenly by all industrial and commercial consumers.

not participating in the spot market, as they either followed existing M2L contracts or were regulated and determined by the government (approximately 30%).

The spot market consists of a day-ahead market and a real-time market, which are jointly operated by exchange and dispatch centers in Guangdong. The market is cleared every 15 minutes, and the clearing price takes the form of the locational market prices (LMPs), defined as the marginal price for energy at the location where the energy is delivered or received. Generators bid volume as well as prices, whereas customers only bid volume. After market participants submit bids and offers, the hourly commitment schedules and LMPs are determined. Finally, generators are paid at LMPs, whereas customers pay a (weighted) average price of all LMPs, namely spot market prices (SMPs).

It is also noteworthy that Guangdong's spot market pilot adopted a variable cost compensation mechanism, where all combined-cycle gas turbine (CCGTs) are compensated for each kWh of electricity they supply in the spot market. This is because in Guangdong the variable cost of electricity generated from CCGTs is usually much higher than that from coal plants. To make CCGTs more competitive, the market operator decides to compensate spot market participants based on the following rules. For any power generation company that participate the spot market,

- Whenever the SMP is lower than the government-set benchmark prices for the company's generation technology (the benchmark prices are different for different generation technologies), the company is compensated by the price difference between the benchmark price and ¥0.463/kWh, which is the benchmark price for coal plants. (Therefore, coal plants will not be compensated.)
- Whenever the SMP is greater than or equal to the government-set benchmark prices, the company will not be compensated.

For example, for a particular hour suppose that the benchmark price for a CCGT is ¥0.663/kWh and the SMP is lower than ¥0.663/kWh, the CCGT will be compensated ¥0.2 for each kWh of electricity they supply in the spot market in that hour. Put differently, this lowers the marginal cost of electricity generation from the CCGT by ¥0.2/kWh whenever the SMP is below its benchmark price. Finally, the compensation is borne evenly by all industrial and commercial consumers.

There is no doubt that the variable cost compensation mechanism will distort market outcomes, as CCGTs may no longer be the marginal fuel that sets market prices, and both coal and gas prices may determine the spot market prices. We leave this for further discussion in Section 4.

As of June 2021, Guangdong had completed five rounds of pilot operations. Table 1 lists the characteristics and improvements of each round. To summarize, the operation period is much longer near recent rounds – the first round of pilots only lasted two days while the 4th and 5th rounds both lasted a month. During this period, with the gradual decentralization of the wholesale and retail markets, the total number of spot market participants is increasing. With each new round of pilots, lessons and experiences from the past are firmly learned, and hence the settlement method has been improved, information has become more transparent, and the decomposition of M2L contracts has become more liberalized.

1.3. Research scope and contributions

In this article, we assess the efficacy of Guangdong's electricity spot market pilot operations. We aim at investigating the stability and reliability of Guangdong's spot market during pilot operations, where "stability" is defined as the relationship between demand and prices, and "reliability" is defined as the inefficiency of the market, measured as market distortion due to a price floor and local market power due to transfer capacity limits. We focus on the 4th and 5th pilots, as sufficient lessons are learned from earlier pilots and both 4th and 5th pilots last a month; hence, (relatively) sufficient data can be collected for econometric analysis. To the best of our knowledge, this is the first article to use *ex-post* market data to investigate the operation of China's electricity spot market.[5]

One of, if not the most important parameters in the electricity spot market is the slope of the supply curve. In a perfectly competitive closed market, one would expect the supply curve following the merit order and the competitive electricity prices equaling the short-run marginal cost of electricity generation. Moreover, valuing the slope of the supply curve is helpful in exploring the economic impact of external shocks. For instance, the slope can specify the possible effects of increasing renewable penetrations and demand responses (i.e., peak-load shaving) on electricity prices. In addition, we can employ the slope to estimate the welfare transfer from electricity generators to consumers due to a price floor on SMPs, which is investigated in this article.

The first aim of this article is, therefore, to use econometrics to estimate the relationship between electricity load and the SMPs. We focus on the day-ahead market (instead of the intraday market) because it is the main arena for trading power, whereas the intraday market supplements the day-ahead market and helps secure a balance between supply and demand. One challenge is that Guangdong proposed a price floor and ceiling to the SMPs (as discussed further below), and hence conventional econometric methods may bias the estimates. We therefore apply censored regression analysis to estimate the supply curve. Our estimates suggest that during the 4th pilot when the residual load (defined as electricity load entering spot market power exchange) is relatively low, a 1 GW (or 1000 MW) increase in the day-ahead total load is associated with a ¥7/MWh increase in the day-ahead SMPs; whereas during the 5th pilot when the residual load is high and approaches the capacity limit of the electricity system, the marginal effect increases to ¥13/MWh. The difference between the two rounds of pilots indicates that the (short-run) marginal benefit of increasing renewable penetration and demand response can be more substantial at the current stage (when renewable penetration is low and demand response is limited) than later (when renewable penetration is already high and demand response has been widely applied).

As the SMPs are determined by supply and demand, market uncertainty may arise, resulting in volatile power prices. One typical example is European electricity markets such as those of Germany, where the rising share of renewables has made negative prices a fairly common phenomenon. Negative prices occur when high and inflexible power generation appears alongside low electricity demand and can greatly burden the renewable surcharge. To stabilize the spot market and avoid disincentivizing renewable investment, Guangdong proposed a price floor (and ceiling) to the SMPs. The price floor, however, raises other issues such as transferring some of the market surplus from consumers to producers (and the price ceiling would have the reverse effect).[6]

Our second aim is to estimate the monetary value of this welfare transfer during pilot operations. It is noteworthy that we observe no SMPs reaching the price ceiling during both rounds of pilots, and all price floors are observed during the 4th round. Therefore, we focus on the welfare transfer caused by the price floor during the 4th pilot round. This is carried out by first using the earlier econometric results to estimate the day-ahead SMPs if the price floor were not implemented. Then, whenever an SMP equals to the price floor, for that hour the welfare transfer equals the difference between the estimated prices and the price floor times the trading volume. Our estimates suggest that during the 4th pilot round, the welfare transfer is estimated to be ¥84 millions, or approximately 1.3% of the total tradable value of the day-ahead market.

Guangdong's electricity wholesale market is considered to be a moderately concentrated marketplace. From 2016 to 2020, 86 of 97 local electricity generation companies participated in power exchanges, with an average Herfindahl-Hirschman Index (HHI)[7] slightly above 1500 in month-ahead forward markets (GPEC, 2020). While the HHI might be an effective measure of system-wide market power, it provides little information about the degree of local market power.[8] Local market power arises because the existing transmission network does not provide the supplier with sufficient competition to discipline its bidding behavior into the wholesale market. Competition in the wholesale market promotes lower electricity bills for consumers, while market power tends to make electricity more expensive.

The final aim of this article is to assess the existence of local market power in the Guangdong electricity market. This is done by first matching the producer-side LMPs with cities in Guangdong and then comparing the LMPs with the consumer-side SMPs. We construct an index to measure the degree of local market power and find evidence suggesting that local market power existed in the west of Guangdong or in cities around Guangzhou and Shenzhen, the political and economic centers of Guangdong province with high electricity demands. This result suggests the need to invest in more power lines connecting the west to the east of Guangdong.

The remainder of this article is structured as follows. Section 2 reviews major literature about China's power market reform. Section 3 presents data from Guangdong's 4th and 5th rounds of spot market pilot operations. Section 4 gives empirical methodologies and results associated with our research scope, and finally, Section 5 concludes and provides policy implications.

2. Literature review

The management of China's electricity system used to be vertically integrated (Bacon and Besant-Jones, 2001), with the planning, investment and operation of the enterprises managed together by administration orders (Kahrl et al., 2013). Aiming at improving the generation efficiency of its thermal power plants, China implemented its first-round power market reform in 2003. The reform increased the productivity of large thermal plants and enabled them to converge to the technological frontier (Zhao and Ma, 2013). However, Meng et al. (2016) found that a significant amount of fossil energy had been wasted due to a lack of electricity price bidding and emphasized the necessity of electricity bidding, over-the-counter transactions,[9] and dynamic incentive mechanisms for renewable energy development.

Aiming at promoting competition in the generation and retail sectors and setting transmission and distribution (T&D) prices based on the grids' efficient operational costs, China launched a new round of power sector reform in March 2015. Pollitt (2020) concluded that the reform has achieved a number of impressive outcomes, including the implementation of T&D prices, the marketization of both wholesale and retail sides, and the reduction of grid companies' revenue. Zheng et al. (2021) found that the reform had lowered the prices of electricity generated

[5] At the time of revising, we found that Wang et al. (2021) also worked on spot market pilot operation in Southern China, but there are major differences between our work and theirs. First, they focused on "the imbalanced funds caused by dual-track pricing and the compensation to gas power generators," while we focus on the reliability and stability of the pilots. Second, these authors only used data in the first three rounds of pilot operations, whereas we focus on the 4th and 5th rounds, and hence our sample size is much larger.

[6] Given inelastic electricity demand, this will not create a deadweight loss as the price increases (or decreases) from the equilibrium price, while the demand remains constant.

[7] The HHI is calculated by squaring companies' market shares and summing the resulting values. This is done to give large companies greater weight, as a large market share owned by one firm could have a negative impact on competition.

