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# Assessing the roles of efficient market versus regulatory capture in China's power market reform

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China began implementing market-based economic dispatch through power sector reform in 2015, but the reform has encountered some political and economic challenges. Here we identify the reform's efficiency changes and explore the influences of market-driven and politically driven mechanisms behind them. We do this through a cost-minimizing dispatch model integrating high-frequency data in southern China. We find 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 emissions reduction and social welfare gains through market reform is not realized.

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[1–3]. This coal-dominated power-generation mix led to 4.4 billion tons of carbon emissions, accounting for 43.1% of the national total[4]. With the challenges of energy security and environmental sustainability, improving the power system's efficiency attracted wide attention from both the public and policymakers. 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[5,6]. Equal share dispatch has often been criticized for its inefficient use of polluting power plants[7,8].

To achieve improved efficiency and environmental outcomes for the 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[9]. 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[10–13]. Nikolakakis et al. found that the operational cost can be reduced by 76% with economic dispatch in the Bangladesh power sector[14]. Abhyankar et al. also presented the emissions reduction potential (10%) of the market-based dispatch system using data from the southern grid region of China[15].

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 it. Such arrangements can easily give rise to local protectionism[16,17]. Power generators in China are owned by different types of enterprise, such as central state-owned enterprises (SOEs), local SOEs, local private enterprises and other enterprises like Sino–foreign joint ventures. Theoretically, the 'out of market' dispatch would not correlate with the enterprise's ownership structure. The dispatch planning before the reform was carried out under the principle of 'openness, fairness and justness'. Under the premise of ensuring the information transparency,

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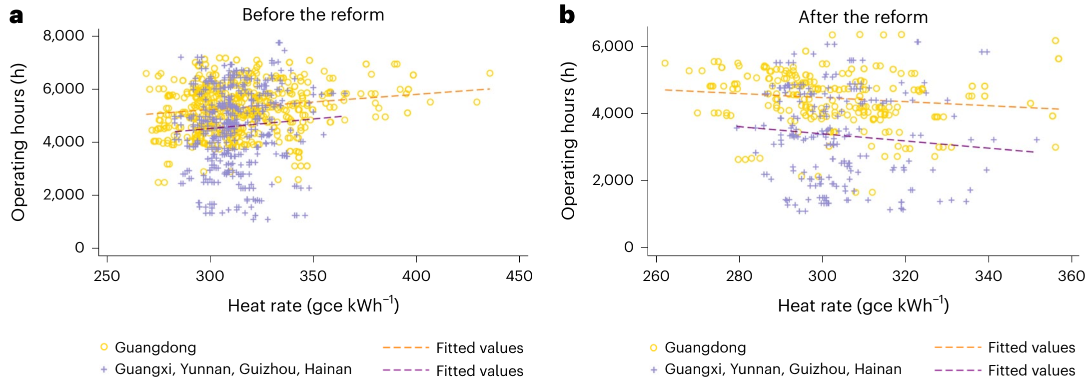


**Fig. 1 | Relationship between operating hours and heat rate of coal-fired generators before and after the reform.** **a**, The mismatch of operating hours and heat rate in China's southern grid region from 2010 to 2015. The yellow fitting curve of scattered points in Guangdong and the purple fitting curve of scattered points in Guangxi, Yunnan, Guizhou and Hainan can be expressed by: hour = 5.75 × heat rate + 3,501 and hour = 7.19 × heat rate + 2,356.2. **b**, The reverse relationship between operating hours and heat rate in the southern grid region from 2016 to 2018. The yellow and purple fitting curves can be expressed by: hour = −6.05 × heat rate + 6,300.3 and hour = −10.72 × heat rate + 6,628.3. Nine outliers with extreme heat rates (exceeding 800 gce kWh$^{-1}$) or extreme operating hours (lower than 500 h) were excluded to avoid their influence on the correlation.

this principle required equal treatment of all market entities, no matter what the ownership of the enterprise is. Practically, however, 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 prefer local enterprises to guarantee local economic development and to enhance local leaders' political performance[18]. Local enterprises also have the motivation to pursue greater influence over regulators in the province to gain favourable regulatory treatment, which is called regulatory capture[19]. 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 emissions reduction[20], 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 evaluate the reform effect with consideration of political economy problems using data at the 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 high-frequency data from Guangdong Province. We first identify the efficiency changes before and after the reform, providing a big-picture view of the overall reform impact. Then, we explore the roles of market-driven and politically driven factors in efficiency improvement. Finally, we assess the efficiency gains of the reform and quantify the influence of the two forces. To do this, we define three provincial market scenarios corresponding to previous planning-dominated dispatch (equal share dispatch), current semi-planned and semi-market dispatch (economic dispatch with allocated generation) and ideal market-based dispatch (economic dispatch). We establish a cost-minimizing dispatch model to simulate electrical grid operations in different scenarios and compare the equilibrium outcome variables. We find that the introduction of market mechanisms improves overall efficiency, but such an improvement is partially impeded by local protectionism 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 ($CO_2$) emissions reduction and social welfare gains that could have been achieved by economic dispatch falls through under the semi-planned and semi-market dispatch approach.

