Title

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Efficient market versus regulatory capture: a political economy assessment of power market reform in China

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Abstract: China began implementing market-based economic dispatch through power sector reform in 2015, but the reform has encountered some political and economic challenges. This paper identifies the reform's efficiency changes and explores and quantifies the influences of market-driven and politically driven mechanisms behind these changes, employing a partial market equilibrium model integrating high-frequency data in southern China. We found that the dispatch transition improves the overall efficiency, but regulatory capture in provincial markets limits its full potential. The preference for local enterprises over central state-owned enterprises (SOEs) by local governments, in the form of allocated generation quotas, demonstrates the political challenge for market reform. The allocated generation quota protects small coal-fired and natural gas generators owned by local SOEs, lessening their motivation to improve generation efficiency, even after the reform. As a result, nearly half of the potential carbon dioxide emission reduction and social welfare gains through market reform is not realized.

Keywords: Economic dispatch, Allocated generation, Regulatory capture, Efficiency gains

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1. Introduction

Over half of the world's coal was consumed by China in 2020, and 47.3% of China's coal was used in the power generation sector (Davidson et al., 2016; BP, 2021; National Bureau of Statistics [NBS], 2021). This coal-dominated power generation mix led to 4.4 billion tons of carbon emissions, accounting for 43.1% of the national total (Institute of Energy of Peking University, 2021). With the challenges of energy security and environmental sustainability, improving the power system's efficiency attracts wide attention from both the public and policy makers. Over a long period of time, thermal generators in China were dispatched in a planning-dominated way called "equal share dispatch," where generating units of a similar type and capacity were assigned an equal amount of annual operating hours, regardless of efficiency (Kahrl et al., 2011; Kahrl et al., 2013). Equal share dispatch has often been criticized for its inefficient use of polluting power plants (Dupuy, 2016; Pollitt et al., 2017). To render an improved efficiency and environmental outcome of power industry, China started a new round of power sector reform in 2015 and sought to introduce market mechanisms into operations by applying the economic dispatch approach (Gallagher et al., 2019). Under this approach, generators are dispatched based on the merit order of their generation costs, which encourages more efficient generators with lower fuel costs to produce more electricity (Steinberg and Smith, 1943; Lynch et al., 2013; Bistline, 2015; Hu and Cheng, 2017; Duan et al., 2022). Nikolakakis et al.(2017) found that the operational cost can be reduced by 76% with economic dispatch in the Bangladesh power sector. Abhyankar et al.(2020) also presented the emission reduction potential (10%) of the market-based dispatch system using data from the southern grid region of China.

However, in China's context, there are some political challenges in the process of reforming dispatch operations. Due to the long history of electricity shortages, China's power supply and demand are first balanced within the province, and local governments are responsible for formulating an annual generation plan and dispatching. Such arrangements can easily give rise to local protectionism (Naughton, 2000; Wei and Zheng, 2017). Power generators in China are owned by different types of enterprises, such as central state-owned enterprises (SOEs), local SOEs, local private enterprises, and other enterprises like Sino-foreign joint ventures. Unlike local generation enterprises whose generation income directly contributes to the local fiscal income, central SOEs are under the charge of State-owned Assets Supervision and Administration Commission of the State Council (SASAC), contributing to the central government. Therefore, local governments have incentives to protect local enterprises to guarantee local economic development and to enhance local leaders' political performance (Wei et al., 2018). Local enterprises also have the motivation to pursue greater influence over regulators in the province to gain favorable regulatory treatment, which is called *regulatory capture* (Stigler, 1971). This is a win-win game for local enterprises and regulators, and the central SOEs as a result are losing out.

Instead of thoroughly transforming from equal share dispatch to economic dispatch, the regulatory capture (or local protectionism) approach has led to a "semi-planned and semi-market" dispatch approach in China, where the in-plan generation is pre-allocated to generators by local governments and the out-of-plan generation is determined through market competition. At the end of each year, the local government makes the next year's generation guidance plan, allocating a certain amount of generation quota to generators in the province, which is similar to the planning scenario before the reform. The residual electricity demand is then met by generators under economic dispatch. We can also call this approach *economic dispatch with allocated generation.* At this point, the final efficiency gains of power market reform will be affected not only by market mechanisms but also by political factors. While many studies have confirmed the effectiveness of power market reform from the perspective of cost cutting, energy saving, and emission reduction (Zhong et al., 2015), they have not considered the underlying political impact. Further verification is required to identify the respective roles of the two forces in the reform.

In this study, we evaluated the reform effect with consideration of political economy problems using data at generating-unit level from the southern grid region in China (including Guangdong, Guangxi, Guizhou, Yunnan, and Hainan Provinces) during the period of 2010 to 2018, alongside the high-frequency data from Guangdong Province. We first identified the efficiency changes before and after the reform, providing a big picture view of the overall reform impact. Then, we explored the roles of market-driven and politically driven factors in efficiency improvement. Finally, we assessed the efficiency gains of the reform and quantified the influence of the two forces. To do this, we defined three provincial market scenarios corresponding to previous planning-dominated dispatch (equal share), current semi-planned and semi-market dispatch (economic dispatch with allocated generation), and ideal market-based dispatch (economic dispatch). We established a partial market equilibrium model to simulate electrical grid operations in different scenarios and compared the equilibrium outcome variables. We found that the introduction of market mechanisms improves overall efficiency, but the potential is not fully realized due to the local protectionism for local enterprises against central SOEs. The local government protects the small coal-fired and natural gas generators owned by local enterprises, especially local SOEs, through allocated generation dispatch, which constitutes the political challenge in achieving market potential. Nearly half of the potential of carbon dioxide (CO_2) emission reduction and social welfare gains that could have been achieved by economic dispatch falls through under the semi-planned and semi-market dispatch approach.

2. Model and data

2.1 Mechanism identification of efficiency change

We used a simple static panel model with fixed effects controlled to identify the efficiency change induced by the new round of power market reform as well as its driving factors, with a dataset at generating unit level during the period of 2010 to 2018. In this paper, we measure the coal-fired generator's efficiency by heat rate (in gce/kWh): the standard coal input used to generate a unit of salable electricity. Generally, a market-based dispatch system "arranges" the generation order according to the marginal costs of generators. And basically, it's the fuel cost which plays a decisive role, since labor costs are unobservable and variable operations and maintenance (O&M) costs only account for a small percentage, normally under 5% (Chen et al., 2020). Generators with lower heat rate consume less coal when producing a kWh of electricity. And as the power coal price in China is mainly decided by port price plus transportation cost, power plants in the same province with similar geographical locations will face similar coal purchase prices, which is also one of the important reasons why China introduced the mechanism of coal-electricity price linkage at the provincial level. Supplementary Figure 1 shows that the electricity coal prices in five provinces in southern China have the same trend. Therefore, in China's context where coal generators compete at provincial level, coal generators with lower heat rates could be approximately seen as having lower fuel costs and thus, higher efficiency in dispatching. Though not perfect, heat rate, as an efficiency indicator, is also a reasonable indicator of fuel as well as marginal costs. The practice of using heat rate as a representation for efficiency is also adopted in many studies such as Chan et al. (2014) and Li and Ho (2022).

After determining the efficiency indicator, we divided the whole sample into two periods, before and after 2015①, and made regression analysis respectively to identify the reform effect. We first regressed the operating hour on generator's heat rate to see the efficiency change after the reform, and then regressed the operating hour on capacity and ownership structure to explore the driving forces of the efficiency change. The regressions in

Table **3** and Table 4 are organized as equation (1) and (2):

$$Hour_{it} = \beta_1 Heatrate_{it} + \lambda_t + \alpha_p + \varepsilon_{it} \tag{1}$$

$$Hour_{it} = \beta_2 Cap_{it} + \gamma Owner_{it} + \lambda_t + \alpha_p + \varepsilon_{it} \tag{2}$$

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① According to the Southern Power Grid 2016 Dispatch Annual Report, some small coal-fired units in Guangdong still undertook the generation task during peak load in 2016, which distorts Guangdong's coal-fired generation dispatch in this year. To eliminate the confusion of this factor, we only include the data in 2017 and 2018 when making the post-reform analysis.

where $Hour_{it}$ is generator *i*'s operating hours in year *t*; $Heatrate_{it}$, Cap_{it} and $Owner_{it}$ are the heat rate, installed capacity and ownership structure of generator *i* in year *t*; λ_t is the time effect that does not change among individuals; α_p is the provincial effect that does not change with time; and ε_{it} is the independent error term.