[8] See Wolak (2005) for the distinction between system-wide and local market power – "System-wide market power arises from the capacity constraints in the production and the inelasticity of the aggregate wholesale demand for electricity, ignoring the impact of the transmission network. Local market power is the direct result of the fact that all electricity must be sold through a transmission network with finite carrying capacity." [p.4].

[9] Electricity users negotiate with power plants directly.

Table 2
Summary statistics.

Variable	Obs.	Unit	Mean	S.D.	Min.	Max.
The 4th Round Pilot Operation						
DA Total Load	2976	MW	96,004	14,134	63,000	123,000
DA Baseload	2976	MW	14,004	3253	6883	19,501
DA Must-runs	2976	MW	5707	1045	3806	8458
DA West-east Trans.	2976	MW	35,981	2487	25,008	39,118
DA GD-HK Trans.	2976	MW	−1888	220	−2363	−863
DA SMP	744	¥/MWh	188.55	80.56	70.00	447.40
DA LMP	5,279,424	¥/MWh	180.35	89.92	70.00	1500.00
RT Total Load	2976	MW	95,094	13,707	64,682	123,125
RT Baseload	2976	MW	14,055	3086	7397	20,538
RT Must-runs	2976	MW	5616	977	3518	7699
RT West-east Trans.	2976	MW	35,954	2369	25,049	39,794
RT GD-HK Trans.	2976	MW	−1770	261	−2396	−1042
RT SMP	744	¥/MWh	195.68	113.87	70.00	1105.19
RT LMP	5,279,424	¥/MWh	187.85	128.67	70.00	1500.00
Temperature	744	°F	85.26	5.13	75.00	98.00
Wind Speed	744	mph	5.45	3.06	0.00	19.00
The 5th Round Pilot Operation						
Variable	Obs.	Unit	Mean	S.D.	Min.	Max.
DA Total Load	2976	MW	100,109	17,454	49,500	122,000
DA Baseload	2976	MW	14,292	3330	−1724	19,918
DA Must-runs	2976	MW	6994	1123	4208	9859
DA West-east Trans.	2976	MW	21,313	5980	7814	30,995
DA GD-HK Trans.	2976	MW	−1645	276	−2334	−820
DA SMP	744	¥/MWh	527.27	155.77	171.41	1101.25
DA LMP	5,279,424	/MWh	499.43	230.33	70.00	1500.00
RT Total Load	2976	MW	99,885	17,602	50,221	124,388
RT Baseload	2976	MW	13,901	3203	7196	19,877
RT Must-runs	2976	MW	7095	1206	3773	10,282
RT West-east Trans.	2976	MW	21,491	5872	8764	31,486
RT GD-HK Trans.	2976	MW	−1434	354	−2392	4
RT SMP	744	¥/MWh	567.83	239.27	97.53	1497.49
RT LMP	5,604,096	¥/MWh	545.67	296.56	70.00	1500.00
Temperature	744	°F	84.99	6.10	67.00	99.00
Wind Speed	744	mph	7.36	3.58	1.00	19.00

*DA: day-ahead; RT: real-time.

from thermal energy and the average retail prices and improved thermal efficiency, but their empirical results also suggested that the reform has increased instances of supply interruption. Davidson and Pérez-Arriaga (2020), on the other hand, built on interviews conducted with stakeholders to examine government plans and numerous market implementations at the provincial level. The study suggested that even though market efforts may achieve efficiency gains, greater centralization of market design and regulatory oversight authorities are preferred to make the market fully operational.

Much of the literature explored the side effects of the new round power sector reform. Lin et al. (2019) examined the impact of market reforms on coal-fired power plants and estimated that the existing coal generators in Guangdong had substantial outstanding debt in 2016, creating risks for banking. Their study, therefore, emphasized the essence of a bilateral or centralized capacity market. Zhang et al. (2017) argued that the reform may encourage the government to attach more importance to demand-side management (DSM), motivate grid companies to employ DSM investment, and encourage demand response applications. Zhang et al. (2018) found that challenges such as intervention from local governments in direct electricity trade and a lack of a quota system for renewable energy may distort the positive impact of the reform on renewable energy integration. The literature argued that developing an electricity spot market would facilitate the transmission of renewable energy from western to eastern China, thereby facilitating the integration of renewable energy.

Literature on China's electricity spot market is rather limited. From a cooperative game theoretical perspective, Peng and Tao (2018) found that developing a spot market could improve market competition in the electricity retailer market. Aiming at stabilizing the electricity market and disciplining market power abuse, Zhang and Yan (2019) developed a market mechanism to support collaboration between the contract and the spot market. Wang et al. (2021) focused on the first three rounds of Guangdong's spot market pilot operations and found that dual-track pricing has caused numerous controversies such as imbalanced funds.[10]

3. Data

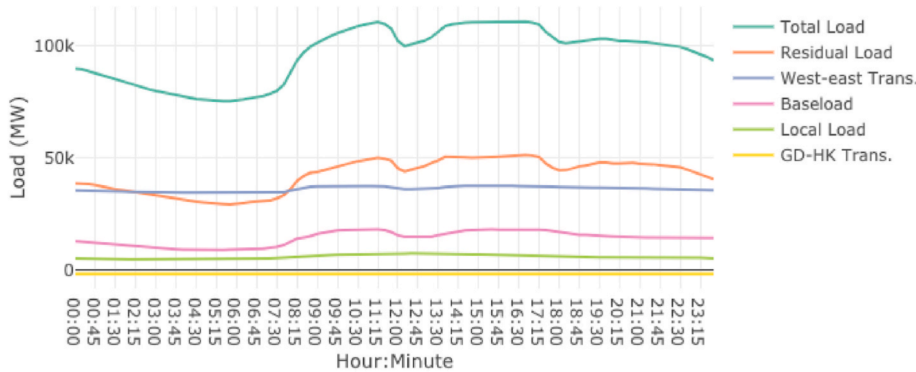
We collect the Guangdong electricity spot market pilot operations data from the Guangdong Power Exchange Center.[11] The data include the day-ahead and real-time LMPs for each node at 15-min intervals and the consumer-side averaged LMPs at an hourly frequency (thereafter, Spot Market Price, SMP). Every day, the day-ahead forecast of the total electricity load, baseload that does not participate in the spot market,[12] local must-runs,[13] and electricity transfer from the West (Yunnan and

[10] Dual-track pricing in electricity retail sector refers to industrial and commercial consumers pay some much higher price rates than residential consumers, such that residential consumers' electricity consumption is compensated by industrial and commercial consumers. Imbalanced funds usually refer to remaining funds or arrears for which the exact beneficiary cannot be found. In China's electricity sector, imbalanced fund may come from ancillary service, variable cost compensation, congestion revenue, and so on.

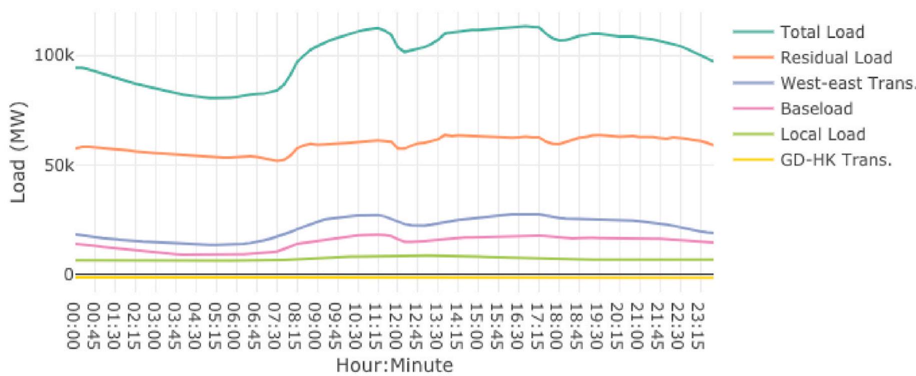
[11] The data are not publicly available and are only available for entities participating in the spot market but are open to public use.

[12] This refers to the load from power plants dispatched via central planning instead of market bidding, which includes renewable energy.

[13] Local must-runs include publicly owned cogeneration steam turbines and distributed solar photovoltaics.



(a) Daily-average Day-ahead Electricity Load, 4^{th} Round (August 2020)



(b) Daily-average Day-ahead Electricity Load, 5^{th} Round (May 2021)

Fig. 2. Daily-average day-ahead electricity load.

Guizhou provinces) and to Hong Kong are also reported at 15-min intervals. The data also cover the actual values of the aforementioned variables. Recall that because most spot market power exchanges took place in the day-ahead market, most of our empirical analysis focuses on the day-ahead market instead of the real-time market. Despite this, summary statistics for both day-ahead and real-time markets are given here to provide the data's full information to readers. Additionally, weather data include half-hourly temperature and wind speed values for Guangdong are collected from Weather Underground[14] and aggregated hourly.