## Generation efficiency changes 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 grams of coal equivalent per kilowatt-hour (gce kWh$^{-1}$)) before and after the reform. The reason why we choose heat rate as an indicator of efficiency is presented in Methods. As seen in Fig. 1a, under the equal dispatch approach before the reform, coal-fired generators with a higher heat rate were allocated more operating hours, while generators with a lower heat rate were not fully utilized, indicating a mismatch between efficiency and operation. Figure 1a fits the scattered points of Guangdong and the other four provinces, and the correlation coefficients are all positive. Conversely, with the reform advancing market competition, the issue of mismatch was alleviated after the reform, as indicated by the different fitting curves in Fig. 1b compared with Fig. 1a. High-efficiency generators began to gain more operating hours.

Figure 1 provides a generalized but rough picture of the efficiency change. However, based on Fig. 1 alone, we cannot precisely tell the strength of correlation and whether some outliers would interfere with our finding. Therefore, we further used a panel data regression at the generating-unit level during the period of 2010–2018 to evaluate the effect of the reform. Similarly, we divided the entire data period into two phases: before and after the reform, taking year 2015 as a cut-off, and regressed operating hours on heat rates of coal-fired generators, with province and year fixed effects controlled. During our observation period, there were 78 generators closed in the southern grid region

**Table 1 | Regression on operating hours and heat rates and fuel costs of coal-fired generators**

| Regression | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|---|---|---|---|---|---|---|---|---|
| Variables | Before the reform | After the reform | Before the reform | After the reform | Before the reform | After the reform | Before the reform | After the reform |
| Heat rate | 6.94[a] | −8.61[a] | 1.58 | −7.54[a] | | | | |
| | (1.30) | (2.82) | (1.76) | (2.87) | | | | |
| Fuel cost | | | | | 19.88[a] | −6.85[c] | 0.49 | −10.15[b] |
| | | | | | (1.13) | (3.75) | (3.01) | (4.31) |
| Constant | 3,099.34[a] | 6,996.64[a] | 5,510.67[a] | 6,537.39[a] | 1,780.92[a] | 5,667.68[a] | 6,004.14[a] | 6,149.74[a] |
| | (413.43) | (835.19) | (557.31) | (856.16) | (202.58) | (693.91) | (621.36) | (793.74) |
| 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 | 504 | 1,303 | 504 | 1,303 | 504 | 1,303 | 504 |

Robust standard errors in parentheses. [a]$P<0.01$, [b]$P<0.05$, [c]$P<0.1$. *P* values are for a two-sided test based on normal distribution. 'Yes' denotes that the fixed effect is controlled in the model; 'No' is vice versa.

after the reform, among which 16 were coal-fired generators, 59 were hydropower generators and the other three were gas, biomass and wind generators, respectively. The total capacity of these 16 coal-fired generators was 2,475 MW. Meanwhile, 18 coal-fired generators entered the market, with a total capacity of 10,880 MW. The capacity of coal-fired power units entering and exiting the market during the reform period accounted for only 0.8% and 3.5% of our sample. Table 1 first displays the results without considering the entry and exit. The positive coefficient of the heat rate became negative after the reform and was significant at the 1% level whether in a one-way fixed-effects model or in a two-way fixed-effects model, which means that generators with a lower heat rate (higher efficiency) operated more hours after the reform. Supplementary Table 1 introduces an after-reform dummy to make a full-sample regression, and the negative coefficient of the interaction term (heat rate × reform) further confirms the robustness of this efficiency improvement. 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 does not change. The regression without generators that left or entered the sample to ensure the balance of data is shown in Supplementary Table 2.

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 rate (Supplementary Note 1)[21]. 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[22]. After the reform, the operating hours of high-efficiency units began to rise, as expected (Fig. 2b). However, the average operating hours of low-efficiency units also increased after the reform, though with a smaller amplitude, implying the potential existence of inefficient protection in the dispatch system (Fig. 2a).

## Regulatory capture versus efficient market

To distinguish between factors that promote and hinder efficiency improvement, Table 2 regresses the operating hours against generators' 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 (1, <300 MW; 2, 300–600 MW; 3, 600–1,000 MW; 4, >1,000 MW) as a substitute.

As seen from the results in Table 2, 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[23,24]. As Supplementary Table 3 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 >1,000 MW units, respectively. These large generators, especially 600–1,000 MW units and >1,000 MW units, were allocated fewer operating hours than small generators (below 300 MW) before the reform (columns (1) and (2) in Table 2). After the reform, this mismatch has been alleviated. Column (3) indicates that the operating hours increase by 0.62 h corresponding to a 1 MW increase in capacity after the reform, and generators 1,000 MW and above obtain about 608 more hours than generators below 300 MW (column (4)).