We used data of coal-fired generators in the five provinces in southern China from 2010 to 2018. We accessed the dataset from the Southern Power Grid Dispatch Annual Report, issued by the Southern Power Grid Dispatching and Control Center. The Report presents the information of all coal-fired generators dispatched by the grid (except for generators in captive power plants), including generator's id, plant name, property owner, nameplate capacity, operating hour, generation, actual coal consumption per kWh, and standard coal consumption per kWh (heat rate), etc. We matched the ownership structure with the property owner, referring to the National Enterprise Credit Information Publicity System which is run by the State Administration for Market Regulation (SAMR) of China. The National Enterprise Credit Information Publicity System publicizes information on enterprises' name, ownership, legal representative and annual report, etc. We divided all the enterprises into four types: state-owned enterprises which are administered by the central government (central SOEs), state-owned enterprises which are administered by local governments (local SOEs), local private enterprises, and other enterprises like Sino-foreign joint ventures and Hongkong-Macao-Taiwan invested enterprises. We have a total of 2416 observations in the nine years, covering more than 90% of coal-fired generators in the southern grid region. Table 1 summarizes the variables in the regression, distinguishing between pre-reform and post-reform. It shows that the average heat rate decreases after the reform, while the average capacity increases. And as seen from Table 2, Guangdong has the largest market share, and generators with larger capacities or belonging to central SOEs always have higher efficiency (lower heat rate).

Table 1. Summary statistics of coal-fired generators in China's southern grid region before and after the reform

Period	Variable	Obs	Mean	Std. Dev.	Unit
Before the reform (2010-2015)	Operating hours	1392	4979.881	1269.258	h
	Heat rate	1430	317.943	50.398	gce/kWh
	Capacity	1581	360.242	227.428	MW
	Ownership structure	1581	1.786	.934	central SOEs=1, local SOEs=2, local private enterprises=3, other=4
After the reform (2016-2018)	Operating hours	795	3685.664	1363.689	
	Heat rate	805	309.016	26.053	
	Capacity	835	418.046	237.664	
	Ownership structure	835	1.668	.826	

Table 2. Capacity, average heat rate and quantity proportion of different types of generators in five provinces

2010-2018	**Capacity (gigawatt, GW)**				**Proportion of coal-fired generators with different ownership structure**			
	Coal 1000MW	Coal 600MW	Coal 300MW	Coal <300MW	Central SOEs	Local SOEs	Private Enterprises	Other Enterprises
Guangdong	105.05	182.91	136.88	47.26	21%	56%	13%	10%
Guangxi	20.63	56.78	31.48	7.21	50%	27%	7%	16%
Yunnan	0.00	49.20	54.30	4.98	90%	6%	3%	1%
Guizhou	0.00	95.19	84.31	19.26	82%	15%	2%	1%
Hainan	0.00	0.00	20.27	2.90	100%	0%	0%	0%
Average Heat Rate (gce/kWh)	281	300	311	345	307	317	326	337

2.2 Impact evaluation under scenario analysis

Three analysis scenarios are defined to estimate and compare the reform impacts under different dispatch rules. (1) *Planning scenario*: This is a counterfactual pre-reform scenario. It simulates the situation before the reform in which the price and production quantity of each generator are determined by the government. (2) *Economic dispatch with allocated generation scenario*: This is a simulation of the current dispatch in China. Part of the thermal power generation is allocated to generators by the local government, and the rest is dispatched through market competition. Renewable energy like wind and solar in this scenario is given priority to power generation and does not take part in market competition. (3) *Economic dispatch scenario*: This scenario stands for the market design where all generators (including coal-fired power, gas-fired power, hydropower, wind power, solar photovoltaic, nuclear, etc.) compete on marginal costs. Generators with lower costs are dispatched first, and the total operating costs can be minimized. All three scenarios are based on a provincial market.

For impact evaluation, we started from the economic dispatch scenario. A partial market equilibrium model was used to simulate the operation at an hourly resolution in Guangdong for the entire year of 2018. We call it equilibrium because in our constraints the power demand should equal the power supply. We call it partial equilibrium because we only consider one market (the power market) and assume that there is no change in other markets. Unlike the planning scenario, the economic dispatch scenario complies with the cost minimization rule. Generators are assumed to bid their quantities at marginal costs, and hourly equilibrium prices for electricity in the province are determined by the available capacity of the least-cost technology to meet demand in this hour. The objective function of economic dispatch can be expressed as in equation (3):

$$\textbf{min} \quad Cost = \sum_{t=1}^{8760} \sum_{g} GEN_{t,g} MC_{g} + \sum_{t=1}^{8760} \sum_{j} TRA_{t,j} TC_{j} \tag{3}$$

where $Cost$ is the estimated total operating cost of the power sector in Guangdong in 2018, including power generation costs and transmission costs; $GEN_{t,g}$ is the generation of technology $g \in \{coal\ 1000MW, coal\ 600MW, coal\ 300MW, coal\ {<}300MW, gas, nuclear, hydro, wind, solar, biomass\}$ at hour *t* in Guangdong; MC_g is technology g's marginal cost; $TRA_{t,j}$ is the trade flow between Guangdong and province $j \in \{\text{Guangxi}, \text{Yunnan}, \text{Guizhou}, \text{Hainan}\}$ at hour *t;* and TC_j is the transmission cost per unit. Since we focused on the provincial market, the interprovincial trades were assumed to be the same as they currently are in reality, planned ahead by the annual governmental contracts with negotiated fixed prices and quantities.

Equations (4) to (6) list some constraints for the objective function. First, the trade flow between Guangdong and province *j* cannot exceed the transmission capacity TL_j between the two provinces. Second, the production of different technologies g is constrained by installed capacity. As equation (5) shows, for stable power such as coal, gas, and nuclear, which are able to run all day, the generation at hour *t* is constrained by the power generation capacity CAP_g after deducting technical losses $loss_{t,g}$; for variable power such as hydro, wind, solar, and biomass, which are unable to operate all day due to natural condition restrictions, their generation is constrained by the installed capacity multiplied by capacity factor $CF_{t,g}$ (the maximum capacity utilization rate of the technology at each hour). Third, the total power generation in Guangdong plus net imports should be equal to the total demand at any time. $TRA_{t,j,Guangdong}$ in equation (6) represents the trade flow from province *j* to Guangdong at hour *t* (import), and $TRA_{t,Guangdong,j}$ represents exports. $line_{j,Guangdong}$ is the line loss rate. D_t is the demand of Guangdong at hour *t* and is assumed to be completely inelastic in the short term.

$$0 \leq TRA_{t,j} \leq TL_j \tag{4}$$

$$\begin{cases} 0 \leq GEN_{t,g} \leq \left(1 - loss_{t,g}\right) CAP_g & g \epsilon \{coal\ 1000MW, coal\ 600MW, coal\ 300MW, coal\ {<}300MW, gas, nuclear\} \\ 0 \leq GEN_{t,g} \leq CAP_g CF_{t,g} & g \epsilon \{hydro, wind, solar, biomass\} \end{cases}$$

(5)

$$\sum_g GEN_{t,g} + \sum_j [TRA_{t,j,Guangdong}(1 - line_{j,Guangdong}) - TRA_{t,Guangdong,j}] = D_t \qquad (6)$$

In economic dispatch with the allocated generation scenario, because part of the generation is determined by the government and renewable energy has not yet participated in market competition, the down limit of $GEN_{t,g}$ needs to be adjusted. With other constraints remain unchanged, the constraints in equation (5) change to equation (7).

$$\begin{cases} ALLO_{t,g} \le GEN_{t,g} \le (1 - loss_{t,g})CAP_g \;\; g\epsilon\{coal\ 1000MW, coal\ 600MW, coal\ 300MW, coal\ {<}300MW, gas\} \\ 0 \le GEN_{t,g} \le (1 - loss_{t,g})CAP_g \;\; g\epsilon\{nuclear\} \\ GEN_{t,g} = CAP_g CF_{t,g} \;\; g\epsilon\{wind, solar\} \\ 0 \le GEN_{t,g} \le CAP_g CF_{t,g} \;\; g\epsilon\{hydro, biomass\} \end{cases} \qquad (7)$$

where $ALLO_{t,g}$ is the allocated generation of technology g at hour *t*. As equation (7) shows, for coal-fired and gas-fired power, their generation allocated by the government must be achieved before competing in the market, so the down limit changes to the amount of allocated generation. For renewable energy such as wind power and solar photovoltaic, since they are given the administrative priority to generate at maximum potential, we assume their down limits equals upper limits in this scenario. The constraints for nuclear, hydro and biomass remain unchanged.

