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Evaluating the impacts of reforming and integrating China's electricity sector

Hao Chen [a], Jian Cui [a], Feng Song [a,*], Zhigao Jiang [b]

[a] School of Applied Economics, Renmin University of China, Beijing, China
[b] Zhineng Consultant Company, Beijing, China

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A B S T R A C T

Addressing the efficiency–equity–environment trade-off is an important part of implementing electricity sector reform. To support China's electricity market reform, this study conducts an *ex-ante* analysis to quantify the economic, distributional and environmental effects of marketization and integration. Three scenarios are designed based on the current reform progress and possible reform directions, including a planning scenario, a provincial market scenario and a regional market scenario. Using high-frequency data of electricity load, production and trade from five southern Chinese provinces in 2018, we quantify the impacts on electricity generation mix, wholesale prices, carbon emissions and social welfare. The potential welfare improvement achieved from establishing provincial markets is 14.3 billion yuan, which could be further increased to 21.0 billion yuan by integrating the provincial markets into a regional market. The regional average wholesale price could be reduced by 23.5% 22.7% and (regional market) (provincial market), respectively. The carbon emissions could be reduced by about 12.4 million tons (2.4%) in the provincial market scenario and 16.6 million tons (3.2%) in the regional market scenario. Moreover, individual provinces are affected heterogeneously from the marketization and integration, and the potential winners and losers have been identified from market reform. The regional market performs better than the provincial market in terms of overall efficiency gains and environmental outcomes but worse in addressing equity concerns.

1. Introduction

Many countries and regions around the world have implemented electricity market reform. The electricity system in China had also experienced several rounds of restructure and reforms, but it has been largely characterized as a planning-based system because the government still played a dominant role in the decisions of investment, production and pricing (Wang and Chen, 2012; Pollitt, 2020). China has the largest electricity sector in the world, whose total installed capacity (2011 GW) accounted for 28% of world's total capacity in 2019. Furthermore, over 60% of the country's electricity production comes from burning coal, emitting large amounts of carbon emissions and air pollutants. With the increasing pressure from climate change and air pollution problems, a new round of market-oriented reform was initiated by the Chinese government in 2015, aiming at enhancing the power system efficiency through establishing a market-based resource allocation mechanism (State Council, 2015).

Transitioning the Chinese electricity industry from planning-based mechanism to market-based mechanism faces many challenges and requires a careful market design (Ngan, 2010; Davidson and Pérez-Arriaga, 2020). Thus far, the majority of Chinese provinces have achieved some progress in establishing wholesale markets within provinces (Guo et al., 2020). In 2019, over 80% of electricity market transactions were conducted through provincial markets. To enlarge the benefits from market trading, a key next step under consideration is to determine whether and how the provincial markets can be integrated across different provinces. There is a vast disparity among different provinces in terms of energy resource endowment and economic development levels. Inter-provincial trades of electricity, which were negotiated between different provincial governments, have been used as ways of ensuring energy security as well as promoting local economic growth. Manifold benefits can be achieved from the integration of provincial electricity markets in China, such as improving industrial efficiency, promoting renewable energy development, and reducing carbon emissions. However, conflicts and tensions may appear from uneven cost and benefit redistributions among different stakeholders. To foster a

* Corresponding author.
E-mail addresses: chenhao9133@126.com (H. Chen), jiancui@ruc.edu.cn (J. Cui), songfeng@ruc.edu.cn (F. Song).

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successful reform and integration of China's electricity sector, it is necessary to have a good understanding of the effects of market reform on efficiency gains, carbon emissions, and benefit distributions and how these effects are influenced by different institutional arrangements of inter-provincial trades.

This study conducts an *ex-ante* analysis to quantify several impacts of establishing and integrating the provincial markets in southern China, including the generation mix and supply structure, wholesale prices, carbon emissions and social welfare. Three scenarios are first defined based on the actual reform progress and possible reform directions. The first one is a planning scenario, which is severed as a business-as-usual scenario for comparison. The other two are the provincial market scenario and regional market scenario, representing different levels of marketization and integration. Then, by integrating high-frequency data of electricity load, production, and trade, a partial market equilibrium model is established to simulate the equilibrium outcome variables.

We find that replacing the planning mechanism by a market mechanism can potentially lead to substantial benefits in terms of generation cost savings, wholesale price reductions, and carbon emission reductions. The total potential welfare achieved from provincial market scenario is 14.3 billion yuan in 2018, while the welfare obtained from regional market scenario is 21.0 billion yuan. Compared with the actual fixed benchmark tariff in planning scenario, the regional average wholesale price could be reduced by 22.7% (regional market) and 23.5% (provincial market). Moreover, the total carbon emissions could be reduced by about 12.4 million tons (2.4%) in the provincial market scenario and 16.6 million tons (3.2%) in the regional market scenario.

Although the southern China region, as a whole, benefits from the positive economic and environmental effects of marketization and integration, the impacts on individual provinces are heterogeneous, potential trade-off should be decided among various targets of local development, environmental protection, and economic efficiency. For example, Guangdong province and Hainan province may enjoy lower electricity prices and more social surplus but increase carbon emissions from the market reform and integration.

In the comparison of the two market scenarios, it is not surprising that the regional market performs better than the provincial market in terms of overall efficiency gains and environmental outcomes but worse in addressing the equity issues. In contrast with the results that every province benefits from reform in the provincial market scenario, the regional market will create winners and losers. This is because there will be a redistribution of the inter-provincial trades based on market competition, resulting in uneven efficiency gains and carbon emission reductions among different provinces. Taking Guangxi province as an example, it will become a net loser due to the negative impact on social surplus and carbon emissions.

Our paper relates to the literature in several ways. One line of related studies is the impact assessment of electricity reform. Although the general goal of electricity sector reform is to improve the efficiency and bring long-term benefits to the society, the potential gains depend on the initial position of the industry and the reform components. Early studies such as Newbery and Pollitt (1997) and Barmack et al. (2007) adopted social cost-benefit analysis framework to quantity the potential economic impacts of electricity sector restructuring in England and US. There are emerging, but still few, quantitative assessment studies on China's new round of market-oriented reform initialed in 2015. Existing studies cover the impact on electricity price and generation costs (Lin et al., 2019a; Xie et al., 2020), coal consumption, and associated carbon emissions (Wei et al., 2018; Chen et al., 2020). Abhyankar et al. (2020) made an *ex-ante* analysis similar to our study, based on the five southern provinces to evaluate the efficiency gains and emission reductions of market-based power-system reform. Compared with these previous assessments, ours is a more comprehensive *ex-ante* impact evaluation study using a partial equilibrium welfare analysis that measures supply cost reductions and impacts in terms of cross-province price differentials, social surpluses, and carbon emissions.

We also examine the efficiency-equity-environment trade-off issue that often arise in the electricity system marketization and integration literatures (Jamasb and Pollitt, 2005; Pollitt, 2009; Abrell and Rausch, 2016; Pollitt, 2019). Although the electricity market integration can improve the overall welfare, it often has a redistribution effect, leading to losses in the welfare of some groups (Finon and Romano, 2009). Due to the negative impact on equity, the redistribution problem is also an important political economy problem during the market reform. To address the equity problem and to reduce the obstacles to market reform, it is essential to evaluate the redistribution effect of market integration.

This study intends to make two contributions to the existing literature. First, the evaluation provides a clear understanding of the efficiency, equity and environmental impacts of the marketization and integration of China's electricity sector, by applying a comprehensive *ex-ante* welfare analysis. We quantify the efficiency improvement, price changes, emission reductions and welfare redistribution from the planning scenario to the provincial market scenario and to the regional market scenario. Although the results of our analysis are most relevant to Chinese stakeholders, some of the findings might also be useful for the market reform and integration in regions with similar geographic diversity and uneven economic development. Second, we evaluate the redistribution of welfare between producers and consumers and among different provinces. We identify the potential winners and losers and quantify their gains and losses. These are important information on the level of redistribution to be considered for effective participation and implementation, which can help policymakers optimize the market design and address the equity issue from the benefits reallocation.

Another merit of our study is a unique dataset of hourly load and generation data of five southern provinces in China. Both the electricity demand and supply are highly dynamic and vary considerably over short time-spans, and our data of smaller time granularity enables us to fully capture the intra-day and inter-day heterogeneity of demand and supply profiles in a large geographic area. Moreover, it can help improving the accuracy of the simulation results compared with studies using daily data or data of a representative day (Abhyankar et al., 2020; Xu et al., 2020).

