Transition from plan to market: Imperfect regulations in the electricity sector of China ☆

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Abstract: We present evidence on the distortions that arise from imperfect regulations compared with market allocation mechanisms. Using a triple differences strategy, we evaluate the effectiveness of the Energy-Saving Generation Dispatch reform in China, which aims to allocate more generating hours to power plants with higher energy efficiency. We find that the new dispatch rule improved resource allocation within provinces compared with the previous equal-share dispatch rule. However, despite these improvements, the reform fell short of its intended goals because of the failure to strictly implement the merit order based on real-time coal consumption rates. We demonstrate how the lack of compensation for losers, technical requirements for grid stability, the existence of multiple goals, and information costs contribute to imperfect regulation.

Keywords: Power plant; Dispatch; Imperfect regulation; Market; China
JEL codes: L51, L94, P21, Q48

1. Introduction

In a planned economy, resources are subjected to government controls and certain regulations are designed to reach policy goals such as equity or minimum consumption guarantees. However, government regulations, even well-intended, can result in substantial inefficiencies and distortions when compared with market-based allocation (Joskow, 2010). Previous research indicates that international lessons in regulatory policies which did not function as intended (Bhattacharyya et al., 1996; Le Grand, 1991; Martimort, 1996; Yavlinsky and Braguinsky, 1994). However, the reasons and mechanisms underlying the regulatory failure remain poorly understood, particularly in the context of public sectors within economies transitioning toward markets.

The Chinese economy was dominated by central planning until 1978 when major reforms began, and the government started to use markets to allocate resources for some goods. While most industries in China have now undergone market reforms, a notable exception is the power generation sector.

The electricity sector is traditionally viewed as a natural monopoly because of economies of scale in generation and distribution networks (Borenstein and Bushnell, 2000; Joskow, 1997). Nevertheless, the average scale of power plants, especially since the surge in renewable power, has drastically declined over time. Many developed and some developing countries have begun marketization or have restructured their electricity sectors in the recent decades (Borenstein and Bushnell, 2015; Erdogdu, 2007; Hogan, 2002). However, China has instead adopted an incremental approach to reforming the electricity sector, previously administered by the Ministry of Electric Power (MEP) (Ngan, 2010; Pollitt et al., 2017). Did the incremental reforms improve the efficiency of the electricity sector or introduce inefficiencies with skewed prices and market segmentation (Young, 2000)? If there were inefficiencies, what aspect of the system, the institution or the reform process created them? What insights can we derive from the gains and losses of previous reforms that are useful for designing and implementing current reforms including electricity market liberalization? Power dispatch reform in the complex multi-layered electricity system in China provides an attractive setting in which to explore these questions.

Power dispatch in China differs from the commonly used economic dispatch.[1] Inherited from the planned economy era, electricity dispatch follows a "Transparent, Fair and Impartial" principle, which is widely known as the *san gong*, or "three fairness"

[1] In many countries, generators are dispatched in order of increasing variable cost, which is called economic dispatch. The order is mainly affected by fuel costs. In countries with generation markets such as the United States, the economic dispatch is realized by market mechanisms based on strategic offers of individual generators through forward and spot markets (Ho et al., 2017; Kahrl et al., 2013).

principle.[2] Provincial agencies set an annual quota for each power plant based on an equal-share principle in which generators of the same class are allocated the same annual hours of operation. This approach was established in part to attract private investment in generation during periods of shortages. Consequently, all coal-fired power plants of a given class were allocated similar annual utilization hours, irrespective of their differences in energy efficiency and technology. This system of allocation failed to discourage investment in small inefficient thermal power plants (Kahrl et al., 2013).

To improve the energy use efficiency realized in this equal-share system, and reduce pollutant emissions, the government initiated a pilot of Energy-Saving Generation Dispatch (ESGD) system in 2007. In the pilot areas, the provincial government determines the power dispatch order according to fuel efficiency and pollutant emission levels. This reform of power generation dispatch changes the administrative allocation from an equal-share dispatch to an energy-saving dispatch.