Table 2 gives summary statistics for the 4^{th} and 5^{th} rounds of pilots, where "Total Load" refers to the total electricity load, "Baseload" includes loads from power plants that have not yet obtained a license to directly trade with consumers, "Local Load" refers to local must-runs, "West-east Trans." refers to electricity transfer via interconnectors from the West, and "GD-HK Trans." denotes electricity transfer via interconnectors to Hong Kong. Compared to that of the 5^{th} round, the "West-east Trans." value of the 4^{th} round pilot was much greater, while the "Must-runs" value was lower, which implies that Guangdong received more external assistance from other provinces in the 4^{th} round than in the 5^{th} round. It is noteworthy that the mean value of the 5^{th} round's day-ahead SMP is nearly three times that of the 4^{th} round. During the 4^{th} round, the day-ahead SMP frequently reached the price floor of ¥70/MWh, whereas during the 5^{th} round, all day-ahead SMPs were well above the price floor, with the highest value reaching over ¥1100/MWh, substantially exceeding the maximum day-ahead SMP of the 4^{th} round.

4. Empirical assessment

This section provides empirical assessments on the 4^{th} and 5^{th} rounds of Guangdong's spot market pilot operations. We first provide some stylized facts about the properties of the SMPs and electricity load. Then, since the SMPs were censored around the price floor of ¥70/MWh in the 4^{th} round, whereas in the 5^{th} round, all observed SMPs are higher than ¥70/MWh, we apply different regression techniques to study the relationship between SMPs and electricity load to demonstrate the electricity supply curve. The estimated electricity supply curve allows us to further investigate the reason for the substantial difference in prices between the two pilot operations – the increases in total load and fossil prices resulted in the much higher SMPs in the 5^{th} round than in the 4^{th} round. Next, because of the existence of a price floor, welfare will be transferred from consumers to electricity generators. We therefore use the results from our earlier estimated electricity supply curve to further estimate this welfare transfer. Finally, by assessing the differences between the LMPs, we demonstrate whether local market power exists in Guangdong.

4.1. *The properties of spot market load and prices*

Fig. 2 presents the daily-average day-ahead load during the two rounds of pilots, where "Total Load", "Baseload", "Local Load", "West-east Trans." and "GD-HK Trans." are predefined as stated in Section 3. As "Baseload", "Local Load", "West-east Trans." and "GD-HK Trans." did not participate in the spot market, we define "Residual Demand" as the remaining electricity load that participated. The total electricity load in the 5^{th} round is slightly higher than that in the 4^{th} round. However, as electricity transfer from the west of Guangdong has drastically reduced in the 5^{th} round due to its increasing electricity demand and decreasing

[14] At https://www.wunderground.com/history/daily/cn/guangzhou/ZGGG/date.

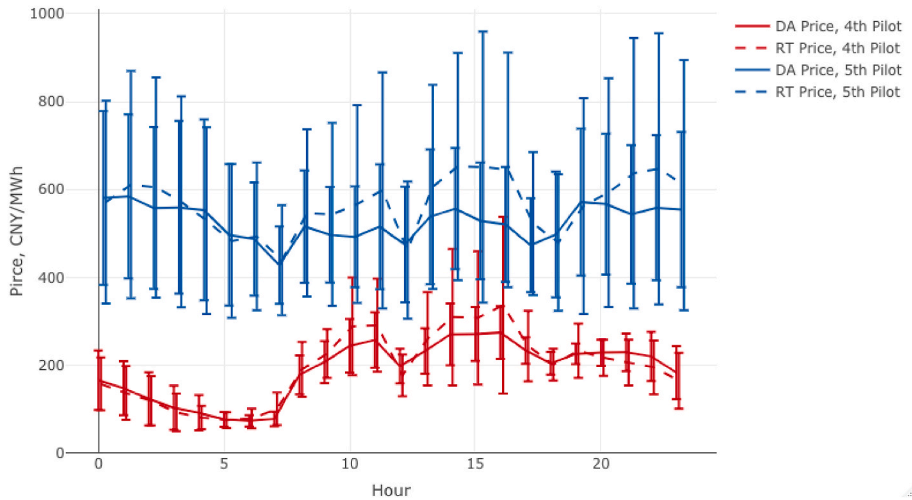


Fig. 3. Daily-average spot market prices.

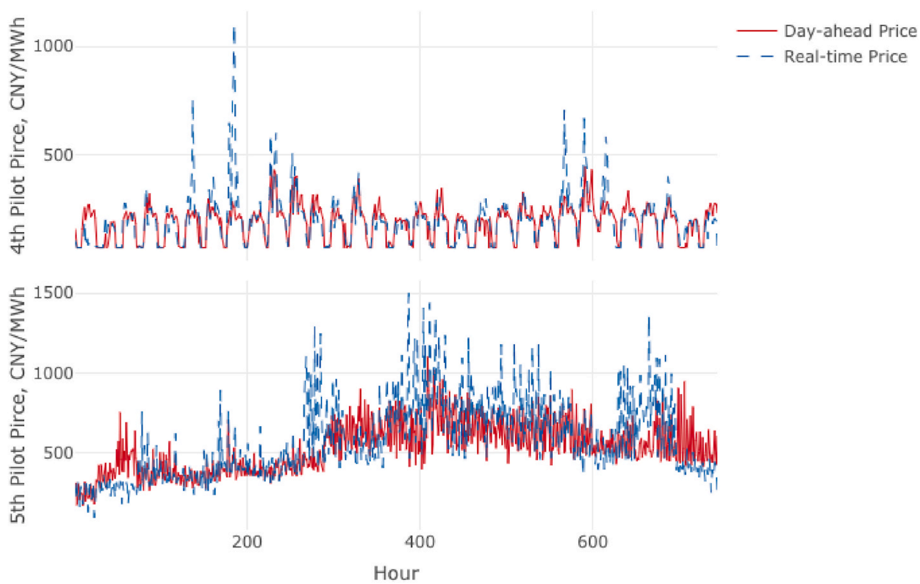


Fig. 4. Day-ahead *v.s.* Real-time Spot Market Prices.

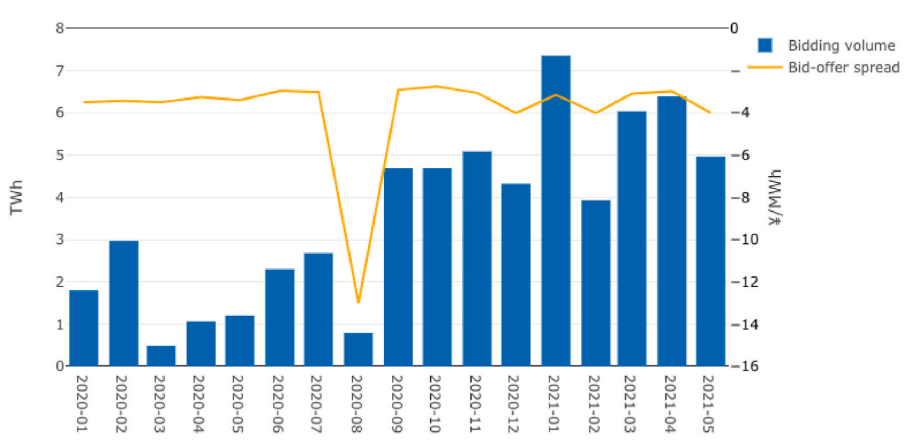


Fig. 5. Bidding volume and bid-offer spread of monthly auctions.

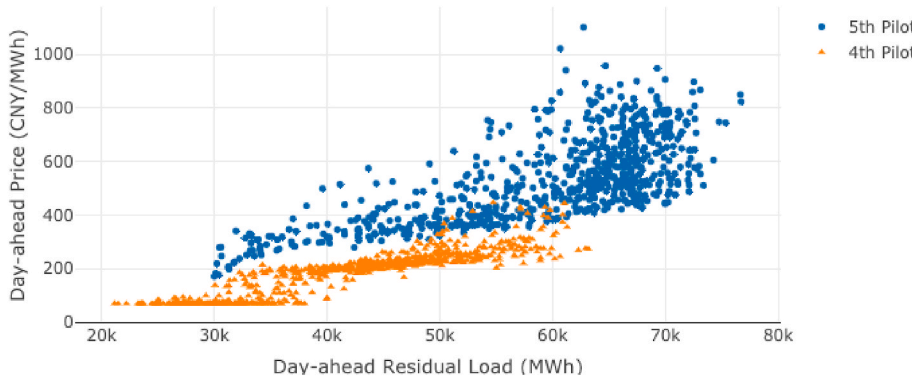


Fig. 6. Day-ahead SMPs *v.s.* Residual Load.

hydro supply, the residual load in the 5th round is much higher (than that of the 4th round).

Fig. 3 presents the daily-average SMPs for both rounds of pilots. Besides the fact that the SMPs of the 5th round were substantially higher than those in the 4th round, in the 4th round, the SMPs during the day were substantially greater than those at night, while this is not the case for the 5th round. The main reason is that nighttime temperatures in the 5th round were high, and hence air conditioners were turned on at night, resulting in high residual demand, as shown in Fig. 2b. Fig. 3 also compares the day-ahead with the real-time SMPs. In the 4th round, the two prices were relatively close, indicating a stable round of pilot operations. However, in the 5th round, the real-time SMPs were much greater than the day-ahead SMPs, mostly because of the unexpectedly high real-time load caused by the historically high temperature. Finally, the bars in Fig. 3 represent the standard deviations of the associated SMPs. Not surprisingly, the SMPs in the 5th round were more volatile than those in the 4th round, and the real-time SMPs were more volatile than the day-ahead SMPs, suggesting higher risk (for retailers) trading in the 5th round than in the 4th round and higher risk trading in the real-time market than in the day-ahead market.