2. China's electricity reform toward marketization and integration

China's electricity system has long been characterized as a governmental planning system, in which the market only plays a limited role. It was vertically integrated and essentially under governmental control until 2002, when the first attempt at market-oriented reform was initiated. The 2002 reform restructured the sector by separating the generation section from the grid, and tried to establish a market-determined on-grid pricing mechanism by encouraging competition among electricity generators. However, the attempt did not fully succeed, as the sector remained a planning-dominated system. The new investment should be approved by the local government, the electricity generation amount was allocated by the local government, and the prices (benchmark on-grid electricity tariff) received by the generators were predetermined on a provincial basis. More detailed description of this round of electricity market reform is discussed in Yeh and Lewis (2004) and Ma and He (2008).

Regulatory fragmentation across provinces has long been another feature of China's electricity system (Qi et al., 2019). Due to the long history of electricity shortages, China's electricity supply and demand was first balanced within the provinces. Provinces have traditionally been reluctant to increase imports from other provinces, unless facing a shortage, so as to protect their local generators. This is also related to the longstanding observation of inter-provincial barriers arising from local protectionism in China's provincial market (Naughton, 2003; Poncet, 2003; Wei and Zheng, 2017; Young, 2000; Zhou, 2004).

Similar to geographically diverse countries or regions like the US and the EU, vast disparities exist among Chinese provinces in terms of economic development, energy resource distribution, and load demand. Clean energy sources, such as hydropower and wind/solar resources, are abundant in the southwestern and northern regions that are economically less developed. Against this background, inter-provincial electricity trades had been implemented as part of top–down energy strategies (such as the Three Gorges Dam and the west-to-east and north-to-south electricity corridor projects) to fulfill multiple goals, including ensuring energy security, environmental protection, as well as offering a way to make provincial transfers from coastal provinces to western provinces to reduce economic inequity (Wei et al., 2020).[1]

In 2015, China inaugurated a new round of reform, its goal was to increase the market-based allocation mechanism's role in the electricity generation and retail segments and to improve the regulation of distribution and transmission. The reform so far has achieved progress toward the marketization goal. The share of market-based electricity transactions in total electricity consumption has increased from 13% in 2015 to 39% in 2019 (Fig. 1). However, the process is still far from establishing an efficient market due to both the common reform obstacles from international experiences and the unique obstacles from China's institutional context. Several papers have provided a comprehensive review on the process and potential pitfalls (Lin et al., 2019b; Davidson and Pérez-Arriaga, 2020).

A critical step moving forward for China's electricity market reform is to achieve market integration among different provinces. Drawing lessons from the failure of the 2002 reform, a strategy of this round of reform is to start from provincial markets to incentivize local governments to gain reform momentum. Provincial governments are responsible for market reform, while the central government provides only broad guidelines (Zhang et al., 2018; Pollitt et al., 2017). This can lead to a striking amount of diversity in the market designs (Davidson and Pérez-Arriaga, 2020) and more difficulties in market integration.

Fig. 1 shows that inter-provincial planning-based electricity accounted for more than 70% of the inter-provincial flow by 2019, indicating that the vast majority of the electricity trading among different provinces is still determined by the government. Both the volumes and the prices were set through central administrative planning and provincial government negotiation, which did not realistically reflect supply and demand. Moreover, reforming the rigid planning and fragmented electricity system has been considered the main hindrance to the integration of renewable energy in China (Lema and Ruby, 2007).

Note: Data are collected from the "Power Exchange Annual Report" published by the State Grid Corporation of China. The total electricity transaction is equal to the total consumption.

3. Methodology

3.1. Conceptual framework

To evaluate the impact of reforming and integrating China's electricity sector, three scenarios are first defined based on the potential reform process of China's electricity system. The first scenario is a planning scenario, which represents a counter-factual non-reform scenario for comparison. The second one is a provincial market scenario, in which only the provincial market is established, and the inter-provincial trades are still determined by the government. The third one is a regional market scenario, in which both provincial generation and the inter-provincial trades are determined by a regional market. With the definition of these three scenarios, the conceptual framework of estimating the reform impacts is shown in Fig. 2.

In the two market scenarios, we assume a perfectly competitive partial market equilibrium model with inelastic demand. The hourly demand is supplied by minimizing the generation costs subjected to physical constraints (e.g., generation capacity, transmission limits, and reserve capacity requirement), as well as different market institutional arrangements. Thus, we can simulate the market clearing prices, the inter-provincial import and export, and the generation mix structure under different market designs. Based on these results, the welfare impacts (both the overall impacts and the redistribution impacts) and the carbon emission impacts could be obtained and compared with the planning scenario.

The time horizon of the analysis is confined to the year of 2018, which implies that the impact assessment is a short-run analysis mainly arising from the gains from eliminating the inter-generator production inefficiency. The long-run efficiency improvement involves investment decisions, which are not considered in this study. This analysis is also a partial equilibrium model, and the impact assessment is confined to the electricity sector itself. The feedback effects from the broader economic system are not considered either.

3.2. Scenario definition

3.2.1. Planning scenario

The starting point of China's electricity sector reform is a central planning system, in which the price and production quantity of each generator are determined by the government. In contrast with the practices in many developed countries, generation dispatch in China can be characterized as equity-based rather than efficiency-based (Kahrl et al., 2013; Zhong et al., 2015; Ho et al., 2017). Generators with similar capacity are assigned similar generation hours on an annual basis. The benchmark on-grid tariffs are based on the average costs of coal-fired power generation, which are province-specific and determined by the performance of advanced generation units in every province. The inefficiency is obvious, since the higher efficiency generators may have similar or even lower operating hours compared with the lower efficiency generators, as shown in Fig. 3. The inefficiency of the central-planning production-allocation mechanism has been analyzed by several previous studies (Chen et al., 2016; Ma and Zhao, 2015; Wei et al., 2018).

In the planning scenario, inter-provincial trades occur as they currently do in reality. The trades are scheduled annually with negotiated fixed prices and quantities, and they are implemented on an average daily basis.

3.2.2. Provincial market scenario

This scenario is similar to what is currently occurring in the five southern provinces. In this scenario, we assume that each province creates their own electricity market and the inter-provincial trade is predetermined. Each province has its own system operator to dispatch the generators, on the basis of a market competition mechanism, to meet the residual demand while considering the predetermined inter-provincial trade. These inter-provincial trades are assumed to be the same as that in the planning scenario, which come from the annual governmental contracts with fixed prices and quantities. Trade flows are counted either as price inelastic supply (imports) or as price inelastic demand (exports).

3.2.3. Regional market scenario

In this scenario, we assume that the wholesale markets of the five southern provinces are integrated into one market in which there is one system operator to balance the instantaneous demand and supply within the five provinces. The distinction between the regional market and the provincial market is that the inter-provincial trade is not planned ahead but determined by the market. The production of generators in all the provinces should meet the aggregated demand based on a regional merit order, but is subjected to the transmission capacity constraints. Inter-provincial trade flows from the high-price provinces to the low-price

[1] The important electricity corridor projects include the Three Gorges Dam transmission project and the West-to-East transmission project and the North-to-South transmission project.

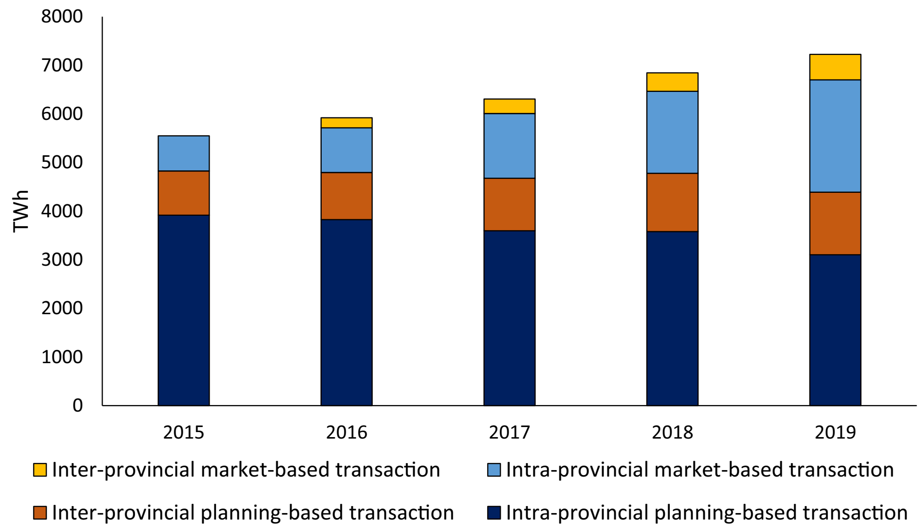


Fig. 1. China's Electricity Transaction from 2015 to 2019.