The dispatch reform is a step toward market allocation. The new merit order is based on energy efficiency which rewards reductions in fuel use and lower marginal cost. Nevertheless, the dispatch allocation remains an administrative decision and is subject to centralized regulation due to political and economic challenges (Kahrl et al., 2013; Wei et al., 2018). In the context of this unique reform setting, this paper revisits the issues of government regulation and market transition with comprehensive power plant level data. The following questions are addressed: Did the reform achieve the desired outcome? What was the energy saved by the reform compared with the equal-share dispatch rule inherited from the planned economy system? How, and why did the realized dispatch differ from the market dispatch? What lessons can be learned for current power system reforms?

We adopt a difference-in-differences (DD) framework to compare output changes in thermal power plants regulated under the policy with those plants that were unregulated. The between-province analysis of power plants shows that, on average, the dispatch reform had insignificant effects on power generation and hours in pilot provinces compared with plants in non-pilot regions.

Despite the overall null effect, we find that the reform caused large compositional changes in power generation within the power plants of a given capacity level in the pilot provinces. According to the ESGD policy, the power plants should be dispatched in an ascending order based on real-time fuel efficiency. However, the triple-difference

[2] The document is available at: http://www.nea.gov.cn/2011-08/16/c_131052767.htm. The principle, *san gong or the three gongs: gongkai, gongping, and gongzheng*, (meaning; transparent, fair, impartial) is a classical reference to the legitimacy of governing systems.

results indicate that, instead of considering real-time coal consumption rates, the pilot provinces dispatched electricity based on nameplate coal rates, which were determined solely by generator capacity. Furthermore, although power plants with larger capacities were indeed allocated more hours, our findings reveal deviations from a strict capacity-based order. These deviations illustrate the operation of imperfect regulation under an administrative system in comparison with market allocation.

We further uncover the underlying drivers of the imperfect regulation. First, we demonstrate that the lack of compensation for power plants allocated fewer hours is most likely the critical reason behind the policy's imperfect implementation. Our empirical analysis reveals that provinces without a specific compensation mechanism for ESGD deviated more significantly from the merit order than those with a mechanism. The lack of compensation failed to adequately address the interests of all stakeholders, resulting in opposition from smaller power plants that were allocated lower generation quotas. Second, we find that regions with fewer fluctuations in net electricity load were more capable of adhering closely to the merit dispatch order. This highlights the technical constraints of maintaining system stability and reliability in changing power dispatch. Additionally, multiple other factors, such as favoritism towards local stakeholders, stringent regulations on air pollution, and incomplete information on real-time coal consumption, could also contribute to intentional or unintentional deviations from the efficiency goal.

This paper contributes to previous work in the following ways. First, our study fits into a large body of literature that discusses the inefficiency in government regulations pertaining to energy and environmental policy. For example, Fowlie (2009) demonstrates how incomplete pollution regulation induces leakages in the imperfectly competitive power industry, and Cicala (2015) highlights how asymmetric information, capital bias and regulatory capture result in regulatory distortion. The inefficiency is also attributed to the heterogeneity in compliance costs across firms under regulation , as discussed by Lade and Rudik (2020). In China, regulations in an administrative style are very common (Greenstone and Schwarz, 2018). Here we provide evidence on the regulatory failure in a market economy mixed with planning characteristics, traits that are also common in other transition economies.

Owing to the regulatory imperfections, the transition from command-and-control to market allocation in the electricity sector has been a primary focus of much research. Chan et al. (2017) find that electricity restructuring has a positive effect on plant efficiency. Discussions of reforms by Borenstein and Bushnell (2015), Jamasb and Pollitt (2005), Fabrizio et al. (2007) and Ibarra-Yunez (2015) also confirm that liberalization leads to allocative efficiency gains. This paper is closely related to that of Cicala (2022) who shows that market dispatch in the US electricity sector significantly reduces total production costs because of gains from trade compared with "economic dispatch" in which dispatchers try to prioritize efficient sources without price signals. Here we find that the ESGD reform, with an intended order akin to economic dispatch, failed to achieve the optimal dispatch in terms of cost saving.