However, the influence of local enterprises on government regulators 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 owned by central SOEs was 22 gce $kWh^{-1}$ and 41 gce $kWh^{-1}$ lower than those of generators owned by local SOEs and private enterprises. In operation, however, these central SOE generators were allocated the fewest operating hours compared with local ones (columns (1) and (2) in Table 2). Such regulatory preference for local enterprises' generators has not diminished since the reform. As seen from columns (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 within the province. Under the fierce economic and political competition between provinces, local governments have sufficient motivation to set higher operation quotas for local SOEs to ensure fiscal income and local development[25]. These local SOEs are thus also more powerful in lobbying either local governments or local power bureaus[26]. Similar to Supplementary Table 1, we further made a full-sample regression with interaction terms in Supplementary Table 4. The positive coefficient of local SOE × reform again illustrates the dominant position of local SOEs compared to central SOEs in the dispatch after the reform.

Because 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 3a displays the heat rate of generators in different enterprises before and after the reform. The leading position of central SOEs has not changed substantially. Before the reform, generators in central SOEs had the lowest

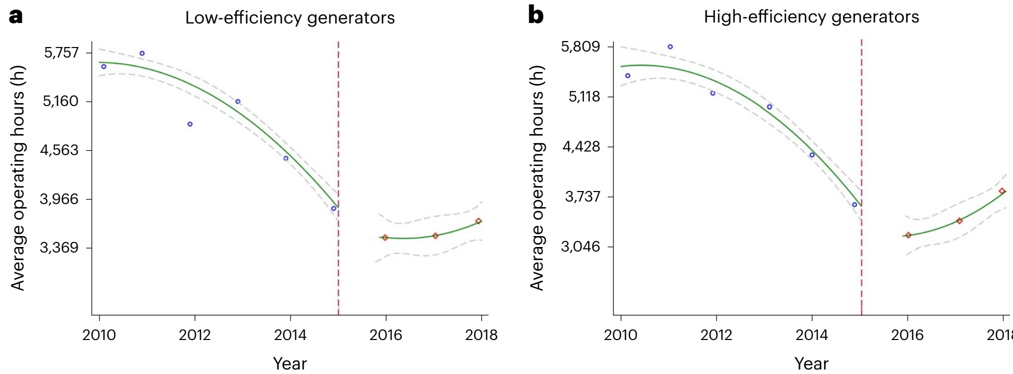


**Fig. 2 | Changes in average operating hours of low-efficiency generators and high-efficiency generators before and after the reform.** **a**, The average operating hours of low-efficiency generators from 2010 to 2018. **b**, The average operating hours of high-efficiency generators from 2010 to 2018. The blue hollow circles and red hollow diamonds represent the means of operating hours, conditional on year. The solid green lines are the fitting curves of operating hours, split at a cut point (red dashed line, year 2015). The fitting procedure is carried out in Stata, using quadratic prediction with ordinary least square method. The grey dashed lines indicate the 90% confidence interval.

**Table 2 | Regression on operating hours, capacity and ownership structure of coal-fired generators**

| Regression | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Variables | Before the reform | Before the reform | After the reform | After the reform |
| Capacity | −0.40[a] | | 0.62[a] | |
| | (0.15) | | (0.23) | |
| Capacity level | | 12.61 | | 427.71[b] |
| (300–600 MW) | | (83.82) | | (168.58) |
| Capacity level | | −187.46[b] | | 395.47[b] |
| (600–1,000 MW) | | (94.42) | | (170.28) |
| Capacity level | | −237.03[c] | | 608.34[a] |
| (≥1,000 MW) | | (143.82) | | (222.99) |
| Ownership | 314.63[a] | 338.33[a] | 227.79[c] | 265.95[b] |
| (Local SOEs) | (89.38) | (92.60) | (123.78) | (124.93) |
| Ownership | 262.12[c] | 291.70[b] | 199.26 | 200.84 |
| (Private enterprises) | (134.93) | (137.76) | (229.60) | (241.78) |
| Ownership | 295.30[b] | 310.05[b] | −762.34[a] | −710.59[a] |
| (Other) | (129.46) | (131.23) | (224.99) | (215.29) |
| Constant | 5,877.14[a] | 5,768.98[a] | 3,802.76[a] | 3,706.19[a] |
| | (120.01) | (119.30) | (181.14) | (192.63) |
| Province fixed effect | Yes | Yes | Yes | Yes |
| Year fixed effect | Yes | Yes | Yes | Yes |
| Observations | 1,303 | 1,303 | 558 | 558 |

Robust standard errors in parentheses. [a]$P<0.01$, [b]$P<0.05$, [c]$P<0.1$. $P$ values are for a two-sided test based on normal distribution. 'Yes' denotes that the fixed effect is controlled in the model. (1) Although we see that 600–1,000 MW generators obtained fewer operating hours after the reform compared with 300–600 MW generators, the coefficient difference between them is not significant statistically ($P=0.759$). (2) Table 2 takes central SOE as the benchmark and generates three dummy variables: ownership-local SOE, ownership-private enterprise and ownership-other. The coefficients of the three variables indicate the difference in operating hours between these three types of enterprise and central SOE, with other conditions remaining the same.

heat rate compared with local SOEs and private enterprises, with a median of 308.7 gce kWh$^{-1}$. The $P$ values of the between-group variation tests among the three groups are all less than 0.05. 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 (though not significant).