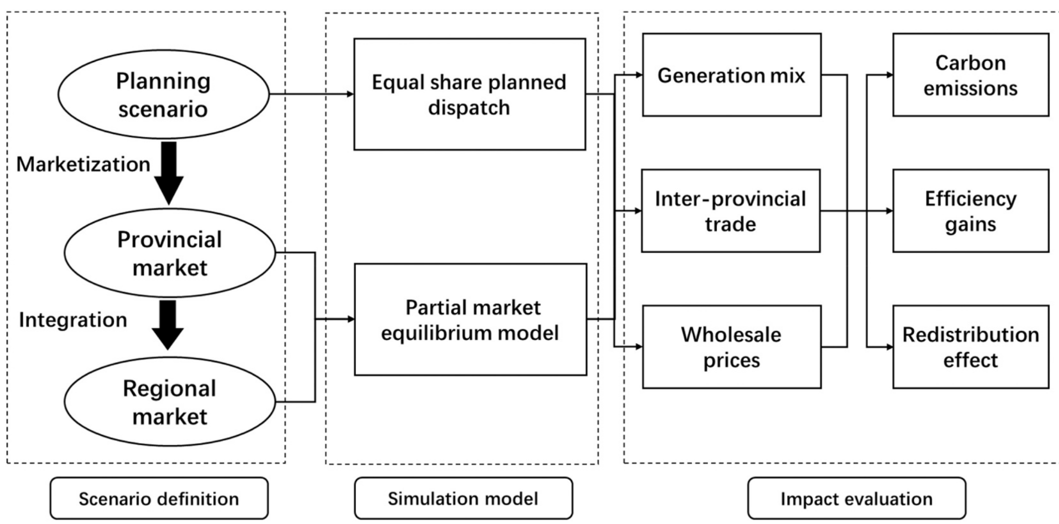


Fig. 2. Research Framework.

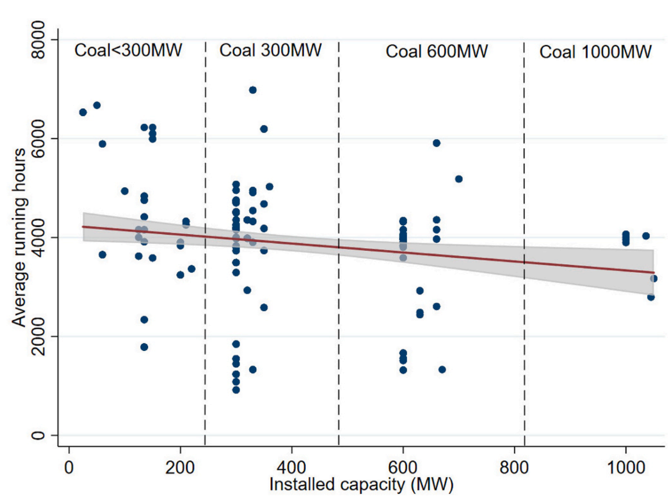


Fig. 3. Installed Capacity and Average Running Hours of Coal-Fired Units in the Five Provinces in 2015.

provinces, implying that a uniform price is cleared based on the marginal unit when the transmission lines among provinces are not congested. However, the clearing prices will be based on the marginal generating units in each province when the transmission line between two provinces reaches the upper limit and congestion occurs.

3.3. Impacts evaluation model

3.3.1. Impacts from the planning scenario to the provincial market scenario

Fig. 4 illustrates the impacts of the marketization reform in terms of price, efficiency improvements, and social surplus redistribution. Assuming that the market mechanism functions perfectly, it will lead to a least-cost supply curve and minimize the total generation cost. The short-term electricity market is typically cleared and settled using market clearing prices, which are based on the marginal cost of the generator dispatched to meet the next incremental demand. Provincial markets can improve the allocation efficiency by eliminating the inter-generator allocation inefficiency within a province. By reallocating power generation to more efficient generators, the supply curve would shift down from S_1 to S_2, and the new equilibrium price would decrease from P_1 to P_2 given an elastic short-term demand. The generation mix would also change in favor of more efficient generators. The overall

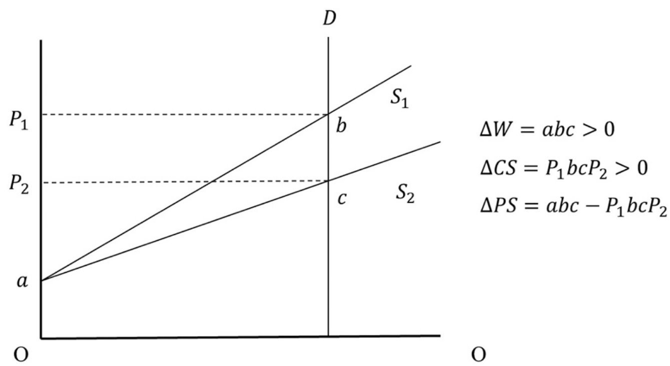


Fig. 4. Welfare Changes from Market Reform.

impact on carbon emissions could also be estimated by comparing the changes in the generation mix.

Comparing the equilibrium results of the two scenarios, we can quantify the changes in social welfare. The assessment is straightforward by comparing the areas under the supply and demand curves in Fig. 4. The overall change in social surplus would increase by the size of abc coming from the efficiency improvement. At the same time, the distributional effect happens among consumers and producers. Producer surplus changes in two opposite directions simultaneously. On the one hand, the declined price from P_1 to P_2 brings a decrease in the producer surplus by P_1bcP_2, which is the same amount of increase in the consumer surplus (rent transfer). On the other hand, the producer surplus increases by savings in the production cost. The total social surplus is obtained by adding producer surplus and consumer surplus.

3.3.2. Impacts from the provincial market scenario to the regional market scenario

Fig. 5 shows the effects of market integration as the price of Province A increases from P_a to P_u, and the price of Province B decreases from P_b to P_u. The impact of market integration on regional average prices is ambiguous, depending on the relative elasticity of the supply curve between importing and exporting provinces. Generally speaking, a more elastic supply curve will lead to a larger price change given the same trading quantity. Therefore, if compared with exporting provinces, the supply curve of importing provinces is more elastic, the market integration may lead to an increase in the regional average price.

In terms of impacts on social welfare, trade theory suggests that a well-functioning market results in inter-trade flows that improve overall efficiency and maximize the sum of the social welfare of all trading provinces. Total welfare would increase by the area of *cef*. It can also lead to distributional effects among the provinces. Their consumer surplus drops by P_udeP_a and increases by P_ubcP_b, respectively. Since the power generation of Province A replaces the generation of B, the producer surplus in Province A increases by P_ufeP_a, while it decreases by P_ufcP_b in Province B.

In sum, the theoretical analysis suggests that the reform toward marketization and integration would improve social welfare because the generation allocation is optimized, and welfare is redistributed among producers and consumers and among the provinces. The size of the efficiency improvement and redistribution effect depends on the following factors: (i) the level of production distortion due to planning (both within a province and inter-province); (ii) cross-provincial differences in marginal generation costs; and (iii) the demand correlation among the provinces.

4. Simulation model and data

4.1. Model

Market competition results in a cost-minimizing supply curve. In the provincial market scenario, technology-specific marginal costs and installed generation capacities define the supply curve for domestically produced electricity in each province. Hourly equilibrium prices for electricity in each province are determined by the available capacity of the least-cost technology to meet demand in this hour, that is, the "price setting" or "marginal" technology.

In the regional market scenario, the generation capacity and demand are pooled together to form the aggregated supply curve and the aggregated demand curve at the regional level. Hourly equilibrium prices for electricity are determined by the marginal technology at the regional level, subjected to the constraint of a transmission capacity limit. A detailed description of the market equilibrium is provided in the Appendix.

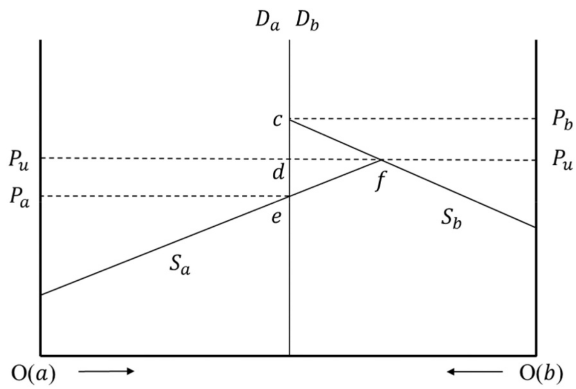
4.2. Study region and data

This study uses a unique dataset that features detailed hourly information on electricity demand, production, and inter-provincial trade in China's southern five provinces for the year 2018. The five provinces are Guangdong, Guangxi, Yunnan, Guizhou, and Hainan, which together account for 19.2% of the total Chinese population and 16.9% of the nation's total GDP. In 2018, electricity consumption in this region was about 1163 TWh, which is similar to the total consumption of Russia and more than the total combined consumption of Central and Southern America.