Our second contribution is to revisit economic reforms in China (e.g., survey by (Xu, 2011)). China takes an incremental approach to reforming its economy, whereby a part of production is allocated by markets and a part is allocated by various administrative plans (Byrd, 1987; Wong, 1987). However, the partial reforms encounter obstacles, such as a breakdown in production coordination, opposition to privatization (Murphy et al., 1992), and rent-seeking behavior from local governments (Young, 2000). Nevertheless, Sicular (1988) concludes that planning and markets are not at odds, and that the mixed system was well justified by the situation at that time. Lau et al. (2000) also argue that economic reforms in China achieve efficiency without creating losers. We attempt to understand the features of economic reform by examining power sector reform in China (Chen et al., 2022; Ho et al., 2017; Williams and Kahrl, 2008; Xie et al., 2020b; Zhao and Ma, 2013). Most ex-post analyses evaluate the effects of the 2002 unbundling of generation and transmission, and the 2015 general reform (Du et al., 2013; Ma and Zhao, 2015; Xie et al., 2020a; Zheng et al., 2021). The dispatch system is a crucial element in the power sector, but its reforms lag behind other changes to the power system. China has introduced markets for long-term contracts and is currently pushing to include diverse sources of power in the electricity markets to establish a market dispatch system (Pollitt, 2021). The efficiency gains and emission reduction benefits of market-based reforms in the electricity sector have been compared with egalitarian distribution (Chen et al., 2020a; Ding et al., 2023; Luo et al., 2023; Yu et al., 2023).

Studies have also focused specifically on the ESGD. Studies by Ding and Yang (2013), Gao and Li (2010), Kahrl et al. (2013), Dong et al. (2015) and Ho et al. (2017) provide comprehensive insights into the implementation of the ESGD policy, illuminating the short-term results obtained, while also dissecting potential challenges and implications for various stakeholders. Notably, these studies do not provide a quantitative analysis of actual effects. Ex-ante modeling analyses are predominant in quantitative research, which involve three distinct phases. During the ESGD pilot phase, potential benefits are estimated based on the literature in terms of energy efficiency, emission reductions and economic costs. The benefits are obtained via either optimization and unit commitment models (e.g., Gao and Li, 2010), or straightforward re-ordering of dispatches (e.g., Kahrl et al., 2013). Research conducted in the latter stages of the policy, particularly after the failure of the pilot rollout, primarily proposed schemes to improve energy-efficient generation dispatch. Various elements are considered, such as generation and demand-side uncertainties (Liu and Li, 2018), renewable energy curtailment (Zhao et al., 2017), obtaining the support of all stakeholders (Zhong et al., 2015; Ding and Yang, 2013), and the transition toward a market mechanism (Wei et al., 2018). Recent papers focus more on evaluating the potential benefits of a successfully implemented economic dispatch compared with the equal-share scheme (Luo et al., 2023; Xiang et al., 2023b; Yu et al., 2023). Our work discusses the effects of the dispatch rule change empirically in detail and investigates the reasons why the implementation of the pilot reforms deviated from a strict interpretation of the regulations. The ex-post exploration of regulatory distortions in the implementation of the ESGD provides a nuanced perspective on the challenges of market-oriented reforms in China. Additionally, it highlights the advances made through incremental policy changes. We find that the dispatch reform was not as effective as sometimes claimed. The incremental reform significantly improved total generation efficiency compared to that achieved with the equal-share dispatch; however, it still falls short of achieving optimal dispatch.

The third notable contribution of this paper is an in-depth discussion on compensation mechanisms in reforms, thereby enriching the literature on redistribution resulting from policy changes. As governments begin policy reforms, it is almost inevitable that even policies with net social benefits will produce losers. How those conflicts of interest are addressed will shape the trajectory of future policies, whether offering satisfactory compensation or staging or postponing the reform initiative (Trebilcock, 2014). A long strand of papers emphasize the significance of compensation in the reform process (Angell and Graham, 1995; Commander, 2012; Jain and Mukand, 2003; Rodrik, 1996). For electricity systems, a shift toward a more liberalized market should take into account the diverse interests of key stakeholders, as evidenced by Arocena et al. (1999) on Spanish reforms and Tankha et al. (2010) on India.