The continued regulatory capture could be an important factor in why these local SOEs are unwilling to make more efforts. When studying the fuel procurement in US electricity generation under a principal-agent framework, Cicala[27] found that local coal suppliers would lobby the state government to set a higher allowed fuel cost for generators and let these generators buy from local coal mines, which have higher prices than out-of-state coal suppliers. With the high allowed costs led by the political influence, local enterprises' generators were less motivated to reduce their costs as well. Similarly, in China's case, local SOEs have an incentive to pursue closer political connections with local governments to obtain favourable regulatory treatment. The preference for local SOEs in operating hour allocation implies the existence of such favourable treatment. When local SOEs could have an impact on the regulator's decisions on allowed costs, they will face less stringent regulation and be less willing 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[28].

Local enterprises' generators with lower efficiency are less competitive under economic dispatch, however, they could obtain favourable treatment through the special 'allocated generation' dispatch. For example, in Guangdong, generators owned by local SOEs were allocated significantly more hours by government regulators than those owned by central SOEs since the reform (Fig. 3b), and the allocated generation seems to favour 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 in Fig. 4a, 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 (Fig. 4b). Supplementary Table 5 further confirms the allocated generation's preference for lower-efficiency generators, opposite to the competitive generation. In some way, the allocated generation can help to alleviate the lost revenue caused by market competition. However, the protection of inefficient generators

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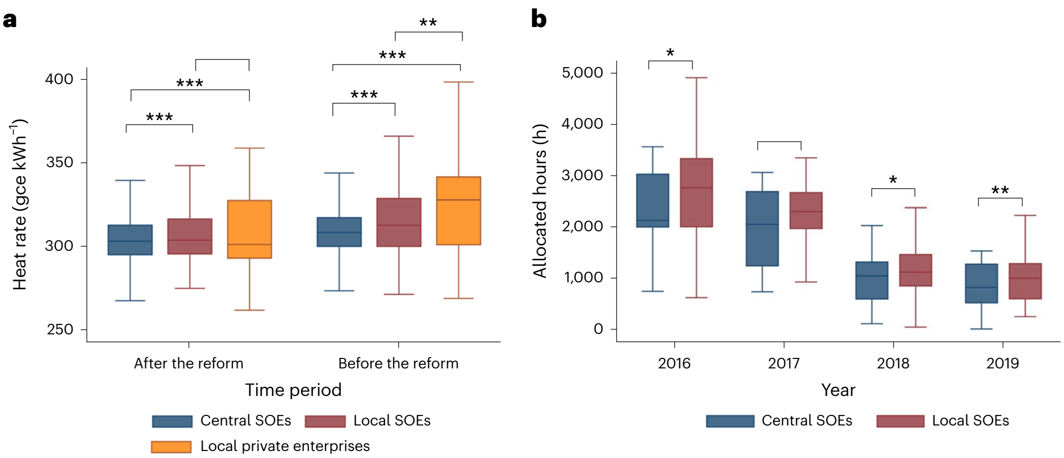


**Fig. 3 | Heat rates and allocated hours of generators with different ownership structures. a**, The heat rates of generators in different enterprises before and after the reform. The sample size is 1,298 and 766 before and after the reform, respectively, including three types of enterprise: central SOEs, local SOEs and local private enterprises. The asterisks indicate the significance degree of between-group variation (*** $P < 0.01$, ** $P < 0.05$, * $P < 0.1$). $P$ values between central SOEs and local SOEs, central SOEs and local private enterprises, and local SOEs and local private enterprises before the reform are $3.0 \times 10^{-10}$, $1.9 \times 10^{-23}$ and 0.013, respectively, whereas $P$ values after the reform are 0.001, 0.002 and 0.36, respectively. **b**, The allocated hours of generators in different enterprises in Guangdong after the reform. The total sample size from 2016 to 2019 is 676, including both coal-fired and gas-fired generators. $P$ values between central SOEs and local SOEs in Guangdong from 2016 to 2019 are 0.082, 0.65, 0.084 and 0.019. A two-sided $t$ test is used for between-group variation comparison. The five lines from top to bottom of each box represent the 75th percentile + 1.5 interquartile range (IQR), 75th percentile, 50th percentile (median), 25th percentile and 25th percentile − 1.5IQR. The outside values (greater than 75th percentile + 1.5IQR or less than 25th percentile − 1.5IQR) are excluded from the figure for clarity.