Data are collected from various sources. The hourly data of provincial electricity demand are obtained from the South China Energy Regulatory Office of the National Energy Administration. The installed capacity and coal consumption of each generation unit and the transmission line capacities are collected from the 2018 Annual Dispatch Report of Southern Power Grid. Information on electricity prices, coal prices, and gas prices are collected from the National Development and Reform Commission, and marginal costs are calculated from fuel costs. The details of the data set are provided in the Appendix.

Fig. 6 shows the distribution of hourly electricity demand in 2018 for each province, alongside the marginal technology that would be used in a given hour assuming that domestic demand would have to be met entirely by domestic production. The horizontal axis plots cumulative capacity or demand (both in GW). It gives a first idea of the cross-province differences in marginal generation costs, as determined by the size and technology type of installed production capacities and electricity demand. There exist sizable cross-province differences, because the technology mix of production capacities and ensuing fuel and generation mixes vary across provinces. For example, Yunnan covers its average demand by relatively cheap hydro generators, whereas Guangdong uses more expensive gas generators. As to the average annual demand, all provinces are excessive in the installed generation capacities, ranging from 56% to 375%. Regarding the peak demand, Guangdong is the only province in which demand cannot be met domestically during a small number of hours over the year. In addition, the shape of the hourly load distribution varies considerably across provinces, which means that hourly demands are weakly correlated across provinces.

The actual generation in each province, as well as the inter-provincial trade in 2018, is shown in Fig. 7. Existing inter-provincial trades belong to the "West to East Power Transmission Project," which is part of the "Go West" national development strategic initiative to boost the development in the western region of China. Under the arrangement, Yunnan and Guizhou are the exporting provinces due to their abundant hydropower and coal, while Guangxi and Guangdong are the importing provinces. Being the largest and most developed economy in this region, Guangdong accounts for about 98% of annual electricity imports.



$$\Delta W_a = def > 0 \qquad \Delta W_b = cdf > 0$$

$$\Delta CS_a = -P_u de P_a < 0 \qquad \Delta CS_b = P_u dc P_b > 0$$

$$\Delta PS_a = P_u fe P_a > 0 \qquad \Delta PS_b = -P_u fc P_b < 0$$

$$\Delta W_a + \Delta W_b = cef$$

Fig. 5. Welfare Changes from Market Integration.

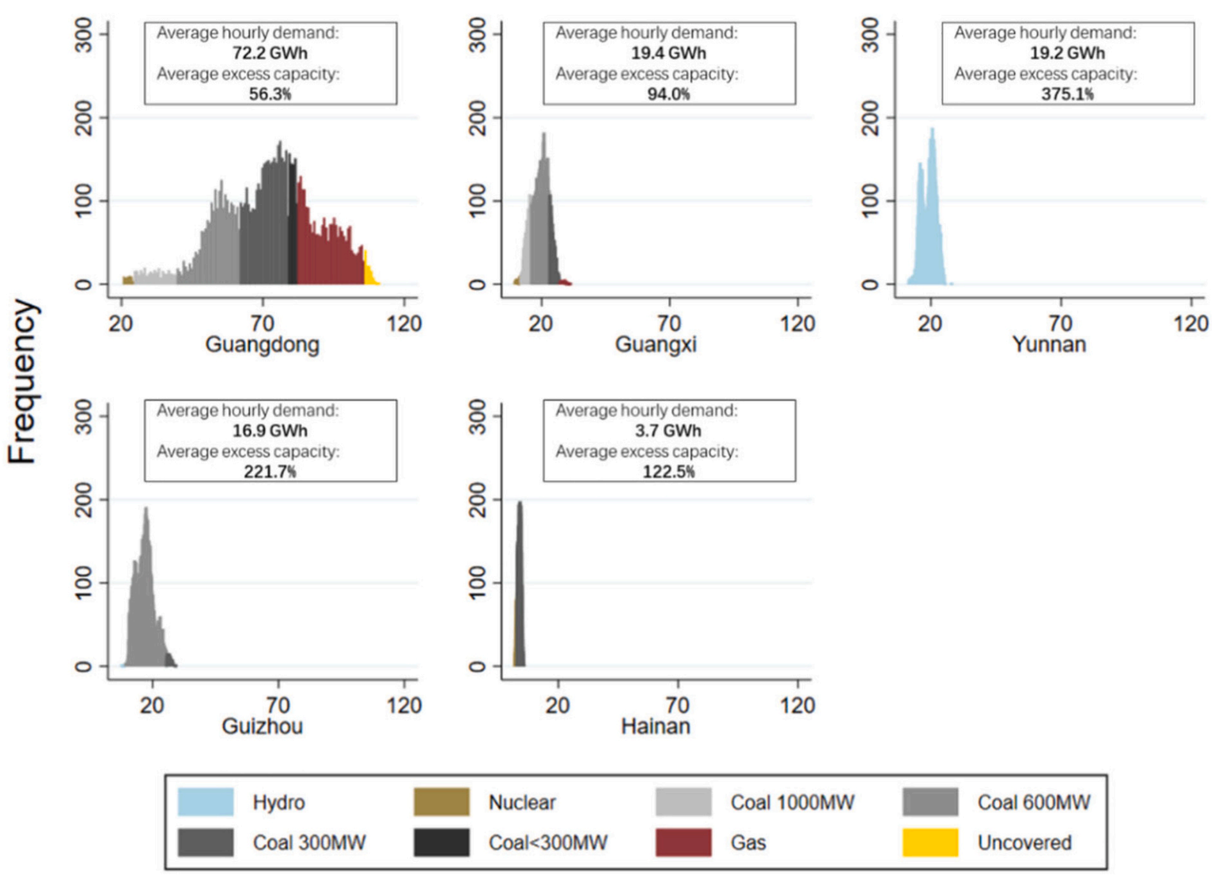


Fig. 6. Frequency Distribution of Hourly Electricity Demand.
Note: All numbers are in GWh; average excess capacity is calculated relative to annual average demand.

5. Results analysis and discussions

In this section, we first report the simulated results of electricity market reform and integration in the five southern provinces in China, including changes in the generation mix on the supply side. We then show the reform impacts on the wholesale electricity prices and the total amount of carbon emissions. Finally, we present the impacts on welfare that achieved from regional market reform and integration.

5.1. Impacts on the generation mix and supply structure

The power system operation results are simulated to analyze the effect of different electricity market scenarios on the supply structure. Consistent with previous theoretical analysis, introducing the market competition into the electricity system will improve economic efficiency by optimizing the generation structure. The generation from high-cost generators would be substituted by low-cost generators through market reforms.

Table 1 shows the changes in the generation structure at the regional level. The share of natural gas generation decreases from 4.6% in the planning scenario to around 1.1% in the provincial market scenario, and the share can be further reduced to 0.05% in the regional market scenario. The reduction in natural gas generation would be replaced by hydropower and coal-fired generation. The share of hydropower would increase from 34.0% in the planning scenario to 34.8% in the provincial market scenario, and further to 35.5% in the regional market scenario.

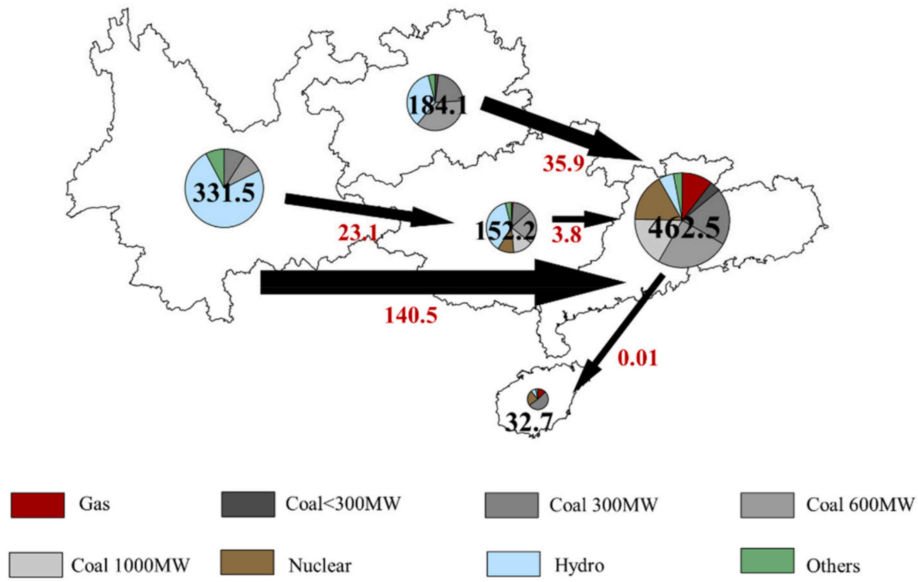


Fig. 7. Power Generation and Trade in the Planning Scenario.
Notes: All numbers are in TWh; "Others" is the sum of wind power, solar power, and biomass energy.