In planning scenario under equal dispatch, we adjusted the actual generation of Guangdong Province in 2018 according to the generation structure before the reform, and directly obtained a counterfactual generation mix in a counterfactual no-reform scenario.

Based on the partial equilibrium model, the generation mixes in each scenario are simulated, and then the corresponding carbon emissions and welfare change can be estimated further. The carbon emission is calculated following equation (8), where $Heatrate_g$ is the heat rate of technology g, and EF is the carbon emission factor of per unit of standard coal consumption (it takes the value of 2.66 gCO_2/gce according to the Southern Power Grid Dispatch Annual Report). We approximately take the carbon emissions of nuclear and renewables as zero. The assessment of social welfare change is straightforward and simply involves comparing the areas under the supply and demand curves. Since the two reform scenarios (economic dispatch with allocated generation scenario and economic dispatch scenario) both lead to a reduction in supply cost (from S to S'), though to different extents, the overall welfare change compared with the planning scenario is the shadow part in Supplementary Figure 2.

$$CARBON_g = \sum_{t=1}^{8760} GEN_{t,g} Heatrate_g EF \qquad (8)$$

We didn't consider the ramp and start-up/shut-down constraints to simplify the model setting. Our estimates of power generation structure and carbon emissions are based on the relative cost position of generators with different technologies. We do admit that gas-fired generators with higher flexibility always have lower start-up/shut-down costs than coal-fired generators. But when compared on a per kWh basis, the total marginal cost of gas power is still much higher than that of coal power, since the fuel cost of gas power in China is quite high, which is proved by Chen et al (2020). As these constraints can't reverse the relative merit order of different power generation technologies, the outcomes of the model will not change. Whereas, it should be noted that these ramp and start-up/shut-down constraints can affect the scale of welfare estimate, as it is based on cost calculation, but not the direction (raise or loss) of welfare assessment.

In impact evaluation we used a unique dataset that features electricity load on the demand side, installed capacity and allocated generation on the supply side, and inter-provincial transmission capacity on the trade side, all at an hourly level and confined to Guangdong Province and the year 2018. Guangdong's electricity consumption was about 55% of southern grid generation in 2018, and the other four provinces in the southern grid region were not included due to a lack of allocated generation data. Some parameters, such as the estimated marginal costs of different technologies, were referred from Chen et al (2022).

Hourly electricity load and installed capacity: The electricity load in Guangdong is shown in Figure 1, which is accessed from the South China Energy Regulatory Office of the National Energy Administration. The installed capacity is obtained from the Southern Power Grid Dispatch Annual Report 2018. The capacity factors of renewables such as wind, solar and hydropower are also from the South China Energy Regulatory Office, and the upper limit of generation $CAP_g CF_{t,g}$ of different renewables is shown in Figure 2.

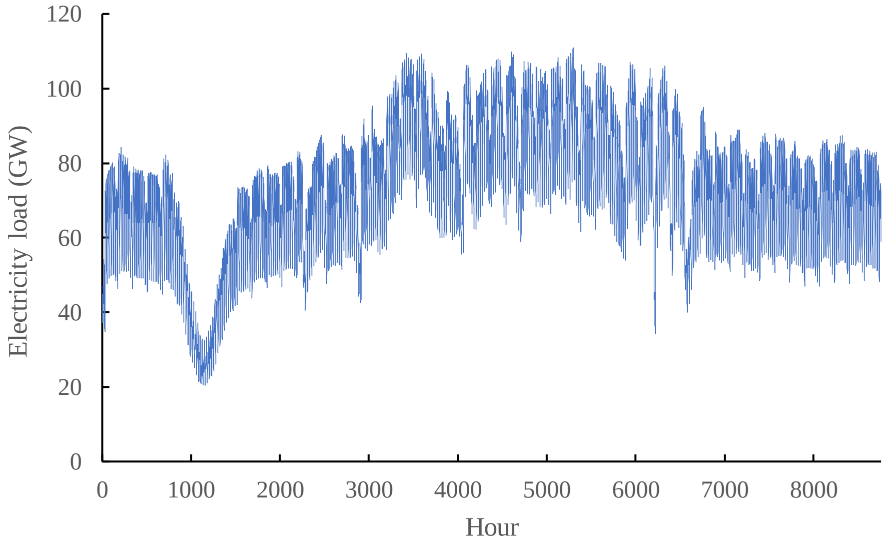

Figure 1. Hourly load curve in Guangdong in 2018

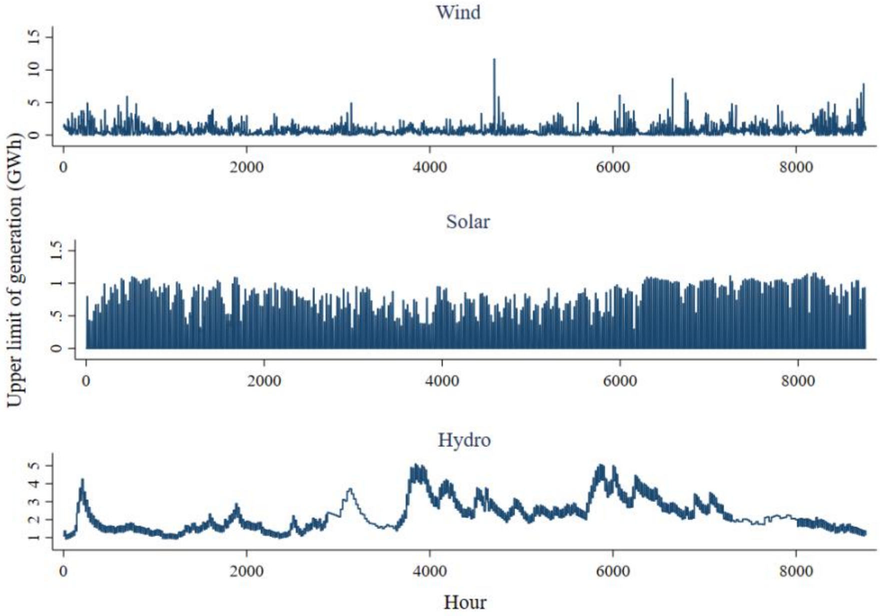

Figure 2. Hourly generation (upper limit) of renewables in Guangdong in 2018

Allocated generation: The Guangdong's Allocated Generation Guidance Plan records the monthly allocated generation of each generating unit (coal-fired and gas-fired) in each year. Figure 3 plots the aggregated allocated generation of coal power and gas power in each month in 2018. In China's practice, the local government does not refine the allocated generation to the hour level, enabling generators to adjust their generation plans in terms of actual situation. In other words, the allocated generation that each generator will produce per hour is random. To make the calculation, we average the monthly data to hourly level given the data limitations.