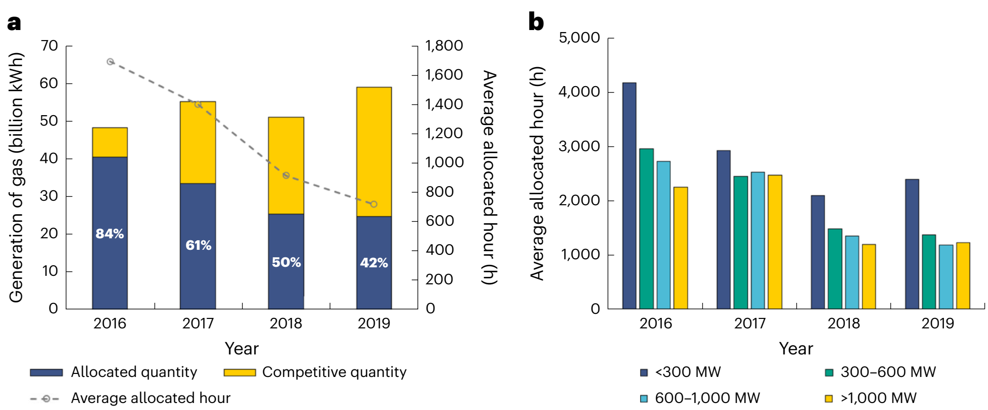


**Fig. 4 | Allocated generation and hours of different generators in Guangdong after the reform. a**, The allocated generation, average allocated hours (right $y$ axis) and total generation of gas-fired generators in Guangdong. **b**, The average allocated hours of coal-fired generators with different capacity levels (<300 MW, 300–600 MW, 600–1,000 MW and >1,000 MW) in Guangdong. The data are accessed from Guangdong's Allocated Generation Guidance Plan, which records the monthly allocated generation of each generating unit in each year. The allocated hours can be calculated by dividing the allocated generation by generator's capacity.

violates the cost-minimization principle and may lead to additional fuel consumption, carbon emissions and welfare loss.

Regular involvement of local SOEs in government planning processes provides a channel for these generators with lower efficiency to lobby for a larger allocation of operating hours. It is hard to imagine physical characteristics such as reliability would favour local SOEs' generators systematically. Guangdong Province implemented the energy-saving dispatching for a short time around 2007, that is, the dispatch order was determined entirely on generator's fuel consumption[20]. During this period, the local small inefficient generators did not get unreasonable preference, which indicates that these local units do not have substantial advantages in reliability or flexibility to attract local government protection. Central SOEs are likely to have newer and more reliable plants, thus these plants should be preferred instead. In this context, the preference in allocation quotas for local SOEs after the reform is largely related to local protectionism. Taking Guangdong as an example again, before 2002 the power industry was invested by Guangdong enterprises alone, with no central SOEs entering, and many small and inefficient generators during this time belonged to local SOEs such as Yudean Group. Because of their important contribution to local fiscal revenue and employment, local governments have a strong motivation to give local SOEs preferential treatment. After the power sector reform introduced market competition in 2015, for the survival of their low-efficiency units, these local SOEs have the incentive to lobby local government to guarantee their operating hours. Certainly, we cannot attribute this semi-planned and semi-market dispatch approach solely to regulatory capture; however, our results do indicate a significant preference for local SOEs in allocated generation.

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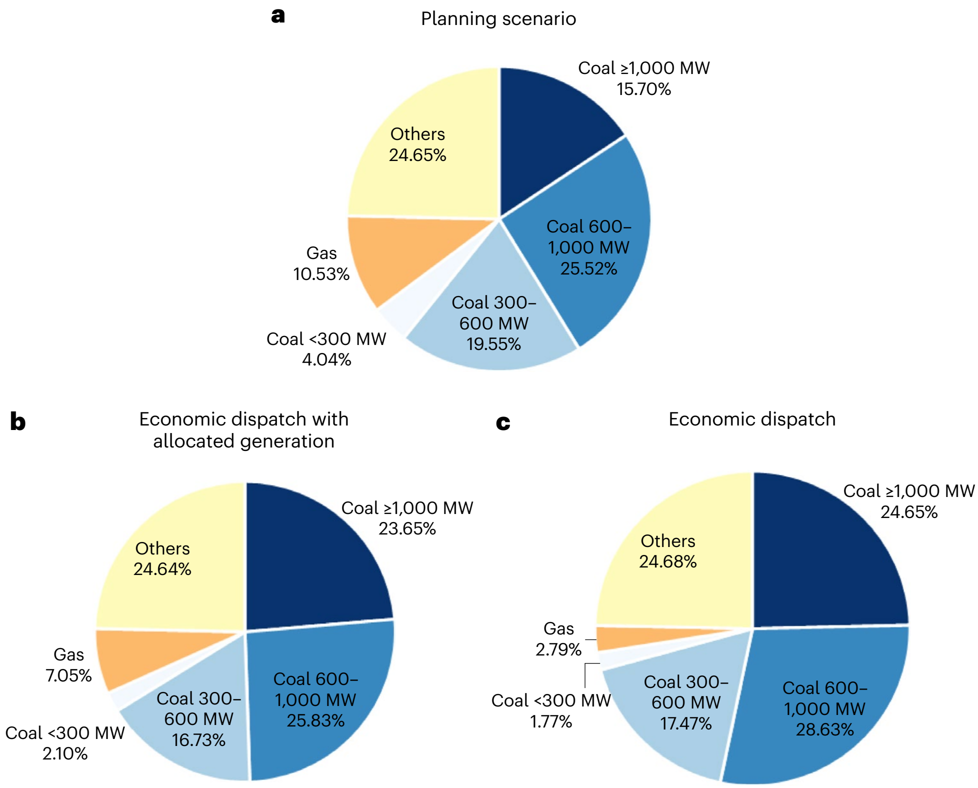


**Fig. 5 | Generation mixes in three scenarios with different dispatch approaches. a**, Generation mixes in previous planning scenario (equal share dispatch). **b**, Generation mixes in current semi-planned and semi-market scenario (economic dispatch with allocated generation). **c**, Generation mixes in ideal market-based scenario (economic dispatch).