Table 1
Production by Technologies in Different Scenarios.

	Planning scenario		Provincial market		Regional market	
	Production (TWh)	Share	Production (TWh)	Share	Production (TWh)	Share
Others	54.2	4.7%	54.2	4.7%	54.2	4.7%
Hydro	395.2	34.0%	404.7	34.8%	412.6	35.5%
Nuclear	100.0	8.6%	100.0	8.6%	100.0	8.6%
Coal 1000 MW	98.1	8.4%	155.6	13.4%	156.9	13.5%
Coal 600 MW	245.4	21.1%	308.9	26.6%	284.0	24.4%
Coal 300 MW	195.5	16.8%	118.1	10.2%	140.6	12.1%
Coal < 300 MW	20.4	1.8%	8.2	0.7%	12.7	1.1%
Gas	54.0	4.6%	13.1	1.1%	0.5	0.05%

Notes: Others is the sum of wind power, solar power, and biomass energy.

This implies that the problem of hydropower curtailment can be alleviated through market reform and regional integration.[2] Structural optimization also occurs within coal-fire power as high-efficiency coal generators replace low-efficiency generators.

Although the regional market can achieve a more optimized generation mix, it reallocates both the provincial electricity generation of different provinces and the inter-provincial electricity trades. Fig. 8 presents the simulated results of the provincial electricity production and inter-provincial trades in the two market scenarios. The most notable result is that the regional market leads to a decrease in the trade flow among the provinces. At the regional level, the inter-provincial trade decreases by 34.9 TWh (17.2%). The domestic generation in Guangdong and Guangxi replace imported electricity from Yunnan and Guizhou. The results indicate that the existing planning-based inter-provincial trades are higher than the amount determined by the economically efficient criteria.

Notes: All numbers are in TWh. "Others" is the sum of wind power, solar power, and biomass energy.

[2] The share of hydropower curtailment in Yunnan province decreases from 6.6% in the planning scenario to 3.0% in the provincial market scenario to 0.05% in the regional market scenario.

5.2. Impacts on wholesale prices

Table 2 shows the impacts of market reform on the annual average electricity prices in different scenarios. As expected, changing the power system operation from planned dispatch to market competition will result in lower electricity prices. At the regional level, the wholesale price is reduced from 442.7 yuan/MWh in the benchmark planning scenario to 338.7 yuan/MWh (a reduction of 23.5%) in the provincial market scenario and to 342.1 yuan/MWh (a reduction of 22.7%) in the regional market scenario.

Although all the provinces have price declines in both two market scenarios, the sizes of the price reduction depend on the existing mix of generation technologies, the capacity surplus, as well as the inter-provincial trade design. Yunnan and Guizhou have lower prices in all scenarios due to its higher penetration of cheap hydropower and more excess generation capacity. In the provincial market scenario, Yunnan's prices decrease by the largest share (46.1%), followed by Hainan (27.4%), Guizhou (27.0%), Guangxi (17.5%), and Guangdong (17.2%). Under the regional market scenario, market integration drives the price to converge. Therefore, Guangdong, as the only net electricity importing province, would enjoy a further price reduction (from 17.2% to 24.9%), while all the other electricity exporting provinces would not enjoy the same price reduction as that in the provincial market scenario. Note that the regional average price in the regional market is higher than that in the provincial market. This is because the supply curve in Guangdong is more elastic than that in other provinces, market integration has a

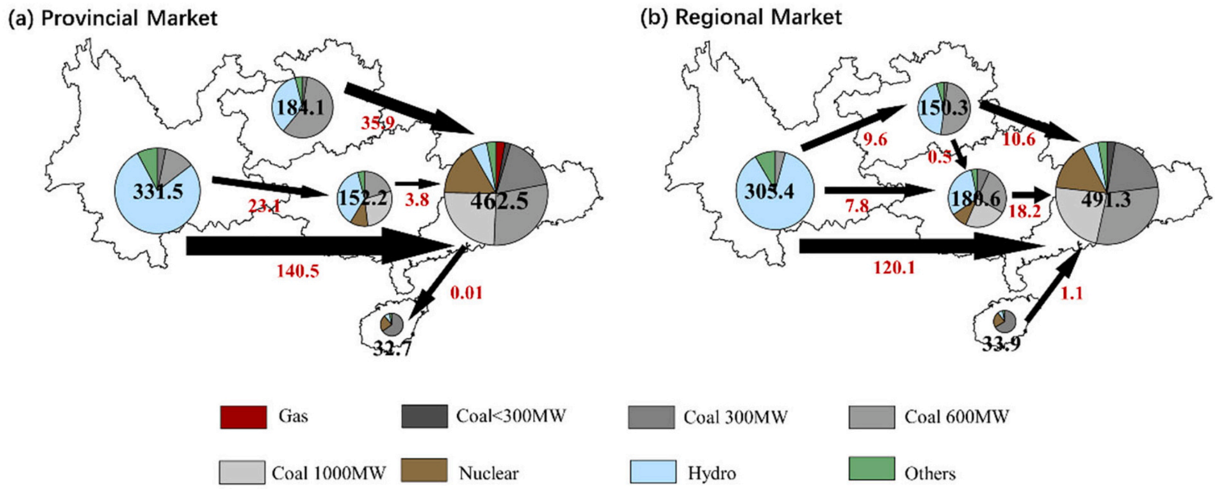


Fig. 8. Power Generation and Trade in Different Scenarios.

Table 2
Price Statistics in Different Provinces.

	Guangdong	Guangxi	Yunnan	Guizhou	Hainan	Regional
Planning scenario:						
Average price (yuan/MWh)	472.4	460.4	259.1	327.2	543.6	442.7
Provincial market:						
Average price (yuan/MWh)	391.4 (−17.2%)	379.8 (−17.5%)	139.8 (−46.1%)	238.9 (−27.0%)	394.7 (−27.4%)	338.7 (−23.5%)
Price standard deviation	44.5	18.4	83.7	5.4	106.5	47.8
Value at Risk (95%)	−0.15	−0.09	−0.93	−0.01	−0.43	−0.35
Regional market:						
Average price (yuan/MWh)	354.8 (−24.9%)	442.4 (−3.9%)	172.6 (−33.4%)	277.8 (−15.1%)	401.9 (−26.1%)	342.1 (−22.7%)
Price standard deviation	42.6	42.6	54.0	42.6	42.6	45.6
Value at Risk (95%)	−0.12	−0.12	−0.42	−0.12	−0.12	−0.20

Note: average price equals electricity bill divided by electricity consumption; the price reduction compared to the planning scenario is reported in parentheses; the value at risk is calculated by the variance-covariance method and the confidence level is 95%.

weaker effect on the price decrease in Guangdong than on the increase in prices in other provinces.

Apart from the lower electricity prices, electricity market reforms would also increase the price fluctuation risk. Compared with the fixed benchmark prices, the market clearing prices vary both temporally and spatially, which would inevitably expose the market participants to the risk of price fluctuations. Table 3 also reports the volatility and risk of wholesale market prices, including the VaR (Value at Risk) values. Since the equilibrium price is mainly determined within each province in the provincial market, the risk levels of provincial electricity markets vary across provinces due to market segmentation. In contrast, the regional market can reduce risk by permitting a higher level of risk sharing between provinces, leading to a lower regional price variance and risk.

5.3. Impacts on carbon emissions

Market reform can also affect environmental externality by changing the electricity structure. Table 3 shows the provincial CO_2 emissions of different market design scenarios in 2018. Due to the decreasing curtailment of hydropower and the more efficient dispatch of coal-powered generators, the total carbon emissions of the Southern Grid region would be reduced in the two market scenarios. Compared with the planning scenario, the total amount of carbon emissions is reduced by 12.4 million tons (2.4%) in the provincial market scenario, while the

Table 3
Carbon Emissions of Different Market Design.