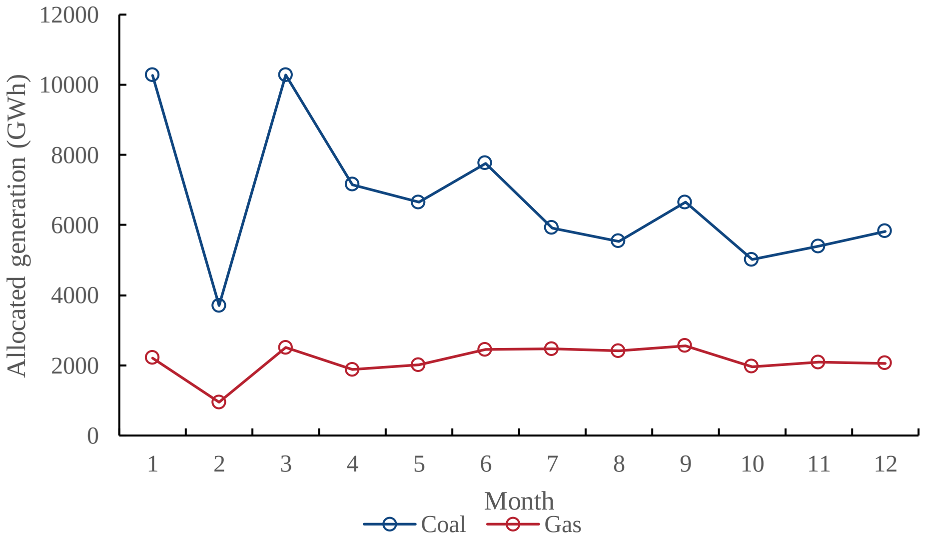

Figure 3. Aggregated allocated generation of coal-fired and gas-fired power in Guangdong in 2018

Inter-provincial transmission capacity: Figure 4 presents the inter-provincial transmission capacities (in GW) between Guangdong and other four provinces. We collected the data from the Southern Power Grid Dispatch Annual Report 2018. Besides, we set the line loss rate as 5.51%, which is the average value calculated from the Dispatch Annual Report.

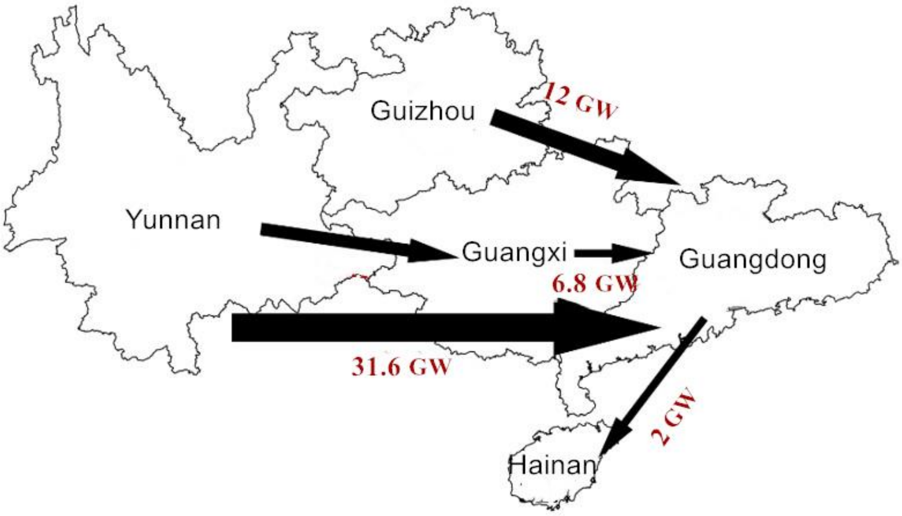

Figure 4. Inter-provincial electricity transmission capacities in 2018

3. Results

3.1 The overall market efficiency improved after the reform

On average, the power market reform in 2015 improved the efficiency of coal-fired power generation in China's southern grid region. We start with an overview of the relationship between operating hour and heat rate (in gram coal equivalent/kilowatt-hour [gce/kWh]) before and after the reform. The reason why we choose heat rate as an indicator of efficiency is presented in Method section. As seen from Figure 5(a), under the equal dispatch approach before the reform, the potential of the electricity market was not fully brought into play. Coal-fired generators with a higher heat rate were allocated more operating hours, while generators with a lower heat rate were not fully utilized, which indicates a mismatch between efficiency and operation. Figure 5(a) fits the scattered points of Guangdong and other four provinces respectively, and the correlation coefficients are all positive. Conversely, with the reform advancing market competition, the issue of mismatch was alleviated after the reform. The fitting curves in Figure

5(b) are significantly different from those in Figure 5(a). High-efficiency generators began to gain market share.

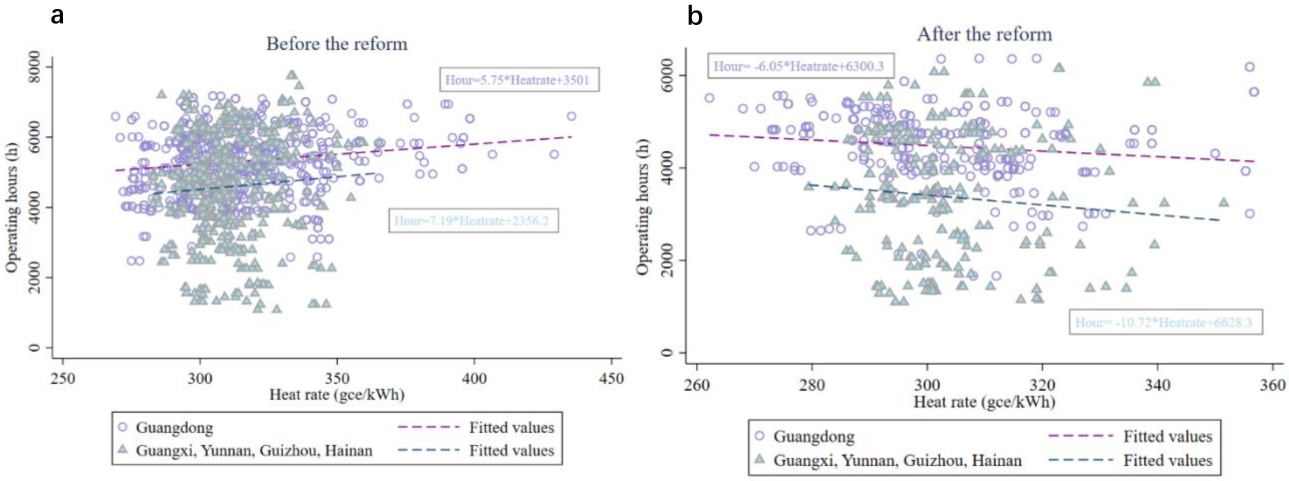

Figure 5. The relationship between operating hours and heat rate of coal-fired generators before and after the reform. **a,** The mismatch of operating hours and heat rate in China's southern grid region from 2010 to 2015. **b,** The reverse relationship between operating hours and heat rate in the southern grid region from 2016 to 2018. The formulas in purple in **a** and **b** represent fitting curves of scattered points in Guangdong, and the formulas in blue represent those in Guangxi, Yunnan, Guizhou and Hainan.

Figure 5 provides a generalized but rough picture of the efficiency change, due to the mixing-up of provinces and years. Therefore, we further used a panel data regression at generating-unit level during the period of 2010-2018 to evaluate the reform effect. Similarly, we divided the entire data period into two phases: before and after the reform, taking year 2015 as a cutoff, and regressed operating hours on heat rates of coal-fired generators, with province and year fixed effects controlled. During the reform, there were 78 generators closed in the southern grid region (from 2016 to 2018), among which 16 were coal-fired generators, 59 were hydropower generators, and the other three were gas, biomass and wind generator respectively. And the total capacity (2475 megawatts [MW]) of these 16 coal-fired generators only accounts for 0.8% of our sample in corresponding years, having no effect on the balance of our panel data.

Table **3** displays the results. The positive coefficient of the heat rate became negative after the reform and was significant at the 1% level, which means that generators with a lower heat rate (higher efficiency) operated more hours after the reform. This efficiency improvement within coal-fired power units is robust whether in a one-way fixed-effects model or in a two-way fixed-effects model. To avoid the interference of coal purchase prices in different provinces on the identification of generators' efficiency, we also used fuel cost as a proxy for heat rate, and the conclusion doesn't change.