## Impact on carbon emission and social welfare

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 emissions reduction and social welfare gains.

For the impact on the generation mix, there are two main differences among the three scenarios. Within coal-fired power, the degree of structural optimization (the shift from low-efficiency power units to high-efficiency power units in the generation mix) gradually deepens with the intensity of economic dispatch implementation. The generation from 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 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 (Supplementary Note 2). Between coal-fired and gas-fired power, allocated generation continues to favour 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 if under the previous equal dispatch or under the current allocated generation dispatch. As shown in Fig. 5, 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 7% of gas-fired generation in the semi-planned and semi-market scenario.

In terms of the impact on carbon emissions, regulatory capture through allocated generation makes it difficult to achieve the highest level of carbon emissions reduction potential. As seen from Fig. 6, 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 emissions 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 emissions reduction effect of economic dispatch is probably substantial[29].

Completely implementing economic dispatch also helps to improve social welfare, because economic dispatch leads to greater generation efficiency and thus lower generation costs (as illustrated by the size of *abc* in Supplementary Fig. 1). 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 increases the total social surplus only

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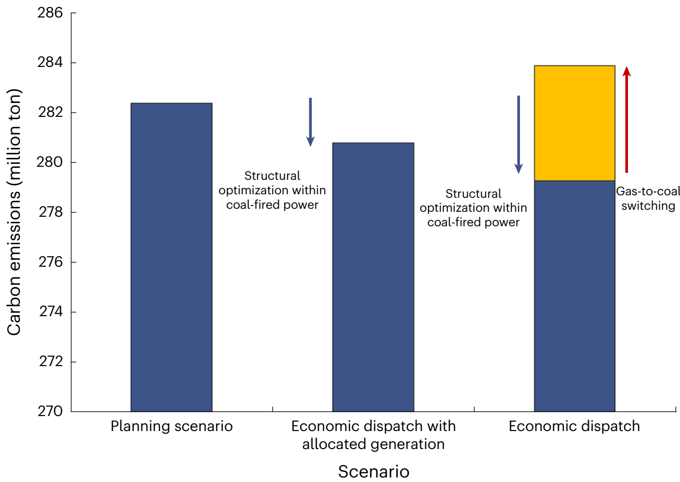


**Fig. 6 | Carbon emissions in three scenarios.** The three blue bars represent carbon emissions in different scenarios without province-specific rebound effect, reflecting the positive impact of coal-fired structure optimization. The yellow bar in ideal market-based scenario (economic dispatch) captures the additional carbon emissions brought by the gas-to-coal switching issue in Guangdong.

by 4.1 billion yuan a year (or by a share of 2.98%), 43.8% lower than the economic dispatch scenario (Supplementary Note 3).

## 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. Our study finds 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.

On the basis of data from five provinces in southern China, this study identifies the overall influence of China's latest reform on efficiency and explores the driving forces of efficiency improvement, considering both economic and political factors. We find 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 could be realized.

The electricity market could play an important role in China's transition to a low-carbon energy system. On the basis of the results obtained above, we propose three ways to mitigate the shortcomings of the current provincial market reform pilots. First, 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. Second, establish a well-functioning regional market to break down provincial barriers and overcome the imbalance of provincial resource endowment[30]. 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[31]. In addition, full-scale regional market competition would change the future investment in renewable resources, as they are becoming cheaper than coal[32]. Finally, considering the unique characteristics of Chinese politics and the economy, we propose the formulation of a relevant compensation mechanism to help some key stakeholders transition to clean energy and the wholesale electricity market[18,26]. 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.

## Methods

### 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 and its driving factors with a dataset at generating-unit level during the period of 2010 to 2018. In this Article, we measure the coal-fired generator's efficiency by heat rate (in gce $kWh^{-1}$): the standard coal input used to generate a unit of saleable electricity. Generally, a market-based dispatch system 'arranges' the generation order according to the marginal costs of generators. Simply put, it's the fuel cost that plays a decisive role because labour costs are unobservable and variable operations and maintenance costs account for only a small percentage, normally under 5% (ref. 33). 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 Fig. 2a 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 a 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 and marginal costs. The practice of using heat rate as a representation for efficiency is also adopted in many studies such as Chan et al. and Li and Ho[34,35].