	Guangdong	Guangxi	Yunnan	Guizhou	Hainan	Total
Planning scenario:						
Emission (million ton)	282.4	61.2	52.0	98.0	16.2	509.8
Share	55.4%	12.0%	10.2%	19.2%	3.2%	
Provincial market:						
Emission (million ton)	283.9	59.6	41.7	94.4	17.7	497.4
Share	57.1%	12.0%	8.4%	19.0%	3.6%	
Change	0.5%	−2.6%	−19.8%	−3.7%	9.6%	−2.4%
Regional market:						
Emission (million ton)	312.1	84.1	12.4	65.8	18.8	493.2
Share	63.3%	17.0%	2.5%	13.3%	3.8%	
Change	10.5%	37.3%	−76.1%	−32.9%	16.4%	−3.2%

Notes: The change rates are calculated in comparison with the planning scenario.

declines are 16.6 million tons (3.2%) under the regional market scenario.

Moreover, the impact of market reforms on CO_2 emissions varies substantially across different market scenarios, and they are consistent with the changes in their generation quantity and structure. Under the provincial market scenario, the variations across provinces are mainly driven by the changes in the generation structure. The substitution of expensive gas generation by cheap coal generation results in a slight increase in carbon emissions for Hainan (1.5 million tons, 9.6%) and Guangdong (1.5 million tons, 0.5%). Similarly, the substitution of low-efficiency coal-fired generation by hydropower and high-efficiency coal-fired generation will result in a decrease in carbon emissions in Yunnan (10.3 million tons, 19.8%), Guangxi (1.6 million tons, 2.6%), and Guizhou (3.6 million tons, 3.7%). Under the regional market scenario, the carbon emissions from Guangxi, Hainan, and Guangdong would increase further because their internal electricity would increase with their hydropower imports being replaced by coal generation. In contrast, the emissions in Guizhou and Yunnan would be reduced due to less coal-fired generation.

5.4. Impacts on social welfare

This section analyses the impacts of electricity market reform on social welfare based on the welfare analysis methodology established in Section 3. Table 4 presents the impact on welfare in each scenario for the year of 2018, which includes both the total welfare amount and its distributional effects.

As expected, marketization and integration can improve social welfare and reduce power generation costs, which is consistent with the findings of other studies (Wei et al., 2018; Abhyankar et al., 2020; Chen et al., 2020). At the regional level, establishing a provincial market would increase the total social surplus by 14.3 billion yuan a year (or by a share of 5.7%), which is equal to the generation cost savings. The regional market can add 6.7 billion yuan to its total surplus by optimizing inter-provincial trade flows. In addition, cost savings are higher than emissions reductions in the two market scenarios. This is because marketization and integration reduce the share of costly but low-emission gas power generation.

Market reform also results in a rent shift from the producers to the consumers, as demonstrated by the changes in producer surplus and consumer surplus (see Table 4). Consumers in all provinces benefit from market reform because they will enjoy lower prices. The rent shift from producers to consumers contributes to the majority of the increase in consumer surplus. Among the producers, the gas-fired generators in Guangdong and the coal-fired generators in Yunnan would be hit the hardest, as their productions would be replaced by cheaper generation technologies.

There are differences in the impact on welfare at the provincial level between the two market scenarios. Every province benefits from establishing a provincial market because their domestic production remains unchanged while the generation structure becomes more economically efficient. However, by reallocating the inter-provincial trades, the regional market creates winners and losers among different provinces. Compared with the provincial market scenario, the welfare gains will decrease in the original electricity importing provinces (i.e., Guangdong, Guangxi, and Hainan). This is because they have to replace the cheaper imported electricity from Yunnan and Guizhou with more expensive electricity generated by their own generators. Guangxi would become the absolute loser since its net social surplus becomes negative. In contrast, the social surplus of Yunnan and Guizhou increases substantially by retaining cheap electricity for their domestic consumers.

Although the regional market can bring more efficiency gains, it also results in an uneven distribution of the efficiency gains among different provinces. The distribution equity level of the efficiency gains among different provinces could be illustrated by the Gini coefficients, which measure the distribution of social surplus improvement relative to the electricity demand among provinces. Fig. 9 shows that the provincial market performs much better than the regional market in terms of the equity criteria.

6. Discussion and conclusion

6.1. Summary of findings

In this paper we conduct an *ex-ante* quantitative analysis to evaluate the economic and environmental impacts of the market-oriented reform and integration of Chinese provincial electricity system. The power system operation results under two potential market scenarios (provincial market and regional market) are compared with that under the planning scenario. As expected, replacing governmental planning with market competition can eliminate generation inefficiency by reallocating the production from higher-cost generators to lower-cost competitors, thus resulting in wholesale price declines, carbon emission reductions, generation cost savings and welfare improvements.

Based on data from five provinces in the southern China, we estimate these potential benefits. Compared with fixed on-grid tariffs in the benchmark planning scenario, the wholesale price could be reduced to 338.7–342.1 yuan/MWh (i.e., by more than 20%) in the market scenarios. Independent provincial markets coupled with government-based inter-provincial trades can reduce the generation costs by 14.3 billion yuan per year (5.7% of the total cost), which is the same amount of the increase in total social surplus. Creating a regional market, in which inter-provincial trade and domestic production are optimized simultaneously, can bring an additional cost reduction (total surplus) of 6.7 billion yuan. Carbon emissions are reduced by 12.4 million tons (2.4%) and 16.6 million tons (3.2%) in the provincial market scenario and regional market scenario, respectively.

Market reform can have asymmetric effects at the provincial level. Establishing provincial markets allows every province to become economically better off, but the regional market creates winners and losers among provinces by reallocating inter-provincial trades. In general, the total welfare decreases in the original electricity importing

Table 4
The social welfare analysis of market reform.

(billion yuan)	Guangdong	Guangxi	Yunnan	Guizhou	Hainan	Total
Provincial market:						
Total welfare impact	7.5	1.3	2.8	1.2	1.5	14.3
	(5.5%)	(4.2%)	(7.8%)	(3.2%)	(16.0%)	(5.7%)
Consumer surplus	50.1	10.7	39.6	16.2	4.2	120.8
Producer surplus	−42.6	−9.4	−36.8	−15.0	−2.7	−106.5
Regional market:						
Total welfare impact	3.3	−6.3	12.3	10.5	1.2	21.0
	(2.4%)	(−20.9%)	(34.0%)	(27.3%)	(12.7%)	(8.4%)
Consumer surplus	72.8	2.4	28.7	9.1	4.0	116.9
Producer surplus	−69.5	−8.7	−16.4	1.4	−2.8	−95.9

Notes: The cost savings compared to the planning scenario are reported in parentheses.

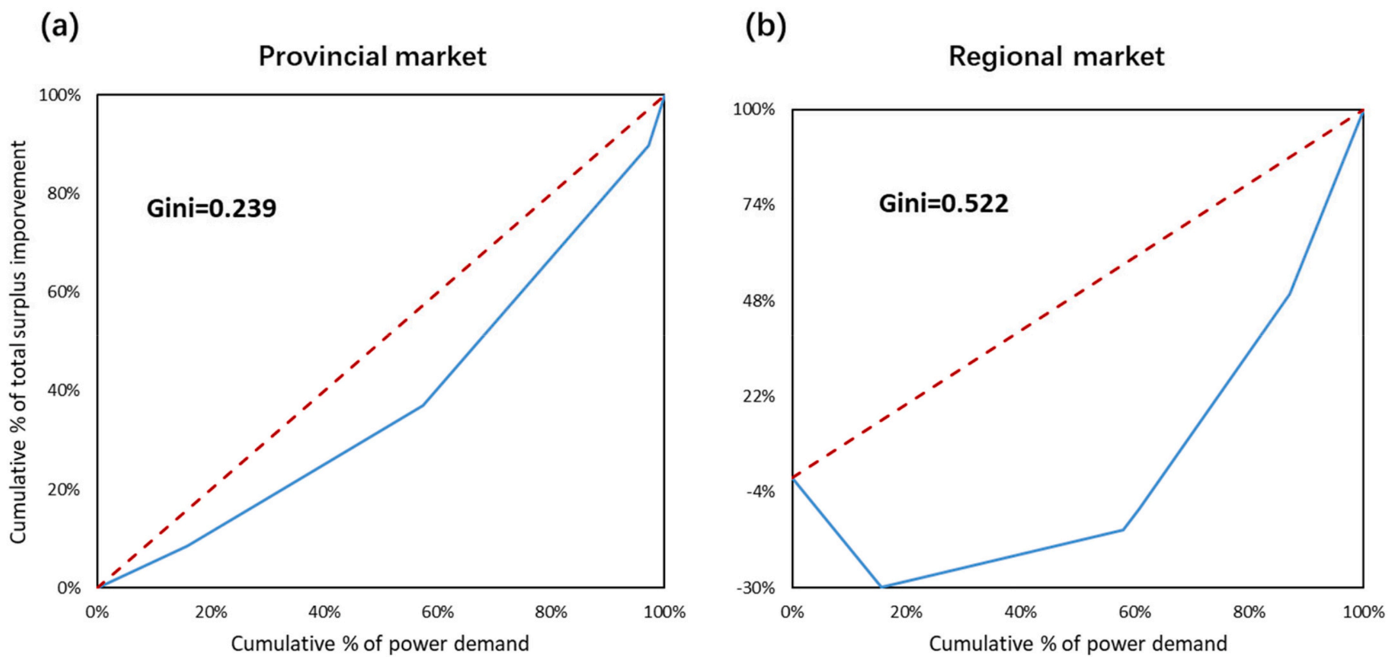


Fig. 9. Gini Value under the Two Market Designs.

provinces (i.e., Guangdong, Guangxi, and Hainan) because they have to replace the cheap imported electricity from Yunnan and Guizhou with more expensive electricity generation that is domestically produced. Guangxi becomes an absolute loser since its net social surplus becomes negative. In terms of carbon emissions, Guangdong and Hainan would experience increases in carbon emissions, while Yunnan and Guizhou would get decreases in carbon emissions under both market designs.