To further demonstrate the difference between the day-ahead and real-time SMPs, Fig. 4 presents the dynamic of the two prices. The SMPs of the 4th round show stable daily seasonality, but surprisingly, in the 5th round, both day-ahead and real-time SMPs were heavily fluctuating with no observable seasonality. It is also noteworthy that in the 4th round, the comovement between day-ahead and real-time SMPs was salient, except on particular days where the peak-hour real-time SMPs were substantially higher. However, matters changed in the 5th round, where comovement was much weaker or even negligible, and extreme prices occurred much more frequently.

Fig. 5 presents the dynamics of bidding volumes and bid-offer spreads[15] for the retailer in the monthly auctions. During August 2020, the bid-offer spread of the monthly auctions slumped to − ¥13/MWh, much lower than those of other months. The main difference between August and other months is that in August 2020, the 4th round of spot market pilot operation took place. Put another way, the slump of the bid-offer spread is mainly due to the introduction of the spot market, potentially increasing competition in the electricity generation sector. In Guangdong's monthly auction, tacit collusion is a very real problem due to repeated interaction among firms making bids and offers.[16] Without the spot market, marginal electricity generation companies turned out to simultaneously raise their bids, and meanwhile, consumers had to take the bids to avoid a deficit because otherwise, there were no other markets that they could purchase electricity from and they could have ended up with hefty fines. As a result, even though the variable cost of electricity generation in 2020 was low (see Table 4), the market clearing prices remained high. The introduction of the spot market provides wholesale consumers another refuge such that even though they failed to get offers from the monthly auction, they could still purchase electricity in the spot market. Additionally, the introduction of the sequential market could help to release the market power and improve efficiency, and thus it is relatively difficult to tacitly collude on the spot market (Allaz and Vila, 1993). Moreover, at the time, the wholesale consumers expected the spot price to be much lower than the monthly auction prices because of low demand, high hydro imports from Yunnan Province and lower fuel costs. This is not observed in May 2021, since coal and gas prices are much higher in the 5th round, as shown in Table 4. Therefore, we observe a slump in the bid-offer spread in August 2020.

Consequently, electricity retail companies made substantial profits in the 4th round of pilots. However, this is not the case for the 5th round, mostly because of the heavy load resulting in high wholesale prices (this is discussed further below). Despite this, spot market pilot operation resulted in the distortion of bid-offer spread in August, and the bid-offer spread soon recovers and returns to normal as the pilot ends.

4.2. Estimating the spot market electricity supply curve

Estimating the relationship between electricity (residual) load and SMPs, namely the spot market electricity supply curve, has multiple benefits. For example, doing so shows how an increase in renewable energy penetration may affect SMPs, and a high price elasticity of supply may imply a need to increase the generation capacity of fossil fuel plants in the electricity system. Another classic application of the electricity supply curve is to estimate the monetary value of welfare transfers and deadweight losses following policy changes. In a series of works, Guo and Newbery (2021, 2023) and Newbery et al. (2019) use the estimated slope coefficients of the electricity supply curve to estimate the reduced deadweight loss from integrating the European electricity market and the deadweight loss induced by asymmetric carbon taxes in electricity generation between Great Britain and the European Continent.

In this article, the slope of the electricity supply curve is used to estimate the welfare transfer induced by a price floor of ¥70/MWh imposed on the SMPs. Under the assumption of a vertical (i.e., inelastic) short-term electricity demand curve, a price floor will result in a welfare transfer from consumers to electricity generators, and we estimate the

[15] The bid-offer spread refers to the difference between the bid price from monthly auctions and the retail price, and hence a lower bid-offer spread refers to higher retail profit.

[16] This has become a common secret among market participants, and many commentators and insiders have discussed the issue. See in Chinese, for example, http://www.360doc.com/content/17/0427/18/34546942_649152080.shtml.

Table 3
Regression results for the day-ahead market.

	Tobit	T-WLS	CQR		
			25%	50%	75%
Total load	0.0119***	0.0119***	0.0089***	0.0104***	0.0121***
	(0.0003)	(0.0003)	(0.0002)	(0.0005)	(0.0003)
Baseload	−0.0122***	−0.0125***	−0.0070***	−0.0114***	−0.0149***
	(0.0011)	(0.0011)	(0.0009)	(0.0010)	(0.0013)
Local Must-runs	−0.0188***	−0.0182***	−0.0067***	−0.0153***	−0.0187***
	(0.0023)	(0.0023)	(0.0010)	(0.0033)	(0.0046)
West-east Trans.	−0.0177***	−0.0178***	−0.0129***	−0.0147***	−0.0161***
	(0.0007)	(0.0007)	(0.0004)	(0.0008)	(0.0009)
GD-HK Trans.	−0.0074	−0.0043	0.0143	−0.0112	−0.0042
	(0.0108)	(0.0112)	(0.0044)	(0.0124)	(0.0129)
Temperature	−0.80**	−0.69	−0.84**	−0.88***	−0.08
	(0.41)	(0.43)	(0.33)	(0.34)	(0.31)
Wind Speed	0.09	0.25	−0.78**	0.45	0.41
	(0.60)	(0.62)	(0.32)	(0.84)	(0.51)
5^{th} Round	54.88***	54.91***	60.53***	71.57***	90.69***
	(10.31)	(10.53)	(4.35)	(11.13)	(23.07)
Constant	−4.65	−8.65	0.09	2.34	−64.40*
	(29.82)	(30.54)	(21.29)	(24.21)	(36.28)
Observations	1488	1488	1488	1488	1488
Pseudo R^2	0.174	0.171			

***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

monetary value of such welfare transfer during the 4^{th} round of pilot operations in Section 4.3.[17]

Fig. 6 presents a scatter plot showing the relationship between the day-ahead SMPs and residual load entering the day-ahead power exchange. The two rounds of pilot operations exhibit completely different market conditions. Day-ahead SMPs in the 4^{th} round were in general in low values and frequently reached the price floor, whereas in the 5^{th} round they were high and all observed prices were well above the price floor of ¥70/MWh.

The price floor indicates that the SMPs are censored from below. Put differently, when the observed day-ahead SMPs were ¥70/MWh, without the price floor their values could be lower. This means that conventional least squares methods (such as the Ordinary Least Squares, OLS method) would be biased, and neither can we remove observations for which the SMPs equal to ¥70/MWh because this will cause an omitted variables problem, resulting in biased and inconsistent estimates.

A commonly used likelihood-based model to accommodate a censored sample is the *Tobit model* (Breen et al., 1996). Let p_i denote the censored day-ahead SMPs for the hourly i, and let p_i^* denote the uncensored day-ahead SMPs or the true value of p_i when the price floor is not applied. Put another way,

$$p_i = \begin{cases} 70, & \text{if} \quad p_i^* \le 70 \\ p_i^*, & \text{if} \quad p_i^* > 70. \end{cases} \tag{1}$$

Then, a Tobit model for latent variable p_i^*, which is partially observed, takes the following form[18]

$$p_i^* = \beta_0 + \beta_1 d_i + \boldsymbol{\beta}_2' \boldsymbol{z}_i + \boldsymbol{\beta}_3' \boldsymbol{w}_i + \varepsilon_i \tag{2}$$

$$= \boldsymbol{\beta}' \boldsymbol{x}_i + \varepsilon_i, \quad \varepsilon_i \sim N(0, \sigma^2) \tag{3}$$

where d_i denotes the total load for hour i, and Z_i is a vector containing baseloads, local must-runs and interconnection transfers, all of which are pre-determined and hence are exogenous. $\boldsymbol{w}_i$ is a vector including temperature and wind speed in Guangdong. $\boldsymbol{\beta} = (\beta_0, \beta_1, \boldsymbol{\beta_2}, \boldsymbol{\beta_3})$ is a vector of slope coefficients, and ε_i is the error term. Given this, we can derive the conditional probabilities of p_i as

$$\text{Prob}(p_i = 70|d_i) = 1 - \Phi[\boldsymbol{\beta}' \boldsymbol{x}_i / \sigma], \quad \text{and} \tag{4}$$

$$\text{Prob}(p_i > 70|d_i) = \Phi[\boldsymbol{\beta}' \boldsymbol{x}_i / \sigma]. \tag{5}$$

Then, applying the Maximum Likelihood Estimation (MLE) technique, we estimate $\widehat{\boldsymbol{\beta}}_{Tobit}$ by maximizing the logarithm of

$$L(\boldsymbol{\beta}, \sigma) = \prod_{i=1}^{n} \left[\frac{1}{\sigma} \varphi\left(\frac{p_i - \boldsymbol{\beta}' \boldsymbol{x}_i}{\sigma} \right) \right]^{D_i} \left[1 - \Phi\left(\frac{\boldsymbol{\beta}' \boldsymbol{x}_i}{\sigma} \right) \right]^{1-D_i}, \tag{6}$$

where φ is the standard normal probability density function and Φ is the standard normal cumulative distribution function. $d_i = 0$ if $p_i = 70$ and 1 otherwise. Equation (6) is the product of likelihood functions for all censored and uncensored observations.