Table 3. Regression on operating hours and heat rate/fuel cost of coal-fired generators

VARIABLES	(1) Before the Reform	(2) After the Reform	(3) Before the Reform	(4) After the Reform	(5) Before the Reform	(6) After the Reform	(7) Before the Reform	(8) After the Reform
Heat rate	6.939***	-8.605***	1.581	-7.540***				
	(1.304)	(2.815)	(1.758)	(2.874)				
Fuel cost					19.880***	-6.853*	0.490	-10.149**
					(1.134)	(3.752)	(3.005)	(4.307)
Constant	3,099.335***	6,996.638***	5,510.665***	6537.392***	1,780.923***	5,667.683***	6,004.143***	6,149.738***
	(413.433)	(835.185)	(557.314)	(856.160)	(202.579)	(693.907)	(621.362)	(793.744)
Province Fixed Effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fixed Effect	No	No	Yes	Yes	No	No	Yes	Yes
Observations	1,303	588	1,303	588	1,303	588	1,303	588

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

The overall efficiency improvement is closely related to the increase in the operating hours of the high-efficiency generators. To further understand the dispatch details of generators with different efficiency before and after the reform, we divided the coal-fired generating units into a low-efficiency group and a high-efficiency group according to their nameplate heat rate② (Global Coal Plant Tracker, 2022). Before the reform, the operating hours of both low-efficiency and high-efficiency units were decreasing, consistent with the decline in the overall utilization rate of China's coal power industry (China Electricity Council [CEC], 2015). After the reform, the operating hours of high-efficiency units began to rise, which helped to alleviate the mismatch (see Figure 6(b)). However, the average operating hour of low-efficiency units is also increasing after the reform, though with a smaller amplitude, implying the potential existence of inefficient protection in the dispatch system (see Figure 6(a)).

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② We matched the generator's nameplate heat rate to our dataset, referring to the Global Coal Plant Tracker. Over 70% of the generators in our dataset are matched. We define a generator as *low efficiency* when its nameplate heat rate is higher than the average value; otherwise, we define it as *high efficiency*. Since the nameplate heat rate doesn't change with time, our grouping is stable.

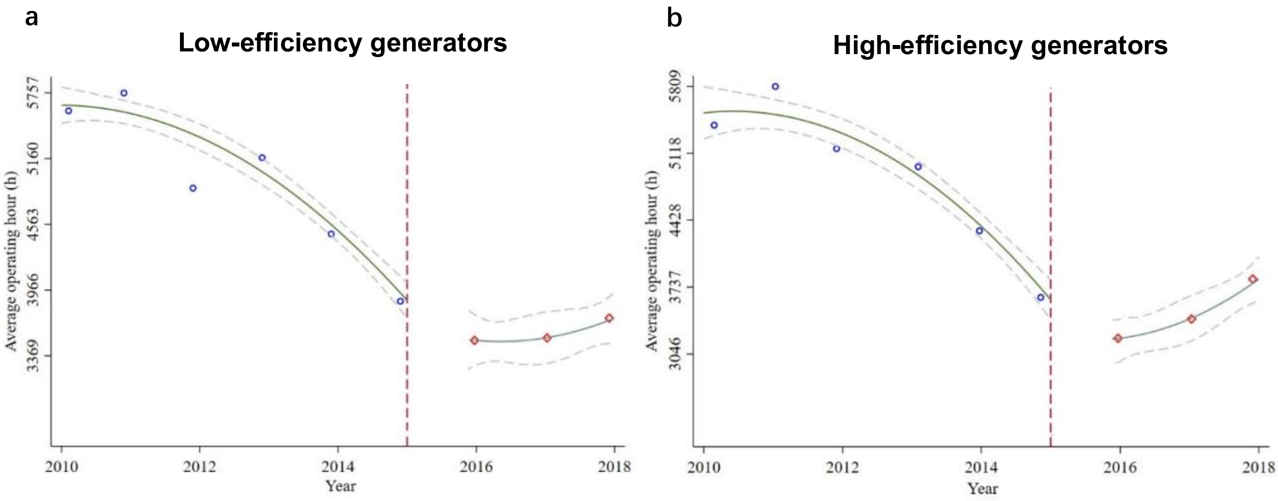

Figure 6. The changes in average operating hours of **(a)** low-efficiency generators and **(b)** high-efficiency generators before and after the reform.

3.2 Regulatory capture hinders the establishment of an efficient market

To distinguish between factors that promote and hinder efficiency improvement, Table 4 regresses the operating hours on generator's capacity and ownership structure, with province and year fixed effects controlled. Columns (1) and (3) use the absolute value of the installed capacity, while columns (2) and (4) use the capacity level (below 300 MW = 1, 300–600 MW = 2, 600–1,000 MW = 3, and above 1,000 MW = 4) as a substitute.

The application of economic dispatch does promote the market share of coal-fired generators with advanced technology and higher efficiency. Generally, technologically advanced generators have larger capacities and lower heat rates, such as 600 MW/1,000 MW supercritical and ultra-supercritical units (Bugge et al., 2006; Yu et al., 2011). As Table 2 in Method section shows, the average heat rate of generators below 300 MW in southern China is approximately 10.9%, 15.0%, and 22.8% higher than that of 300–600 MW units, 600–1,000 MW units, and over-1,000 MW units, respectively. These large generators, especially 600–1,000 MW units and over-1,000 MW units, were allocated fewer operating hours than small generators (below 300MW) before the reform (see column (1) and (2) in Table 4). After the reform, whereas, this mismatch has been alleviated. Column (3) indicates that the operating hours increase by 0.619 h corresponding to a 1 MW increase in capacity after the reform, and generators 1000MW and above obtain about 608 more hours than generators below 300MW (see column (4)).

However, the influence of local enterprises on government impedes efficiency improvement. Before the reform, the central SOEs in the southern grid region owned higher-efficiency coal-fired generators. In 2015, the average heat rate of coal-fired generators in central SOEs was 22 gce and 41 gce lower than that of generators in local SOEs and private enterprises. In operation, however, these central SOE generators were allocated the fewest operating hours compared with local ones (see column (1) and (2) in Table 4). This regulatory capture by local generators has not diminished since the reform. As seen from column (3) and (4), except for other enterprises like Sino-foreign joint ventures, local enterprises still occupy more operating hours than central SOEs after the reform. Among them, the local SOEs benefit the most. This is not difficult to understand because local SOEs are often an important source of tax revenue and gross domestic product (GDP) within the province. Under the fierce economic and political competition between provinces, local governments have enough motivation to set higher operation time quotas for local SOEs to ensure fiscal income and local development (Bai et al., 2004). These local SOEs are thus also more powerful in lobbying either local governments or local power bureaus (Lin et al., 2019a).

Table 4. Regression on operating hours, capacity and ownership structure of coal-fired generators

VARIABLES	(1) Before the reform	(2) Before the reform	(3) After the reform	(4) After the reform
Capacity	-0.395***		0.619***	
	(0.151)		(0.230)	
Capacity Level		12.608		427.709**
(300–600 MW)		(83.821)		(168.579)
Capacity Level		-187.463**		395.473**
(600–1,000 MW)		(94.417)		(170.277)
Capacity Level		-237.027*		608.338***
(⩾1,000 MW)		(143.820)		(222.990)
Ownership	314.628***	338.326***	227.785*	265.952**
(Local SOEs)	(89.384)	(92.595)	(123.784)	(124.930)
Ownership	262.112*	291.702**	199.263	200.842
(Private enterprises)	(134.934)	(137.757)	(229.602)	(241.780)
Ownership	295.304**	310.053**	-762.335***	-710.588***
(Other)	(129.463)	(131.228)	(224.997)	(215.291)
Constant	5,877.137***	5,768.983***	3,802.764***	3,706.191***
	(120.012)	(119.304)	(181.135)	(192.634)
Province Fixed Effect	Yes	Yes	Yes	Yes
Year Fixed Effect	Yes	Yes	Yes	Yes
Observations	1,336	1,336	588	588

Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1. Although we see that generators among 600-1000MW obtained fewer operating hours after the reform compared with generators among 300-600MW, the coefficient difference between them is not significant statistically (p=0.759).