6.2. Policy implications on China's electricity sector reform

The results of this study could provide policymakers with scientifically sound measures to evaluate the pros and cons of different market designs and to create an informed roadmap of the market integration.

First, consistent with theories and international experiences, electricity market integration can provide substantial economic and environment benefits (Pollitt, 2019). Considering that our estimation only confines to a one-year period and limited geographic boundaries, establishing regional markets or even a national market in China is expected to realize much more benefits in the long run, especially to effectively support the achievement of China's carbon neutrality target. Power sector is the largest contributor to China's carbon emissions. Market integration across provinces can not only reduce more carbon emissions in the short term, but also promote the development of renewable energy in the long term (Chang and Li, 2015; Zhang et al., 2018). Moreover, the nationwide carbon emission trading market needs the cooperation of a more integrated electricity market to achieve more emission reductions. In a larger market, carbon pricing can promote the replacement of low-carbon intensity plants with high-carbon intensity plants across provinces, thereby amplifying the carbon pricing incentives for emission reduction.

Second, market integration in a larger geographic area with diverse institutional arrangements is also feasible based on international experience. Many countries have made great success to promote the integration of the electricity markets. Australia's national electricity market was established in 1998 in response to the liberalization of power sector (Nepal and Foster, 2016). With the European Commission's promotion of improving cross-border trading rules and expanding transmission capacity, almost all the markets of north-west Europe with 19 countries were coupled by 2015 (Jamasb and Pollitt, 2005; Geske et al., 2020). In the United States, there are also several well-functioning regional power markets and market integration mechanisms, such as Pennsylvania-New Jersey-Maryland (PJM) regional electricity market (Dempster et al., 2008). China has also made some progress in the construction of regional markets. Since 2015, China has established inter-provincial power trading centers to conduct mid-term and long-term trading of electricity between provinces. In 2021, inter-provincial power spot trading rules have been introduced by the government. The additional cost of establishing a regional market is the administrative cost to improve the regional market system, which is acceptable compared with the substantial efficiency improvement and emission reduction.

Third, moving from provincial markets to regional markets needs to address equity issue to overcome the inertia or reluctance of provincial governments. Thus far, the electricity markets in China have been designed and constructed by provincial governments in various ways (Davidson and Pérez-Arriaga, 2020). Due to the diversity in resource endowment and economic development, provinces may have different expectations for the electricity sector. Considering the key role local governments play in crafting and implementing the market reform, this uneven distribution of costs/benefits could be a factor hindering regional market establishment. There are several types of policies that can address the equity issue in establishing larger markets. Given that some provinces may suffer loss from phasing out low efficiency coal generators, inter-governmental transfer payment could be used to compensate their short-term losses. In addition, low efficiency coal generators may also have values for providing emergent capacity reserve. Thus, a regional capacity reserve compensation mechanism should be established, which could also help alleviate the equity problem. In the meantime, provincial market design standards should be imposed in order to maintain future integration compatibility.

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Availability of data and material

The datasets used during the current study are available from the corresponding author on reasonable request.

Code availability

The code used during the current study are available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Hao Chen: Validation, Writing – review & editing. **Jian Cui:** Methodology, Data curation, Formal analysis, Writing – original draft. **Feng Song:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

There are no conflicts of interest to declare.

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Appendix A. Appendix

A.1. Model

In this section, we will describe a partial market equilibrium model to simulate the Southern Grid operation at an hourly resolution in five provinces for the entire year of 2018.

Power generation: In a perfectly competitive market, electricity firms are assumed to bid their quantities at a marginal cost, where the electricity generation is the decision variable. Coal-fired power generation is operated at the unit level, and the generation units of other technologies are represented in an aggregated way. The total generation of the representative firm using technology $g \in G$ at hour $t \in [1, 8760]$ in province $i \in \{Guangdong, Guangxi, Yunnan, Guizhou, Hainan\}$ is denoted by $GEN_{t,\ i,\ g}$ with a marginal cost of $MC_{i,\ g}$. The set G comprises coal-fired, gas-fired, nuclear, hydro, wind, solar, and biomass plants. The production of different technologies at any time is constrained by installed capacity:

$$0 \le GEN_{t,i,g} \le \left(1 - loss_{t,i,g}\right) CAP_{i,g} \; g \epsilon \{coal, gas, nuclear\} \tag{A1}$$

$$0 \le GEN_{t,i,g} \le CAP_{i,g} CF_{t,i,g} \; g \epsilon \{hydro, wind, solar, biomass\} \tag{A2}$$

Where $CAP_{i,\ g}$ represents the installed capacity using technology g in province i. Due to the different generation feature, we divide the power generation constraints into stable output and variable output. Eq. (A1) represents the stable power generation capacity constraints for coal-fired, gas-fired, and nuclear units. $loss_{t,\ i,\ g}$ represents the loss rate calculated from the maintenance rate and the self-consumption rate. The production cannot exceed the power generation capacity after deducting technical losses. Eq. (A2) represents the variable power generation capacity constraints for hydro, wind, solar, and biomass units. $CF_{t,\ i,\ g}$ indicates the capacity factor, which is the maximum capacity utilization rate of the technology in each hour. Due to the intermittent and periodicity of their power generation technologies, production cannot exceed the installed capacity multiplied by the capacity factor.

Inter-provincial power trade: The trade flow $TRA_{t,\ i,\ j}$ from province i to province j at hour t is constrained by the transmission capacity $TL_{i,\ j}$ between the two provinces:

$$0 \le TRA_{t,i,j} \le TL_{i,j} \tag{A3}$$

In the provincial market, electricity trade is determined by the same inter-provincial contract as that in the planning scenario, but the inter-provincial trade would be liberalized in the regional market. In line with the idea of "iceberg transport cost" (Samuelson, 1954; Krugman, 1991) and the concept of line losses in electricity network models, the proportion of electricity lost in trade between provinces is $line_{i,\ j}$, and the unit transmission cost is $TC_{i,\ j}$.

Hourly electricity market balance: For province i, total power generation plus net imports is equal to demand at any given hour:

$$\sum_g GEN_{t,i,g} + \sum_j \left[TRA_{t,j,i}\left(1 - line_{j,i}\right) + TRA_{t,i,j}\right] = D_{t,i} \tag{A4}$$

Where $D_{t,\ i}$ is the demand of province i at hour t. We assume that the demand curve is completely inelastic in the short term.

Power dispatch: System operators implement economic dispatch to minimize total operating costs, including power generation costs and transmission costs:

$$min\ Cost = \sum_{t=1}^{8760} \sum_{i=1}^{5} \sum_g GEN_{t,i,g} MC_{i,g} + \sum_{t=1}^{8760} \sum_i \sum_j TRA_{t,i,j} TC_{i,j} \tag{A5}$$

where $Cost$ is the estimated total production cost of the China Southern Grid in 2018. Comparing the changes in production cost, we can calculate the potential total welfare gains from market reform and integration.

Market clearing price: Different from the exogenous benchmark electricity price under the planning scenario, the electricity prices under the two market scenarios are determined endogenously by the power dispatch model, and the clearing prices are equal to the marginal costs of the marginal generating unit in each hour. In the provincial market, prices are separately cleared in each province, and trade flows are paid at fixed inter-provincial contract prices. In the regional market, the market prices are uniformly cleared. As shown in Fig. A1 panel (a), when the transmission line between the two provinces is not congested, a uniform regional price P_u would be cleared based on the marginal generation units. When congestion occurs, as shown in panel (b), the power transmission between the two provinces reaches the upper limit, and consumers in the two provinces pay prices P'_a and

P'_b, respectively, based on their own marginal generating units.