One may also have noticed from Fig. 6 that the distribution of error terms ε_i might be heteroskedastic, whose variance might depend on residual demand d_i. If this is the case, we can assume $|\sigma_i| = \alpha_1 d_i + \alpha_2 d_i^2$ and replace σ with σ_i in equations (2)–(6). This technique is known as Tobit regression with Weighted Least Squares (T-WLS) and the associated estimator can be denoted as $\widehat{\boldsymbol{\beta}}_{T-WLS}$. Amemiya (1984) proved that the Tobit model is consistent in dealing with censored dependent variables.

Quantile models, which are more robust to outliers in the response measurement, have also been established and developed to deal with censored samples (Powell, 1984, 1986). Whereas the least squares method estimates the conditional mean of the response variable across values of the predictor variables, quantile regression estimates the conditional median (or other quantiles) of the response variable. Powell's method is known as *Censored Quantile Regression* (CQR).

In our case, the conditional quantile functions,

$$Q_{p_i|\boldsymbol{x}_i}(\tau|\boldsymbol{x}_i) = F^{-1}(\tau) + \boldsymbol{\beta}' \boldsymbol{x}_i \tag{7}$$

can be consistently estimated by

$$\widehat{\boldsymbol{\beta}}_{CQR} = \arg\min_{\beta} \sum_{i=1}^{n} \rho_\tau(p_i - \max\{70, \boldsymbol{\beta}' \boldsymbol{x}_i\}), \tag{8}$$

[17] The welfare transfer only took place in the 4th round because the SMPs in the 5th round were always above ¥70/MWh.

[18] An alternative specification is $p_i^* = \beta_0 + \beta_1 r_i + \varepsilon_i, \quad \varepsilon_i \sim N(0, \sigma^2)$, where r_i denotes the residual load. In both specifications, β_1 estimates the relationship between SMPs and the residual load because in equation (2), the estimated β_1 is conditional on the baseload, local must-runs, and interconnector transfers.

Table 4
Comparison of day-ahead SMPs to variable costs, load and weather.

	4^{th} round	5^{th} round	Δ*
DA SMP (¥/MWh)	188.6	527.3	338.7
V_{coal} (¥/MWh)**	169.8	257.7	87.9
V_{CCGT} (¥/MWh)	501.0	649.8	148.8
Res. Load (MW)	42,200	59,155	16,955
Temperature (F°)	85.3	85.0	−0.3
Wind Speed (mph)	5.5	7.4	1.9

*Δ refers to the difference between the two rounds.
***V* represents variable costs.

Table 5
Regression results for the 4^{th} round of pilots, day-ahead market.

	(i)Tobit	(ii)T-WLS	CQR		
			(iii)25%	(iv)50%	(v)75%
Total load	0.0073***	0.0072***	0.0067***	0.0063***	0.0065***
	(0.0003)	(0.0003)	(0.0003)	(0.0002)	(0.0003)
Baseload	−0.0039***	−0.0041***	−0.0033**	−0.0021**	−0.0044***
	(0.0010)	(0.0011)	(0.0014)	(0.0010)	(0.0009)
Local Must-runs	−0.0086***	−0.0072***	−0.0055***	−0.0072***	−0.0104***
	(0.0017)	(0.0018)	(0.0010)	(0.0020)	(0.0016)
West-east Trans.	−0.0079***	−0.0078***	−0.0085***	−0.0072***	−0.0071***
	(0.0007)	(0.0007)	(0.0007)	(0.0006)	(0.0012)
GD-HK Trans.	0.0097	0.0116	0.0089	0.0111	−0.0029
	(0.0081)	(0.0080)	(0.0062)	(0.0100)	(0.0112)
Temperature	0.35	0.39*	−0.03	0.13	0.72***
	(0.24)	(0.24)	(0.19)	(0.20)	(0.26)
Wind Speed	0.07	0.01	0.04	0.05	−0.23
	(0.41)	(0.43)	(0.40)	(0.35)	(0.29)
Constant	−145.58***	−146.47***	−79.82***	−85.47***	−118.56***
	(27.30)	(27.67)	(25.24)	(20.28)	(21.34)
Observations	744	744	744	744	744
Pseudo R^2	0.184	0.182			

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.10$.

where $\rho_\tau(u) = [\tau - I(u < 0)]u$ is the check function and $I(\cdot)$ is the usual indicator function. It is also noteworthy that F in equation (7) denotes the cumulative distribution function of ε_i, which does not have to be normal. One advantage of the CQR therefore lies in it allowing for the consistent estimation of the censored regression model under far fewer distributional assumptions than commonly required. Another advantage is also straightforward - the model can distinguish between differential effects across conditional quantiles.

To explore the impact of electricity load on the day-ahead SMPs, we first combine data from the 4^{th} and 5^{th} rounds. It is noteworthy that besides load and weather, fuel and carbon prices are also key determinants of SMPs. However, there is little variation in fuel and carbon prices within a month and price variables are usually nonstationary, and therefore including them in the regression may result in spurious correlations.[19] Consequently, fuel and carbon price variables are not included in the regression. To capture the difference in fuel and carbon prices between the two rounds, we add a dummy variable equal to one for the 5^{th} round and zero for the 4^{th} round, and the results are reported in Table 3. Not surprisingly, total load is positively related to the day-ahead SMPs. On average, a 1 GW (or 1000 MW) increase in the total load is associated with an ¥11.9/MWh increase in the day-ahead SMPs. Moreover, total load has a greater effect on higher quantiles of day-ahead SMPs. The results also show that conditional on load and weather, on average the day-ahead SMPs in the 5^{th} round are roughly ¥55/WMh higher than those in the 4^{th} round, which might due to the differences in fuel and carbon prices between the two rounds of pilot operations.

To further investigate the underlying mechanisms for the differences in the day-ahead SMPs between the two rounds of pilot operations, we list the variable cost of electricity generation (with the carbon price included) in August 2020 and May 2021 in Table 4.[20] The variable costs for coal and gas plants were higher in the 5^{th} than the 4^{th} round. Notably, in the 4^{th} round, the average SMPs were much closer to the variable cost of coal plants, whereas in the 5^{th} round, they were much closer to the variable cost of CCGTs. This may indicate that due to low residual demand, coal was more often the marginal fuel of electricity generation in the 4^{th} round whereas matters changed in the 5^{th} round, when gas became the marginal fuel of electricity generation most of the time. Recall that Guangdong's spot market adopted a variable compensation mechanism, which will in turn affect the variable cost of electricity generated from CCGTs. Given that the compensation for a CCGT was 200/MWh (0.2/kWh), the variable costs of CCGTs would reduce to 301.0/MWh and 449.8/MWh in the 4th and 5th rounds, respectively. Despite being compensated, the variable cost of CCGTs was still greater than average day-ahead SMPs in the 4^{th} round and lower than that in the 5^{th} round. In the 5^{th} round, it is possible that when the electricity demand approached the capacity limit, the marginal plants (CCGTs) may exercise their market power, resulting in greater markups. Overall, the increase in variable costs cannot fully explain the increase in the day-ahead SMPs, and hence we may need to identify other factors.

Based on the estimated relationship between electricity load and day-ahead SMPs as well as the estimated relationship between weather and day-ahead SMPs, we also estimate the extent to which the difference

[19] We conducted Dickey-fuller tests and found the daily coal, gas and carbon prices are indeed nonstationary processes.

[20] Monthly coal and gas prices were collected from Wind at https://www.wind.com.cn/, and carbon prices were collected from the Guangzhou Carbon Emissions Exchange Center at http://www.cnemission.cn/.

Table 6
Regression results for the 5th round of pilots, day-ahead market.

	(vi)OLS	(vii)WLS	QR		
			(viii)25%	(ix)50%	(x)75%
Total load	0.0136***	0.0134***	0.0103***	0.0131***	0.0160***
	(0.0004)	(0.0003)	(0.0005)	(0.0005)	(0.0006)
Baseload	−0.0136***	−0.0129***	−0.0098***	−0.0121***	−0.0150***
	(0.0020)	(0.0018)	(0.0025)	(0.0025)	(0.0032)
Local Must-runs	−0.0273***	−0.0271***	−0.0077	−0.0188***	−0.0335***
	(0.0036)	(0.0034)	(0.0050)	(0.0050)	(0.0065)
West-east Trans.	−0.0210***	−0.0210***	−0.0158***	−0.0223***	−0.0269***
	(0.0012)	(0.0012)	(0.0015)	(0.0015)	(0.0020)
GD-HK Trans.	−0.0250	−0.0300**	−0.0162	−0.0506**	−0.0478*
	(0.0166)	(0.0151)	(0.0219)	(0.0218)	(0.0287)
Temperature	−1.84**	−2.03***	−2.47**	−2.40**	−1.94
	(0.73)	(0.66)	(0.99)	(0.98)	(1.30)
Wind Speed	2.01*	1.94*	0.29	1.84	2.24
	(1.12)	(1.09)	(1.38)	(1.38)	(1.81)
Constant	76.39	89.69**	123.93*	66.69	45.81
	(46.81)	(42.15)	(65.52)	(65.14)	(85.72)
Observations	744	744	744	744	744
R^2	0.656	0.700			

***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

in load and weather may affect day-ahead SMPs as reported in Table 4. We find that the increase in residual load contributed approximately 65% of the increase in the day-ahead SMPs,[21] whereas the difference in temperature and wind speed between the two rounds does not contribute the difference in SMPs.[22]

In sum, the substantial difference in the day-ahead SMPs between the two rounds of pilot operations is mainly due to the increases in residual load and fuel and carbon prices.