Since the preference for local enterprises has not diminished since the reform, is it possible that the efficiency of local enterprises is improved and exceeds that of central SOEs? Figure 7 displays the heat rate of generators in different enterprises before and after the reform, with the significance of between-group variation. The leading position of central SOEs has not changed substantially. Before the reform, generators in central SOEs had the lowest heat rate compared with local SOEs and private enterprises, with a median of 308.7 gce/kWh. The p values of the between-group variation tests among the three groups are all less than 0.01. After the reform, although the efficiency of local SOEs has improved, their heat rates were still higher than central SOEs and the difference was significant. Local private enterprises have instead made some progress, overtaking local SOEs in efficiency.

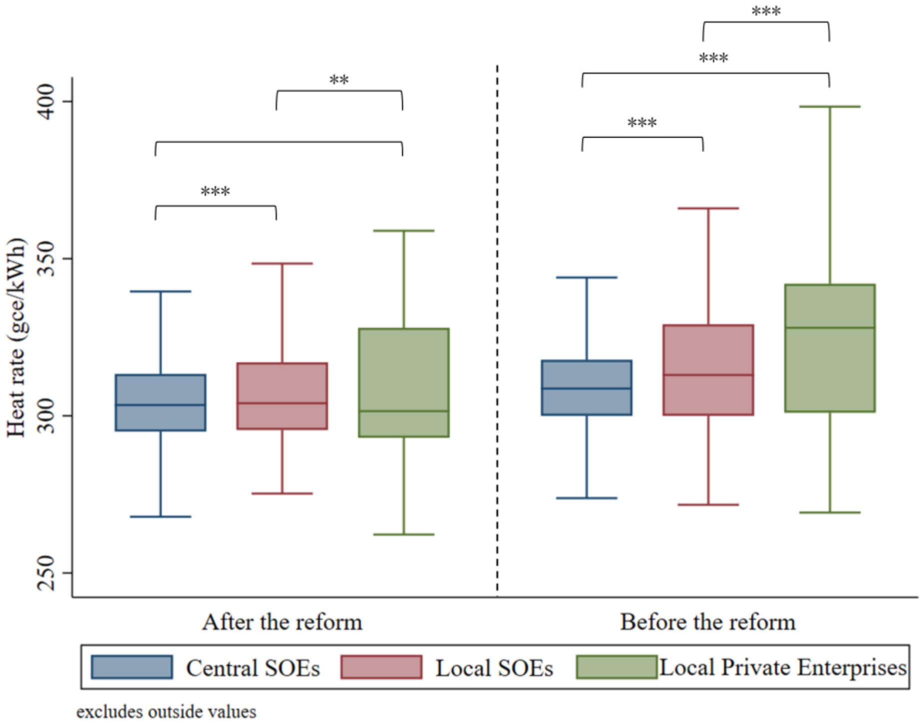

Figure 7. The heat rate of generators in enterprises with different ownership structures before and after the reform. The five lines from top to bottom of each box represent the 75th percentile+1.5IQR (interquartile range), 75th percentile, 50th percentile (median), 25th percentile, and 25th percentile-1.5IQR. The "*" in the figure stands for the significance degree of between-group variation (*** p<0.01, ** p<0.05, * p<0.1). Almost all the between-group variations are significant, except for the group of central SOEs and local private enterprises after the reform.

Why are these local SOEs unwilling to make more efforts? The continued regulatory capture could be an important factor. Cicala presented that the influence of companies on regulators increases the likelihood of allowing high fuel costs and reduces penalties for not working hard, so an increase in political influence leads to a decrease in cost-reducing effort (Cicala, 2015). In our case, as local SOEs continue to have an impact on local governments after the reform, they will face less stringent cost regulation and have less incentives to strive to improve efficiency. Fang also pointed out that the pressure on local SOEs to reduce costs in China is relatively small because they are subject to fewer financial incentives and constraints compared with central SOEs supervised by the SASAC (Fang, 2014).

Local generators with lower efficiency are less competitive under economic dispatch, so the key way for regulatory capture to take effect is through the special "allocated generation" dispatch. For example, in Guangdong, generators in local SOEs were allocated more hours from the government than those in central SOEs since the reform (see Figure 8), and the allocated generation mainly protects small coal-fired generators and natural gas generators. According to our dataset, the total allocated generation in Guangdong changed from 198.4 billion kWh in 2016 (accounting for 49.2% of total generation) to 105.4 billion kWh in 2019 (accounting for 21.7%). In these four years, 79% of allocated generation went to coal-fired generators, and 21% was allocated to natural gas generators. Although the allocated generation and average allocated hours both decrease with the deepening of marketization, they still show a clear preference for less efficient generators. As seen from Figure 9(a), the allocated generation to natural gas accounted for over 50% of the total gas-fired generation, and this ratio even reached 84% in 2016. Small coal-fired generating units below 300 MW were allocated the most hours—nearly double those of large units above 1,000 MW (see Figure 9(b)). Supplementary Table 1 further confirms the allocated generation's preference for lower-efficiency generators with higher heat rate. In some way, the allocated generation can help to alleviate the lost revenue caused by market competition. However, the protection of inefficient generators violates the cost minimization principle and may lead to significant energy waste, carbon emissions, and welfare loss.

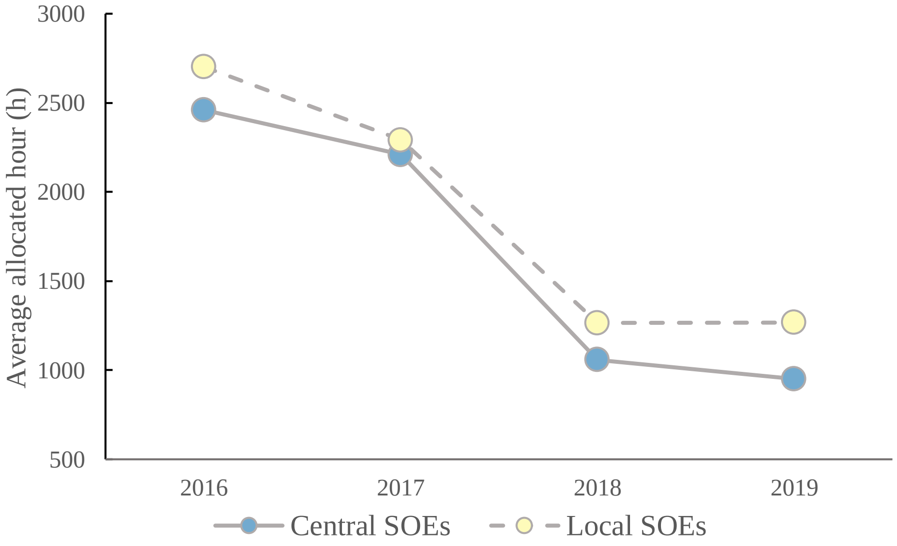

Figure 8. The average allocated hour of enterprises with different ownership structures in Guangdong after the

reform.