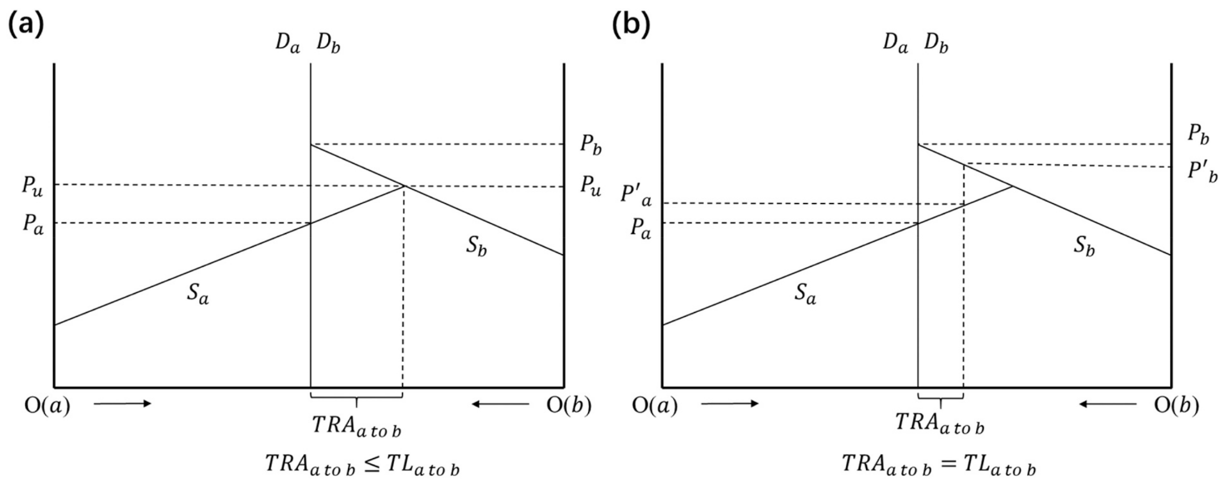

Fig. A1. Regional Market Price Clearing Mechanism.

A.2. Data

Hourly electricity load: The electricity loads in the five southern provinces are shown in Fig. A2.

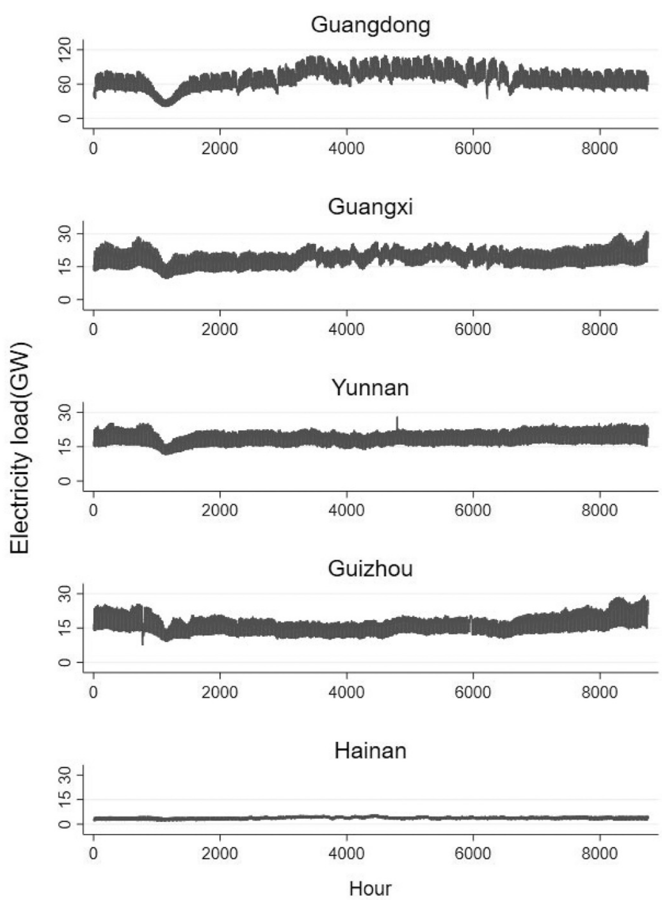

Fig. A2. Hourly Load Curves in 2018.

Installed capacity: The installed capacity by technology and province are reported in Table A1. For coal-fired power, unit-level technical parameter data, such as installed capacity and coal consumption, are listed in the 2018 Annual Dispatch Report of Southern Power Grid. According to the installed capacity, we divide the coal-fired units into four categories: 1000 MW, 600 MW, 300 MW and < 300 MW for reporting and comparison.

Table A1
Installed capacity of different technologies in 2018.

(GW)	Solar	Wind	Hydro	Nuclear	Coal 1000 MW	Coal 600 MW	Coal 300 MW	Coal <300 MW	Gas
Guangdong	5.27	3.57	9.19	13.30	15.17	22.25	17.19	3.26	23.62
Guangxi	1.24	2.08	16.75	2.17	4.09	7.09	3.96	0.00	0.33
Yunnan	3.43	8.57	66.66	0.00	0.00	6.00	6.40	0.00	0.00
Guizhou	1.78	3.86	22.12	0.00	0.00	16.23	9.60	0.84	0.00
Hainan	1.36	0.34	1.54	1.30	0.00	0.00	3.04	0.00	0.72

Fixed benchmark price: The benchmark Fixed-in-Tariffs prices of different technologies set by the National Development and Reform Commission are reported Table A2.

Table A2
Benchmark price of different technologies in 2018.

(yuan/kWh)	Solar	Wind	Hydro	Nuclear	Coal 1000 MW	Coal 600 MW	Coal 300 MW	Coal <300 MW	Gas
Guangdong	0.979	0.603	0.280	0.414	0.441	0.441	0.441	0.441	0.634
Guangxi	0.948	0.607	0.258	0.379	0.399	0.399	0.399	–	0.634
Yunnan	0.734	0.456	0.199	–	–	0.413	0.413	–	–
Guizhou	0.948	0.534	0.292	–	–	0.332	0.332	0.332	–
Hainan	0.443	0.607	0.408	0.429	–	–	0.438	–	0.658

Marginal cost: The marginal costs of different technologies are reported in Table A3. Since there is no official source for the marginal cost data of generation units, these data are estimated by ourselves in this study. For the coal-fired and gas-fired power units, we use fuel cost as a proxy for marginal cost. The coal consumption (gas consumption) at the unit level is collected from the Southern Power Grid 2018 Dispatch Annual Report. The coal price and gas price are set as 600 yuan/t and 2.7 yuan/m^3, respectively, which are the average fuel prices of coal and natural gas for the power sector in 2018, as published by the National Development and Reform Commission (NDRC). For the hydro and nuclear power units, we deduct the fixed cost from the levelized cost to estimate the marginal cost. The cost parameters are derived from the Renewable Power Generation Costs in 2018, published by the International Renewable Energy Agency (IRENA), and the Projected Costs of Generating Electricity, published by the International Energy Agency (IEA) and the Nuclear Energy Agency (NEA).

Table A3
Marginal Cost of Different Technologies.

(yuan/kWh)	Solar	Wind	Hydro	Nuclear	Coal 1000 MW	Coal 600 MW	Coal 300 MW	Coal <300 MW	Gas
Guangdong	0.000	0.000	0.074	0.172	0.265	0.288	0.297	0.338	0.436
Guangxi	0.000	0.000	0.074	0.172	0.273	0.287	0.305	–	0.615
Yunnan	0.000	0.000	0.074	–	–	0.292	0.322	–	–
Guizhou	0.000	0.000	0.074	–	–	0.291	0.310	0.349	–
Hainan	0.000	0.000	0.074	0.172	–	–	0.288	–	0.647

Inter-provincial transmission capacity: The inter-provincial electricity transmission capacities between the five provinces in 2018 are shown in Table A4. The transmission costs are reported in the parentheses, and the line loss rate is 5.51%, which is the average rate calculated from the Southern Power Grid 2018 Dispatch Annual Report.

Table A4
Inter-provincial Electricity Transmission Capacity in 2018.

(GW)		To				
		Guangdong	Guangxi	Yunnan	Guizhou	Hainan
From	Guangdong	0	0	0	0	2 (0.057)
	Guangxi	6.8 (0.057)	0	0	0	0
	Yunnan	31.6 (0.080)	3.2 (0.057)	0	3 (0.057)	0
	Guizhou	12 (0.080)	3.4 (0.057)	0	0	0
	Hainan	2 (0.057)	0	0	0	0

Notes: the transmission costs are reported in the parentheses and the unit is yuan/kWh.

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