Next, we separately explore the spot market electricity supply curves of the 4th and 5th rounds. Table 5 presents regression results from Tobit regression, the T-WLS, and the CQR. The slope coefficients are consistent, not only among different regression techniques, but also for different quantiles of the day-ahead SMPs. On average, a 1 GW (1000 MW) increase in the total load resulted in a roughly ¥7/MWh increase in the day-ahead SMP. Not surprisingly, baseload, local must-runs, and interconnector transfers negatively affect the SMPs, as they reduce the residual load entering the spot market.[23] From the CQR results, the differences between the estimates at different quantiles are not statistically significant; therefore, we cannot conclude that total load and other variables have different effects at different quantiles of the day-ahead SMPs. One exception is temperature, whose impact on the day-ahead SMP varies substantially at different quantiles. The day-ahead SMPs are more sensitive to temperature at higher quantiles.

The next step is to estimate the slope of electricity supply during the 5th round of pilot operations. For the 5th round, as all day-ahead SMPs were higher than the price floor, it is not necessary to employ censored regressions; instead, we conduct the uncensored version of the regression techniques employed in the 4th round, namely Ordinary Least Squares (OLS), Weighted Least Squares (WLS), and Quantile Regressions (QR). Table 6 presents the results, where the slope coefficients for total load are substantially greater than those in the 4th round; on average, a 1 GW (1000 MW) increase in the total load resulted in a roughly 13/MWh increase in the day-ahead SMP. It may be that during the 5th round, the total load is generally higher than that in the 4th round; as the residual load approaches the capacity limit of the electricity system, the market becomes less competitive as the number of generators than can bid into the day-ahead market becomes decreases. Therefore, these generators bid higher prices to make more profit, resulting in a steeper electricity supply curve. This argument is also verified by the QR results. The changes in the total load have a greater effect on higher quantiles of day-ahead SMPs. At the 25% quantile, a 1 GW (1000 MW) increase in the total load is only associated with a 10/MWh increase in the day-ahead SMP, whereas at the 75% quantile, the number increases to 16/MWh. With the increase in day-ahead SMPs, the impact of the total load on the price change increases.

As in the 4th round of pilots, baseload, local must-runs, and interconnector transfers were also negatively associated with the day-ahead SMPs. However, counter to those of the 4th round, the QR results suggest that these effects are heterogeneous at different quantile levels; in general, the effects are greater at higher quantiles. Perhaps counterintuitively, we find that temperature lowered the day-ahead SMPs, whereas wind speeds raised the day-ahead SMPs. It may be that extremely high SMPs occurred when temperatures happened to be low with high wind speeds. For small sample periods such as the ones we examine, this can bias the results. As the sample size increases (in future rounds of pilots or when the spot market is formally operated), the signs of the estimates may change. Finally, once may notice that the R^2s in Table 6 is much greater than the pseudo R^2s in Table 5, but these numbers are not compatible is because we adopted different regression techniques.

4.3. *Estimating the welfare transfer from the price floor*

Recall that a price floor of ¥70/MWh is set on the SMPs. Given inelastic electricity demand, the price floor will unavoidably result in some welfare transfers from consumers to generators. Intuitively, suppose that without the price floor the SMP is less than ¥70/MWh at, for example ¥65/MWh, but the price floor forces consumers to pay ¥70/MWh to generators; because the consumer demand is inelastic, consumers will not change their demand; but for each 1 MWh of electricity consumed, consumers transfer an additional ¥5 (than the equilibrium market clearing price) to generators. Put differently, the price floor damages the welfare of consumers and benefits the generators.

To quantify the welfare transfer caused by the price floor, we need to estimate the SMPs without the price floor and then subtract it by the price floor, which is then multiplied by the trading volume to derive the

[21] Based on the regression results of the T-WLS model in Table 3, we estimate that the change in residual load is associated with a $16955 \times 0.0119 =$ ¥201.8/MWh increase in the day-ahead SMPs, representing approximately 65% (=201.8/338.7) of the change in the SMPs between the two rounds.

[22] Note that the results are estimates *conditional on* electricity load. A higher temperature would result in an increase in electricity load, but this effect is demonstrated as the impact of electricity load on SMPs.

[23] Although the estimated coefficients for “GD-HK Trans.” are sometimes positive, they are not statistically significant.

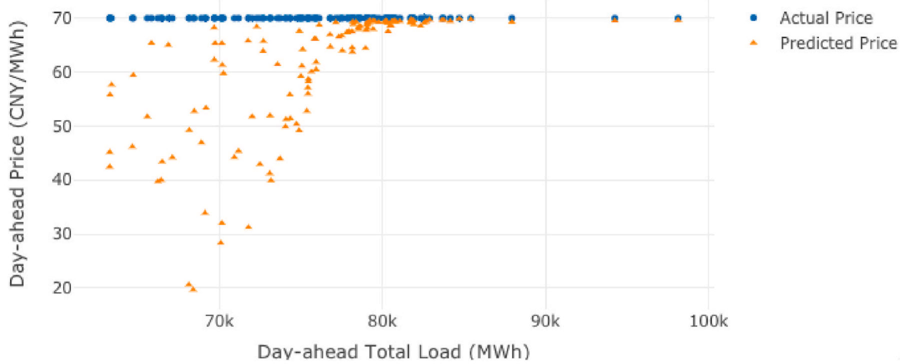


Fig. 7. Actual *v.s.* Predicted Day-ahead SMPs without the Price Floor, 4th Round.

monetary value of the welfare transfer.[24] If we assume that without the price floor, the SMPs follow a normal distribution as suggested by the Tobit model (3), then it is natural to assume that the latent SMPs follow truncated normal distribution $f(p_i^*;\overline{\mu},\overline{\sigma}_i,-\infty,70), \forall p_i^* \leq 70$ derived from the normally distributed p_i^* with mean $\overline{\mu}$ and variance $\overline{\sigma}_i^2$. To estimate the welfare transfer, we employ the results from the T-WLS model and use the predicted value of p_i^* as $\overline{\mu}$ and the standard deviation of error term σ_i as $\overline{\sigma}_i$. Then, the probability density function of p_i^*, conditional on $p_i^* < 70$, can be evaluated by

$$f(p_i^*;\overline{\mu},\overline{\sigma}_i,-\infty,70) = \frac{1}{\overline{\sigma}_i}\frac{\varphi\left(\frac{p_i^*-\overline{\mu}}{\overline{\sigma}_i}\right)}{\varphi\left(\frac{70-\overline{\mu}}{\overline{\sigma}_i}\right)}, \tag{9}$$

where $\varphi(.)$ is the probability function of the standard normal distribution. If we apply $\gamma \equiv (70-\overline{\mu})/\overline{\sigma}_i$, the conditional mean of one-sided truncated normal distribution with an upper tail of ¥70 is

$$E(p_i^*|p_i^* \leq 70) = \overline{\mu} - \overline{\sigma}_i\frac{\varphi(\gamma)}{\Phi(\gamma)}, \tag{10}$$

where $\varphi(.)$ is the cumulative distribution function of the standard normal distribution. Then, the welfare transfer can be estimated via the following formula

$$W = \sum_j \left[70 - E(p_j^*|p_j^* \leq 70)\right] \times r_j, \tag{11}$$

where j denotes hours in which the observed SMPs are equal to ¥70/MWh, and r_j denotes the residual load that enters the spot market.

In the 4th round of pilot operations, in 126 of 744 hours, the day-ahead SMPs equaled ¥70/MWh. Following the aforementioned approach, Fig. 7 presents the estimated day-ahead SMPs from the Tobit-WLS regression results for if the price floor were not implemented. We then estimate that the welfare transfer was ¥84 million during the month or approximately 1.3% of the total tradable value of the day-ahead market.

4.4. Measuring local market power

Competition sets market prices at an efficient level where necessary investments are financed and firms are provided with "incentive to reduce costs, increase efficiency, and innovate as the only means of increasing profits" (Newbery, 1995)[p.39].

Market power refers to a firm's ability to manipulate the market price and maintain the profit margin for a considerable period. However, the electric power network is different from other markets, which requires electricity supply and demand to be balanced at any time to maintain the stabilization of the electric power network. As electricity is transferred via cables with limited transfer capacity, when local electricity load reaches the capacity limit, local market power arises, resulting in electricity scarcity in the congested area and high LMPs (He et al., 2004). In this subsection, we use the LMPs during the 4th and 5th rounds of pilot operations to investigate whether local market power exists in Guangdong's electricity supply system. Local market power exists mostly due to transfer capacity limits from one node to another; in this case, if more electric grids were built and the capacity of electricity transfers increased (from lower-price to higher-price nodes), the market would be more efficient.