After determining the efficiency indicator, we divided the whole sample into two periods, before and after 2015, and made regression analysis respectively to identify the reform effect. 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 included only the data in 2017 and 2018 when making the post-reform analysis. 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 1 and Table 2 are organized as equations (1) and (2):

$$\mathrm{Hour}_{i,t} = \beta_1 \mathrm{heat\ rate}_{i,t} + \lambda_\mathrm{t} + \alpha_\mathrm{p} + \varepsilon_{i,t} \quad (1)$$

$$\mathrm{Hour}_{i,t} = \beta_2 \mathrm{cap}_{i,t} + \gamma \mathrm{owner}_{i,t} + \lambda_\mathrm{t} + \alpha_\mathrm{p} + \varepsilon_{i,t} \quad (2)$$

where $\mathrm{Hour}_{i,t}$ is generator $i$'s operating hours in year $t$; heat $\mathrm{rate}_{i,t}$, $\mathrm{cap}_{i,t}$ and $\mathrm{owner}_{i,t}$ are the heat rate, installed capacity and ownership structure of generator $i$ in year $t$; $\beta_1$, $\beta_2$ and $\gamma$ are the coefficients of heat rate, installed capacity and ownership structure, respectively; $\lambda_\mathrm{t}$ is the time effect that does not change among individuals; $\alpha_p$ is the provincial effect that does not change with time; and $\varepsilon_{i,t}$ 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 China Southern Power Grid Dispatch Annual Report[36], issued by China Southern Power Grid Dispatching and Control Center. The report annually 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) and so on. To further confirm the generators' ownership type, we query the industrial and commercial information of their property owners (that is, the largest shareholders) one by one through the National Enterprise Credit Information Publicity System[37], which is run by the State Administration for Market Regulation of China. If the largest shareholder is administered by the central government (that is, its controlling shareholder is SASAC or the Ministry of Finance), we designated the power plant as a central SOE; if the largest shareholder is administered by provincial, municipal and lower-level governments (that is, its controlling shareholder is local SASAC or local finance bureau), we designated the power plant as a local SOE and so on. In other words, the enterprise's ownership structure is defined based on relative majority state shareholding in this paper. We divided all the enterprises into four types: state-owned enterprises that are administered by the central government (central SOEs); state-owned enterprises that are administered by provincial, municipal and lower-level governments (local SOEs); local private enterprises and other enterprises like Sino–foreign joint ventures and Hongkong–Macao–Taiwan-invested enterprises. Previous studies have often used the data from Chinese Industrial Enterprises Database (Industrial Enterprise Surveys) to make these designations[38], but because the last time this database updated was in 2015, we did not use it as the main data source in this paper. To ensure the accuracy of ownership definition, we have also compared the data from Chinese Industrial Enterprises Database with ours during the period of 2010–2015, and the information of the shareholders is consistent.

We have a total of 2,224 observations in the nine years, covering around 90% of coal-fired generators in the southern grid region. Supplementary Table 6 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 Supplementary Table 3, Guangdong has the largest market share, and generators with larger capacities or belonging to central SOEs always have higher efficiency (lower heat rates).

### 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 in 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 and so on) 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 dispatch model is used to simulate the operation at an hourly resolution in Guangdong in 2018. Unlike the planning scenario, the economic dispatch scenario complies with the cost-minimization rule. To minimize total operating costs, generation is allocated to generators based on their merit order, 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):

$$\min\ \text{Cost} = \sum_{t=1}^{8,760}\sum_{g}\text{GEN}_{t,g}\text{MC}_g + \sum_{t=1}^{8,760}\sum_{j}\text{TRA}_{t,j}\text{TC}_j \tag{3}$$

where Cost is the estimated total operating cost of the power sector in Guangdong in 2018, including power-generation costs and transmission costs; $\text{GEN}_{t,g}$ is the generation of technology $g \in$ {coal 1,000 MW, coal 600 MW, coal 300 MW, coal <300 MW, gas, nuclear, hydro, wind, solar, biomass} at hour $t$ in Guangdong; $\text{MC}_g$ is technology $g$'s marginal cost; $\text{TRA}_{t,j}$ is the trade flow between Guangdong and province $j \in$ {Guangxi, Yunnan, Guizhou, Hainan} at hour $t$; and $\text{TC}_j$ is the transmission cost per unit. Because we focused on the provincial market, the inter-provincial 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 $\text{TL}_j$ 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, nuclear and biomass, which are able to run all day, the generation at hour $t$ is constrained by the power-generation capacity $\text{CAP}_g$ after deducting technical losses $\text{loss}_{t,g}$; for variable power such as hydro, wind and solar, which are unable to operate all day due to natural condition restrictions, their generation is constrained by the installed capacity multiplied by capacity factor $\text{CF}_{t,g}$ (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. $\text{TRA}_{t,j,\text{Guangdong}}$ in equation (6) represents the trade flow from province $j$ to Guangdong at hour $t$ (import), and $\text{TRA}_{t,\text{Guangdong},j}$ represents exports. $\text{Line}_{j,\text{Guangdong}}$ 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.