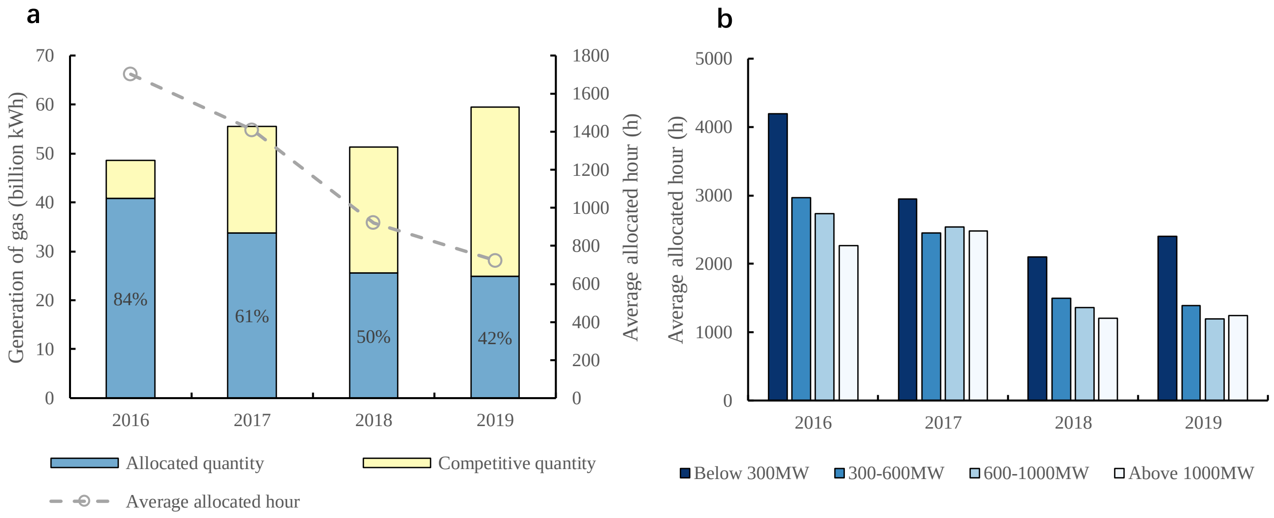

Figure 9. The allocated generation and hours of different generators in Guangdong after the reform. a, The allocated generation, average allocated hours (on the secondary y-axis) and total generation of gas-fired generators in Guangdong. **b,** The average allocated hours of coal-fired generators with different capacity levels (below 300 MW, 300–600 MW, 600–1,000 MW, and above 1,000 MW) in Guangdong. The data is accessed from Guangdong's Allocated Generation Guidance Plan which records the monthly allocated generation of each generating unit in each year, and the allocated hour can be calculated by dividing the allocated generation by generator's capacity.

3.3 Only half of the potential of CO_2 emission reduction and social welfare gains has been realized due to politically allocated generation dispatch

After identifying the relations in efficiency change, we compared impacts of the reform under three dispatching scenarios in Guangdong with data from 2018. The results show that replacing equal dispatch with economic dispatch can improve economic and environmental efficiency by optimizing the generation mix, but the allocated generation approach caused by regulatory capture slows the process both in carbon emission reduction and social welfare gains.

For the impact on the generation mix, there are two main differences among the three scenarios. Within the coal-fired power, the degree of structural optimization③ gradually deepens with the intensity of economic dispatch implementation. The generation of low-efficiency generators below 300 MW decreases from 18.7 terawatt-hours (TWh) in the planning scenario to 9.7 TWh in the economic dispatch with the allocated generation scenario, and then

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③ The structural optimization here indicates the shift from low-efficiency power units to high-efficiency power units in the generation mix.

to 8.2 TWh in the economic dispatch scenario. In contrast, the generation of high-efficiency generators above 1,000 MW increases from 72.6 TWh to 109.4 TWh, and then to 114 TWh. Between coal-fired and gas-fired power, allocated generation continues to favor gas-generators. In China, the gas-fired power has a much higher fuel cost than coal-fired power. Therefore, under economic dispatch which pursues marginal cost minimization, the market share of gas-fired power would decrease. However, for the sake of flexibility and environmental protection, the government always protects the generation of gas power, no matter under the previous equal dispatch or under the current allocated generation dispatch. As shown in Figure 10, the proportion of gas-fired generation drops from 10.5% in the planning scenario to 2.8% in the economic dispatch scenario, but the allocated generation still ensures a 7% of gas-fired generation in the semi-planned and semi-market scenario.

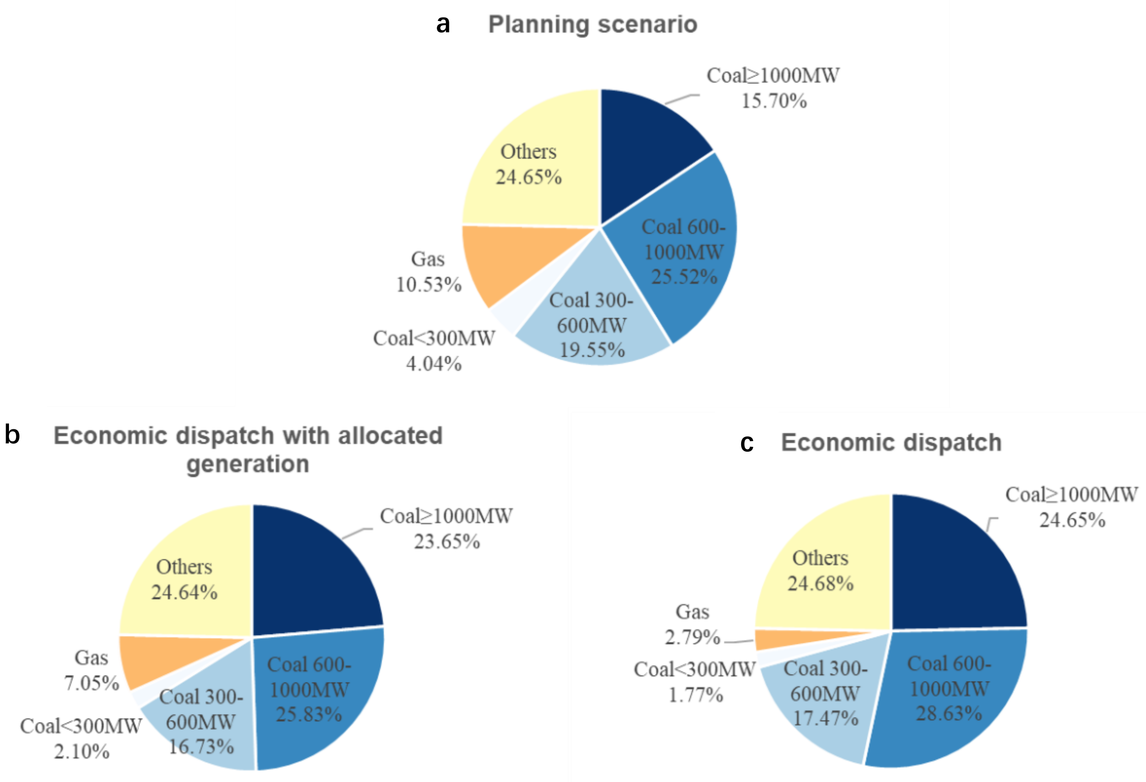

Figure 10. Generation mixes in **(a)** the previous planning scenario (equal share dispatch), **(b)** the current semi-planned and semi-market scenario (economic dispatch with allocated generation), and **(c)** the ideal market-based scenario (economic dispatch)

For the impact on carbon emissions, regulatory capture through allocated generation makes it difficult to achieve the highest level of carbon emission reduction potential. As seen from Figure 11, with the structural optimization effect within coal-fired generators, economic dispatch can save 1.5 million tons of CO_2 compared to economic dispatch with allocated generation and save 3.1 million tons of CO_2 compared to equal dispatch in the planning scenario. In other words, allocated generation dispatch impedes the realization of nearly 50% of potential emission reductions. However, despite the positive effect from coal-fired structure optimization, there is also a negative effect on emissions brought by gas-to-coal switching. When gas-fired generation declines under economic dispatch and the total demand is fixed, other technologies need to fill this gap. Generally, this reduction would be replaced by both hydropower and coal-fired generation, but as Guangdong is not rich in hydropower, most of the gas generation is replaced by coal-fired power. With the absolute quantity of coal-fired generation increasing, economic dispatch will bring about approximately 4.6 million tons of additional carbon emissions instead. However, this result is just a province-specific problem, largely affected by the supply structure of Guangdong itself. In provinces with less gas or more hydropower, the emission reduction effect of economic dispatch will like to be substantial (Chen et al., 2022).