By comparing the LMPs of different cities, we assess the existence of local market power, and if local market power exists, one may observe some much higher LMPs in some cities than others. Inspired by Lerner (1934), we define an index of local market power for city c for the entire month of a pilot as

$$L_c = \frac{1}{N}\sum\nolimits_{i=1}^{N} I_{c,i}, \tag{12}$$

where

$$I_{c,i} = \begin{cases} (\widetilde{p}_{c,i} - p_i)/\widetilde{p}_{c,i} & \text{if } \widetilde{p}_{c,i} > p_i \\ 0 & \text{otherwise} \end{cases}, \tag{13}$$

where $\widetilde{p}_{c_i}$ denotes the LMP for city c at time i, and p_i is the SMP at time i.[25] Therefore, index L_c ranges from 0 to 1. A perfectly competitive local market has $L_c = 0$, such that no local market power exists; the index approaches 1 when the LMPs are substantially and consistently greater than the SMPs.

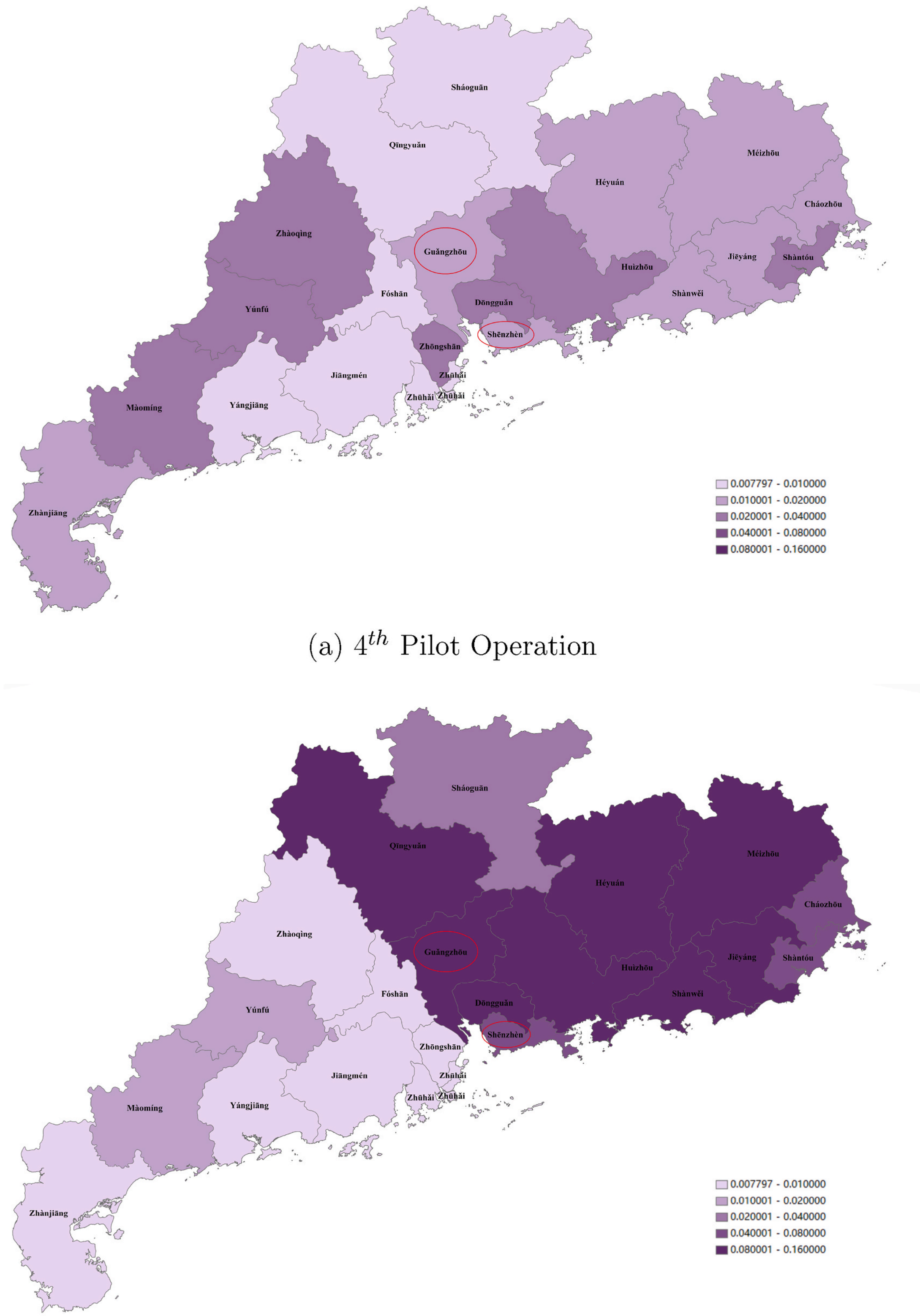
We then calculate L_c for each city in Guangdong. The assessment of local market power is depicted in Fig. 8, with Fig. 8a assessing the 4th round and Fig. 8b assessing the 5th round. A darker color represents a greater value of index L_c and hence more substantial local market power. Recall from Fig. 4 that due to the heavier load, the SMPs in the 5th round were much higher than those in the 4th round, and therefore it is not surprising that the indices L_c, $\forall c$ are in general higher in Fig. 8b than in 8a.

We find that cities with greater L_c values such as Huizhou, Dongguan, Zhongshan and Shantou are located around Guangzhou and Shenzhen, the political and economic centers of Guangdong accounting for over 30% of electricity consumption in the province.[26] The reason is simple: electricity load is transferred from these cities to Guangzhou and

[24] In fact, the price floor and ceiling were also applied to the LMPs. However, as we have no information about electricity load at each node, we are unable to use the LMPs to estimate the welfare transfer.

[25] Note that there may be multiple nodes (and LMPs) in a city.

[26] Source: websites of Guangdong Statistics Department other cities' Statistics Department.