$$0 \le \text{TRA}_{t,j} \le \text{TL}_j \tag{4}$$

$$\begin{cases} 0 \le \text{GEN}_{t,g} \le (1-\text{loss}_{t,g})\text{CAP}_g\, g \in \\ \{\text{ coal 1,000 MW, coal 600 MW, coal 300 MW, coal} \\ <300\text{ MW, gas, nuclear, biomass }\} \\ 0 \le \text{GEN}_{t,g} \le \text{CAP}_g\text{CF}_{t,g}\, g \in \{\text{hydro, wind, solar}\} \end{cases} \tag{5}$$

$$\sum_g \text{GEN}_{t,g} + \sum_j [\text{TRA}_{t,j,\text{Guangdong}}(1-\text{line}_{j,\text{Guangdong}}) - \text{TRA}_{t,\text{Guangdong},j}] = D_t \tag{6}$$

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 $\text{GEN}_{t,g}$ needs to be adjusted. With other constraints remaining unchanged, the constraints in equation (5) change to equation (7).

$$\begin{cases} \text{ALLO}_{t,g} \le \text{GEN}_{t,g} \le (1-\text{loss}_{t,g})\text{CAP}_g\, g \in \\ \{\text{coal 1,000 MW, coal 600 MW, coal 300 MW coal} < 300\text{ MW, gas}\} \\ 0 \le \text{GEN}_{t,g} \le (1-\text{loss}_{t,g})\text{CAP}_g\, g \in \{\text{nuclear, biomass}\} \\ \text{GEN}_{t,g} = \text{CAP}_g\text{CF}_{t,g}\, g \in \{\text{wind, solar}\} \\ 0 \le \text{GEN}_{t,g} \le \text{CAP}_g\text{CF}_{t,g}\, g \in \{\text{hydro}\} \end{cases} \tag{7}$$

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, because they are given the administrative priority to generate at maximum potential, we assume their down limits equal upper limits in this scenario. The constraints for nuclear, hydro and biomass remain unchanged.

In the 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.

On the basis of the cost-minimizing dispatch model, the generation mixes in each scenario are simulated, and then the corresponding carbon emissions and welfare change can be estimated further. The carbon emissions are calculated following equation (8), where heat $rate_g$ is the heat rate of technology $g$, and EF is the carbon emissions factor per unit of standard coal consumption (it takes the value of 2.66 $gCO_2\,gce^{-1}$, according to the Southern Power Grid Dispatch Annual Report). We approximately take the carbon emissions of nuclear and renewables as zero.

$$\mathrm{Carbon}_g = \sum_{t=1}^{8,760} \mathrm{GEN}_{t,g} \mathrm{heat\ rate}_g \mathrm{EF} \quad (8)$$

The assessment of social welfare change is straightforward and simply involves comparing the areas under the supply and demand curves. Here we estimated the welfare change at economic level, and the environmental externalities such as air pollution and climate impacts are not included. Because 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 Fig. 1. In economic dispatch scenario, we assumed that the allocation of operating hours depends entirely on the market and estimated the welfare improvement. However, we admit that there may be some unobservable factors that limit the operating hours for more efficient plants, so our estimation provides an upper bound under observable conditions.

We did not 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 because the fuel cost of gas power in China is quite high, which is proven by Chen et al.[33]. As these constraints cannot 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. Besides, we did not consider the impact of an emissions trading system (ETS) in our dispatch simulation because during our sample period, the carbon price of Guangdong/Shenzhen ETS pilot was not high enough to change the dispatch order (Supplementary Fig. 2b), while the national ETS has not yet started.

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 that in southern grid in 2018, and the other four provinces in the southern grid region were not included due to a lack of allocated generation data.

The electricity load in Guangdong is accessed from the South China Energy Regulatory Office of the National Energy Administration, shown in Supplementary Fig. 3a. The installed capacity and inter-provincial transmission capacities (in GW) between Guangdong and other four provinces are 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 $CAP_gCF_{t,g}$ of different renewables is shown in Supplementary Fig. 3b. Besides, we set the line loss rate as 5.51%, which is the average value calculated from the Dispatch Annual Report. Some parameters, such as the estimated marginal costs of different technologies, were referred from Chen et al.[29]

The Guangdong Allocated Generation Guidance Plan records the monthly allocated generation of each generating unit (coal-fired and gas-fired) in each year. Supplementary Fig. 3c 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. Because the marginal costs do not change with time and our estimates are finally summed up to the year level, the assignment rules of allocated generation at the hour level would actually not affect our estimates. Supplementary Fig. 3d shows the estimated results when the allocated generation is allocated per hour according to demand fluctuations. It could be seen that the result under semi-planned and semi-market scenario in Supplementary Fig. 3d is consistent with that in Fig. 5. The change in assignment rules does not lead to a change in estimated results.

## Data availability

The unit-level data and high-frequency data used during the current study were obtained under a confidentiality agreement and hence cannot be made publicly available. Other data are available from the corresponding author on reasonable request.

## Code availability

Requests for the code developed and annotated in Stata (Version 15) and Matlab (Version R2016a) to process and analyse the primary data will be reviewed and made available upon reasonable request.

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## Author contributions

C.X., X.Z., J.L. and F.S. designed the study. X.Z., F.S. and Z.J. supported the data collection. C.X. performed the modelling, carried out the analysis and drafted the paper. J.L. supervised the work, co-wrote the paper and provided policy recommendations. All authors reviewed the paper.

## Competing interests

The authors declare no competing interests.

## Additional information

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