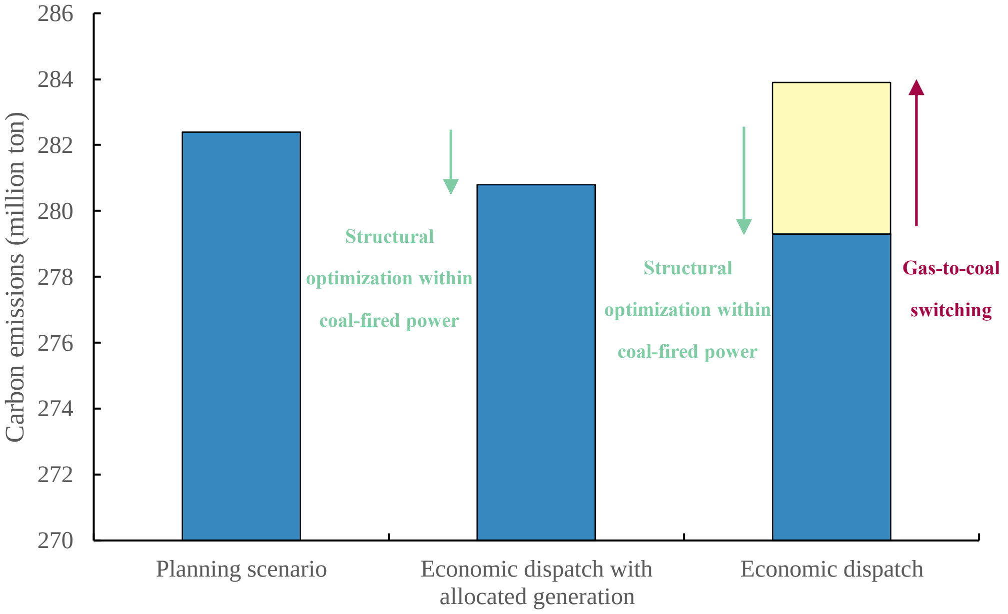

Figure 11. Carbon emissions in three scenarios

Completely implementing economic dispatch also helps to improve social welfare. The electricity market under economic dispatch would increase the total social surplus by 7.3 billion yuan a year (or by a share of 5.35%), which is equal to the generation cost savings. However, due to the protection for small coal-fired generators and gas-fired generators with higher costs, the economic dispatch with allocated generation scenario only increases the total social surplus by 4.1 billion yuan a year (or by a share of 2.98%), 43.8% lower than the economic dispatch scenario.

4. Conclusion and discussion

Reforming the dispatch rule is a good first step to improve the efficiency of the electricity sector; however, implementing such a reform faces some political obstacles in China. Under various goals, such as economic development and political promotion, the local government is unwilling to relax its power of supervision and tends to be partial to local enterprises. This study discovers that the "semi-planned and semi-market" dispatch approach being implemented in China currently allows regulatory capture to continue, making it possible to evaluate both the market-driven and politically driven effects of the reform.

Based on data from five provinces in southern China, this study identified the overall influence of China's latest reform on efficiency and explored the driving forces of efficiency improvement, considering both economic and political factors. We found that the power sector reform since 2015 has improved the overall efficiency of power generation by increasing the operating hours of high-efficiency generators. However, small inefficient coal-fired generators and gas-fired generators owned by local SOEs are still under the shelter of local governments through an allocated generation quota. Economic dispatch has the potential to reduce 3.1 million tons of carbon emissions annually in Guangdong and increase the total social surplus by 5.35% compared to the pre-reform planning scenario. However, with the allocated generation, only half of the potential was realized.

The electricity market could play an important role in China's transition to a low-carbon energy system. Based on the results obtained above, we propose three ways to mitigate the shortcomings of the current provincial market reform pilots: (1) Maximize the current market potential by allowing renewables to participate in market competition, which would help to displace more coal generation and reduce carbon emissions. (2) Establish a well-functioning regional market to break down provincial barriers and overcome the imbalance of provincial resource endowment (Sasse and Trutnevyte, 2020). On the one hand, what regional market dispatch pursues is the minimization of regional costs, and local protectionism is inconsistent with the overall objective function at this point. On the other hand, a regional market can allow more hydro and renewables to be used ahead of coal and thus avoid situations such as the rise of total emissions caused by the gas-to-coal switch in Guangdong (Lin et al., 2019b). In addition, full-scale regional market competition would change the future investment in renewable resources, as they are becoming cheaper than coal (Zhuo et al., 2022). (3) Considering the unique characteristics of Chinese politics and the economy, formulate a relevant compensation mechanism to help some key stakeholders transition to clean energy and the wholesale electricity market. Reforming the dispatch rule in the electricity system is a complex process, and it is important to adopt measures that could address implications for all stakeholders involved to achieve the intended goals of economic efficiency, environmental benefits, and equity.

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Appendix

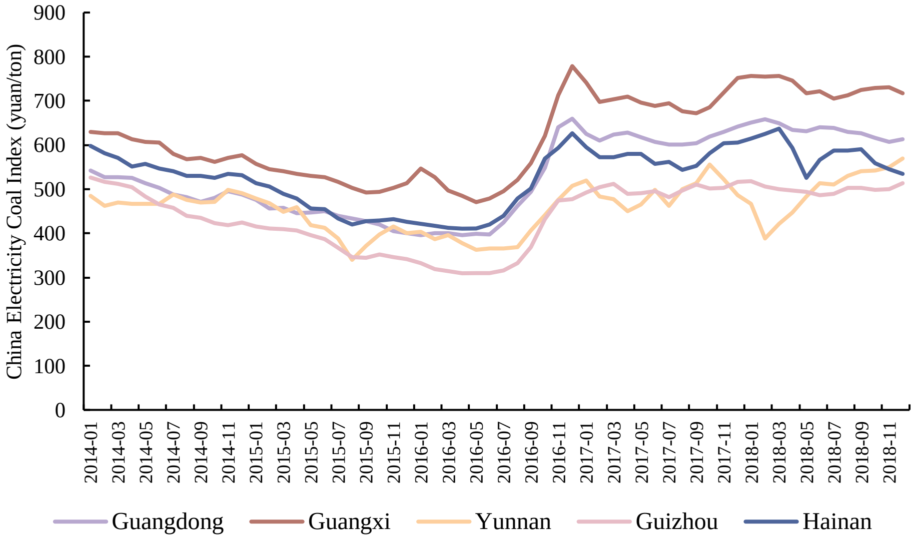
Appendix Table 1:

Regression on allocated hours and heat rate of coal-fired generators in Guangdong after the reform (2016-2018)

	(1)	(2)
VARIABLES	Allocated hour	Allocated hour
Heat rate	10.036***	7.926***
	(2.024)	(2.914)
Constant	-20.765	1,676.827*
	(637.455)	(927.027)
Year Fixed Effect	Yes	Yes
Plant Fixed Effect	No	Yes
Observations	346	346

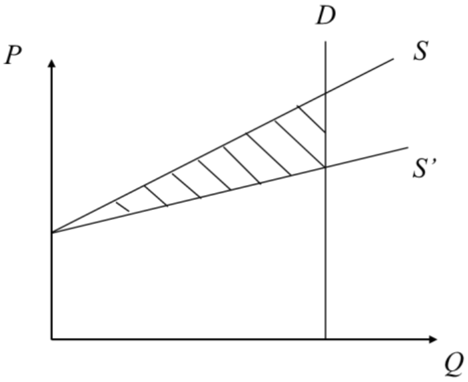
Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1. To ensure the robustness, we not only controlled the year fixed effect in column (1), but also controlled year and plant fixed effects in column (2).

Appendix Figure 1. The prices of electricity coal in the southern grid region



Data source: National Development and Reform Commission

Appendix Figure 2. Welfare changes of the reform scenarios



Author contributions statement

C. X., X. Z. and J. L. designed the study. X. Z., F. S. and Z. J. collected the high-frequency hourly data used in the paper. F. S. provided technical support in power system modeling. C. X. ran the models, performed the analyses of the results, provided policy recommendations, and wrote the main body of the manuscript. J.L. supervised the work and cowrote the paper. All authors reviewed the manuscript.

Declaration of Interests

The authors declare no competing interests.