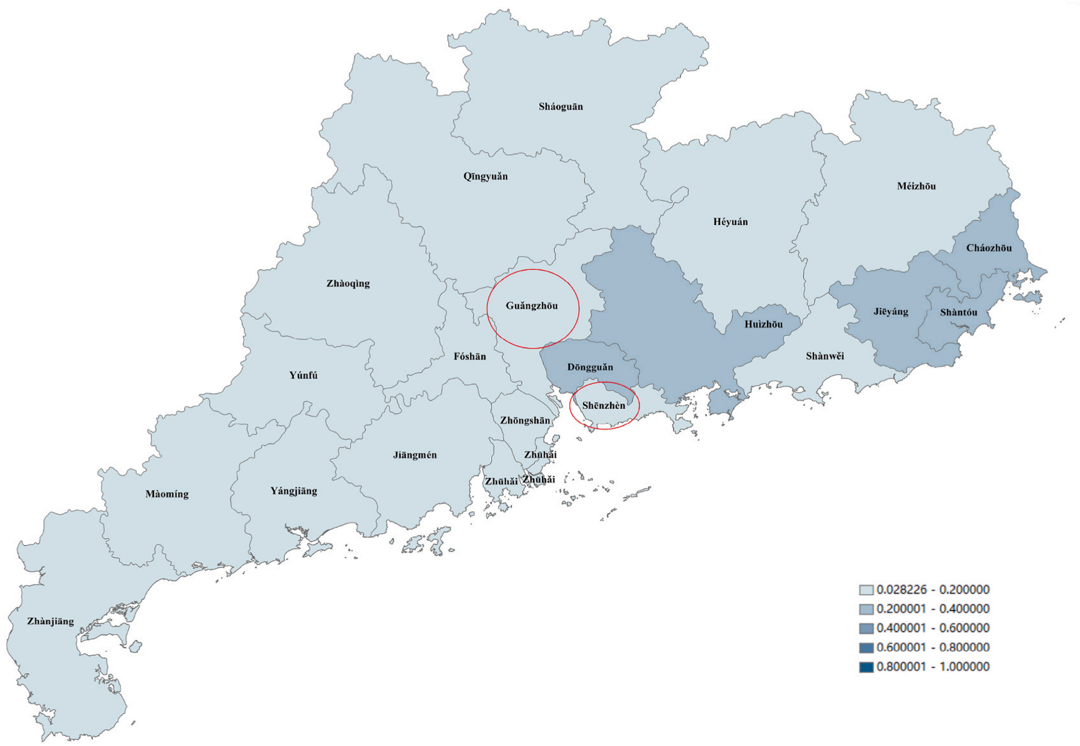
(a) 4^{th} Pilot Operation

(b) 5^{th} Pilot Operation

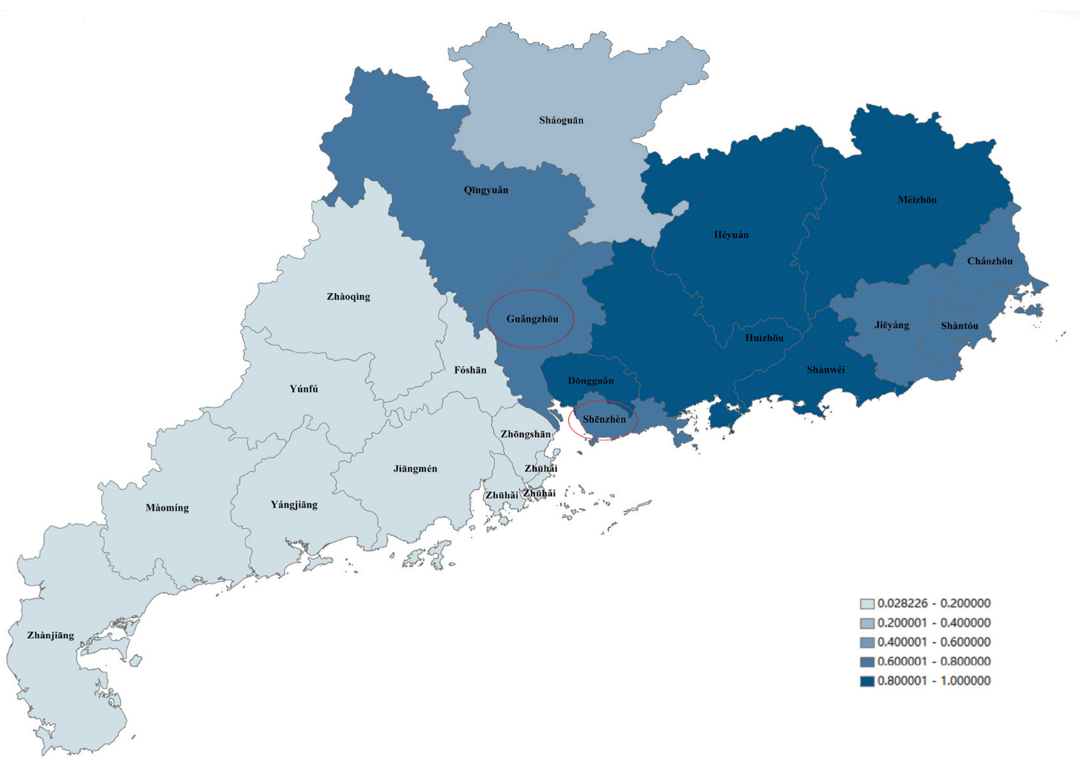
Fig. 8. Local market power assessment of Guangdong.

Shenzhen, increasing the load needed in the surrounded cities and resulting in local market power. This argument is further supported by Fig. 8b, which shows that the load is heavy at the provincial level, much broader areas around Guangzhou and Shenzhen are affected, especially in the northeastern cities of Guangdong, which are closely connected to Guangzhou and Shenzhen via high-voltage power lines.

To enhance the robustness of our assessment, we also use a naive method to assess local market power – the percentage of hours during which the LMPs are greater than the SMPs. The results are presented in Fig. 9 and allow us to draw the same conclusion: local market power



(a) 4^{th} Pilot Operation



(b) 5^{th} Pilot Operation

Fig. 9. Local market power assessment of Guangdong.

exists in cities around Guangzhou and Shenzhen, suggesting the need to invest in more power lines connecting the west to the east of Guangdong to achieve market efficiency. However, it is also noteworthy that a more realistic research topic might be whether such investment can be profitable, and to answer this question, further cost-benefit analysis is needed and we shall leave this to future research.

5. Conclusions and policy implications

China is still in a process of power sector reform. With mid-to-long-term (M2L) power exchange in operations since 2016, the share of electricity load managed via market exchanges increased from 8% in 2016 to 40% in 2020, and the ratio is expected to be higher in the future. However, China does not yet have a formal electricity spot market, which would normally improve efficiency of electricity allocation and reduce market power. Moreover, if the market is competitive, the associated spot market prices should represent the short-run marginal cost of electricity generation.

Eight provinces (and regions) were selected for electricity spot market pilot operations, among which Guangdong has the highest electricity demand and is usually considered to be the province leading China's power market reform. As of June 2021, Guangdong had completed five rounds of pilot operations. In this article, we use *ex-post* data to assess the efficacy of China's electricity spot market pilot operations.

Our results suggest that in the 4th and 5th rounds of Guangdong's spot market pilot operations, the spot market prices (SMPs) are more volatile in the real-time market than in the day-ahead market, suggesting higher risk trading in the real-time market. Due to historically high temperatures, increasing coal prices, the recovery from Covid-19, and a moderately concentrated wholesale market, we observe much higher SMPs in the 5th round than in the 4th round. The impacts of electricity load on the day-ahead SMPs are also highly varied. During the 4th round, a 1 GW increase in the total load is associated with a ¥7/MWh increase in the day-ahead SMPs, while the number increases to ¥13/MWh in the 5th round. During the 4th round, the SMPs are frequently censoring around the price floor of the SMPs at ¥70/MWh. This indicates a welfare transfer from electricity consumers to generators, and we estimated the monetary value of the transfer to be ¥84 millions, or approximately 1.3% of the total tradable value of the day-ahead market. Finally, we assessed local market power in Guangdong and argued that under heavy load, Guangzhou and Shenzhen, the political and economic centers of Guangdong, received electricity transfers from nearby cities, resulting in non-negligible local market power.

Guangdong's recent attempts to operate the electricity spot market are valuable in the sense that they revealed the possible range in which the SMPs lie within. In the 4th round the price floor took effect, suggesting that without the price floor, some much lower or even negative SMPs may occur. This, therefore, reflects the lowest possible prices of power generation in Guangdong. In the 5th round, for multiple aforementioned reasons, electricity demand was high and the grid was stressed by hefty load, resulting in some very high SMPs, which may reflect the highest possible prices of power generation in Guangdong.

In Guangdong, the average Herfindahl-Hirschman Index (HHI) exceeded 1,500, raising concerns of large generators abusing (system-wide) market power. Evidence also shows the existence of local market power in Guangdong, especially when electricity demand approaches the capacity limit of the power system. As the discussants point out, the spot market electricity supply curve of the Guangdong pilot is much steeper, and the price variations are more sensitive to the changes in the loads. When the system load is higher, it is difficult to predict the price changes.[27] Our results of quantile regressions and the comparison between the two rounds also hold well on the findings. We further find that in the 5th round of pilot operation, electricity demand approached the capacity limit, the slope of the supply curve became much steeper, which is twice as large as the slope of the 4th round. One of the possible reasons is sufficient electricity supply and low demand in August 2020,[28] while the electricity demand was close to the capacity limits of grids in May 2021. In the scenario of the 5th round, a small increase in demand would result in a substantial increase in the SMPs. In the long run, encouraging private investment in thermal capacity would not only promote market competition, but also flatter the supply curve to avoid high fluctuations. Moreover, when local demand exceeds transfer capacity, local market power arises. This indicates further investment in power capacity and electricity grid is desirable. It is also suggested that further investigations of market power abuse are vitally important, and large power companies must be further regulated.

The day-ahead SMPs in the 4th round of the pilot operation were much lower, and thus electricity retail companies made substantial profits. However, due to the heavy load leading to unexpectedly high SMPs in the 5th round, 136 out of 161 electricity retailers were making a loss participating in the spot market. The reason is simply because prior to spot market pilot operation, retailers had already signed long-term contracts with their customers, where the retail prices of electricity were even lower than the SMPs. As the retailers are unable to immediately pass on the wholesale cost to customers, in May 2021, the total loss for all retailers was over ¥5 billion (approximately 21% of total tradable value in the 5th round), and one retailer went bankrupt. Because of this, the system operator decided to postpone the next round of spot market pilot operations to early 2022.

Guangdong's spot market pilot operations therefore offer us multiple lessons. First, market power needs to be firmly monitored and regulated, as otherwise oligarchic conspiracy may emerge and harm the benefit of small retailers. Second, the government's plan and policy need to be transparent and upfront, as otherwise retailers' prior plans might be distorted and their long-term investment may be disincentivized. Third, a longer period of spot market pilot operation is desirable and system operators should "let the market decide." Even though in May 2021 the retailers were losing, the hope was that if the spot market continued to operate for several months, their losses might be recovered. Last but not the least, the price floor (and ceiling) needs to be gradually removed because a price floor harms consumers while benefiting generators; on the other hand, a mechanism that can properly deal with extreme pricing is also needed to ensure the stabilization of the market.

Finally, many commentators observed that the Guangdong spot market pilot operations display some strange price behaviors, which might be attributed to poor market design, poor market oversight or excessive government interference, or inexperienced and inappropriate bidding strategies. The spot market pilots have been criticized for their poor market design from many aspects, such as the lack of a functioning ancillary service market, excluding renewable and nuclear energy from the market, the variable cost compensation mechanisms, and so on. The impact of the poor market design on the efficiency of the spot market could be a variable research topic for future studies. The market structure may also raise the concern of collusion in the spot market among oligopolies, therefore investigating whether market power exists and whether the market power is due to collusive oligopolies may also be an interesting topic for future research. One may also worry about inexperienced and inappropriate bidding strategies when the spot market started operation. If that is the case, a standard economic theory may fail to explain market outcomes. It is therefore worthwhile investigating generators' bidding strategies and whether they can learn from past market outcomes to make greater profits.

[27] As discussed in Chinese, https://mp.weixin.qq.com/s/jIEJeoiZb2iD2d_Qo48Gig.

[28] As discussed in Chinese, https://mp.weixin.qq.com/s/qZuUz35ZQzrE_gYN_SJRrA.

CRediT authorship contribution statement

Yang Liu: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Zhigao Jiang:** Conceptualization, Resources, Validation. **Bowei Guo:** Conceptualization, Formal analysis, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing.

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