We provide empirical evidence emphasizing how insufficient compensation structures led to less effective implementation of dispatch reform. We find that compensation strategies differed across regions, and remarkably, market-driven compensation methods often underperformed when accompanied by imperfect market-supporting elements. By contrast, administratively directed compensation was effective but unsustainable. The feasibility of enforcing compensation, especially amidst fluctuations in market-driven coal prices, remains uncertain. We also examine the role of local governments in balancing diverse interests and achieving multiple objectives.

When the government is intertwined with a losing sector, local protectionism can be a coping strategy during a redistributive process (Jain and Mukand, 2003). A transition to market-based economic dispatch would make inefficient local state-owned enterprises (SOE) lose market share (Ding et al., 2023). This study highlights the preferential treatment extended by local governments to non-central SOEs in dispatch reform. Such preferential treatment illustrates the selective enforcement of reforms in response to local interest lobbying by myriad groups.

The remainder of this paper is organized as follows. Section 2 provides the policy background, whereas Section 3 describes the empirical framework, including data description and econometric models. Section 4 presents the main results, and Section 5 explores underlying mechanisms. Section 6 analyzes the welfare effects, Section 7 discusses dispatch change after ESGD, and Section 8 provides conclusions.

2. Background on the electricity system and dispatch

2.1. Chinese electricity reform

Before 1985, the central government, via the MEP, had total control of the electricity industry. Then, beginning in 1985, electricity generation was opened to other investors, and electricity tariffs were adjusted to attract private investment. Beginning in 1997, the central government reformed the management system, separating the regulatory functions from enterprise operation. The State Power Corporation was founded in 1997 to operate the power system and the MEP was dissolved in 1998, transferring regulatory responsibilities to the State Economic and Trade Commission. In 2002, the State Council passed further reforms to develop an electricity market system. Generation units were separated from transmission and distribution, which were assigned to the State Grid Company. In 2003, a new independent regulator, the State Electricity Regulatory Commission, began to conduct trials of regional wholesale markets. However, the experiment was suspended because of power shortages. In 2015, Chinese authorities launched a new round of reform with the issuance of "Document No. 9".[3] The aims of the new policies were to improve the reliability of the power system, introduce more market mechanisms, protect residential and agricultural consumers, realize energy savings and emission reductions, promote renewable energy generation, and improve governance and regulation. Some pilot provinces promoted power market construction by introducing and expanding market-based electricity

[3] "Document No. 9", titled "Opinions on Further Deepening the Reform of the Electricity System", is available at https://zcfg.cs.com.cn/chl/58f5139dbe0648a3bdfb.html?libraryCurrent=InnerParty.

trading (Guo et al., 2020).

2.2. Power dispatch reform in China

A distinctive feature of Chinese dispatch organization is unified dispatch among multilevel management (Ho et al., 2017). There are five levels of dispatch organization, which correspond to different jurisdictions and functions. They are national dispatch organization (DO), and regional, provincial, prefectural, and county DOs. Most generators are dispatched by provincial DOs.

Chinese electricity reform includes reform of the dispatch system to adapt to the new decentralized system. Energy-Saving Generation Dispatch is one of the past reform attempts that was not very successful.

With the major economic reforms that began in 1978, gross domestic product (GDP) grew rapidly and increasing demand for electricity posed an enormous challenge. Before the dispatch reform of 2007, every coal-fired generator in a given class was entitled to an equal-share of the generation quota under the *san gong* system noted in the Introduction (Teng et al., 2017). This “equal-share” dispatch rule is associated with the pricing principle of “cost-plus reasonable profit,” which can provide an equal opportunity for cost recovery for generating units. However, this equalitarianism ignores the different energy efficiencies and pollution intensities of generators. Therefore, small generators of low energy efficiency and high emissions are allocated the same annual generation hours as efficient and environmentally friendly ones, which impedes the low-carbon transformation of the electricity sector (Kahrl et al., 2013). By the end of the 1990s, the electricity shortages were effectively relieved, but instead, an over-construction of generation capacity resulted in low utilization rates. Thus, reform of dispatch to reduce energy inefficiency became urgent.

In August 2007, the State Council approved the “Pilot Measures for Energy-Saving Generation Dispatch (ESGD)” to minimize energy consumption and pollutant emissions. This policy was an important change in power dispatch principles. In December of the same year, detailed pilot measures for implementing the policy were published. The government selected Guangdong, Guizhou, Jiangsu, Henan and Sichuan as five pilot provinces for ESGD. Guizhou Province was the first to launch its ESGD pilot program on January 1, 2008. On November 17, 2008, Guangdong officially initiated its dispatch policy, followed by Sichuan, Jiangsu, and Henan. Additional details about the program procedure are described in Appendix A in Supplementary

Materials.[4] In the five pilot provinces, the merit order for dispatching generating units is based on their fuel consumption and pollutant emission intensities (Table D.1 in Supplementary Materials). Renewable energy is favored first, and the reliability of power supply is also considered. Among coal units, they are placed to be in an ascending order of coal consumption rate. For a given energy consumption level, the government prioritizes low emissions.

In addition to the fundamental merit order, the implementation of this policy also needs a series of supporting services such as pollutant emission monitoring, information provision and economic compensation.

After several years of experimentation, the reform seemed to achieve remarkably positive results in some pilot provinces. In 2009, the five pilot provinces claimed to have saved a total of 4.14 million tonnes of standard coal equivalent (tce) and reduced carbon dioxide emissions by 9.55 million tonnes.[5] The reduction was 1.27% of national reference carbon dioxide emissions in 2009, based on the 7,567.6 million tonnes reported by Shan et al. (2018). As the first pilot province to initiate the ESGD program, the Guizhou Power Grid claimed to have saved approximately 1.35 million tce after implementing ESGD from January to September in 2008.[6] In 2011, the coal consumption rate for power generation of the Guizhou Power Grid decreased by 21 g/kWh compared with 327 g/kWh in 2008 (Dong et al., 2015). In 2010, the China Southern Power Grid launched ESGD in all five provinces under its jurisdiction. However, contrary to initial expectations, the dispatch method was not extended to other provinces. In 2015, the "Special Supervision Report on ESGD in East China and Central China" issued by the National Energy Administration stated that ESGD had not been perfectly implemented in the pilot provinces owing to opposition from many coal plants, and some provinces even switched back to equal dispatch plans.[7]

A group of papers discuss the barriers that led to inappropriate dispatching order in the actual implementation. Technically, the dispatch system is constrained by stability and reliability requirements. The establishment of the ESGD mechanism can increase stability risks to the power grid with the closing down of small coal-fired power units as well as the large-scale integration of renewable energy (Dong et al., 2015). Dispatch implementation is also inseparable from the installation of real-time monitoring systems, which provide the most crucial foundation for determining the

[4] The separate Supplementary Materials is available online.
[5] The announcement can be found at http://www.gov.cn/govweb/jrzg/2010-12/27/content_1773607.htm.
[6] This is given in an announcement by the Asset Supervision and Administration Commission at http://www.sasac.gov.cn/n2588025/n2588124/c3898929/content.html.
[7] The National Energy Administration report is given at http://zfxxgk.nea.gov.cn/auto92/201506/t20150612_1937.htm.

merit order (Ding and Yang, 2013). However, such monitoring systems are far from completion (Dong et al., 2015). Moreover, there are institutional obstacles to reform (Gao and Li, 2010), and the redistribution of benefits is resisted by powerful stakeholders in the absence of a mature financial compensation system (Ding and Yang, 2013). Relations between central and local governments are structured in a way that makes local implementation more uncertain. Owing to varying natural endowments and levels of economic development, provinces might dispatch generators differently (Ho et al., 2017). Furthermore, ESGD is essentially a centralized dispatch mechanism rather than a market-based approach, which is inconsistent with power industry marketization (Gao and Li, 2010). Changing only the merit order is not sufficient to achieve efficiency. Thermal power plants are paid a flat, benchmark tariff, and without changes in either wholesale or retail pricing, such a system lacks the incentives to increase energy efficiency and reduce emissions (Kahrl et al., 2013).

3. Empirical strategy

3.1. Data and variables

The plant-level data for 2005–2012 are collected from the China Electricity Council.[8] The data set encompasses thermal power plants with an installed capacity of 6 MW and higher, excluding self-owned power plants. It is highly representative of the entire set of thermal power plants in China, considering the low cutoff. As shown in Table D.2 of the Supplementary Materials, the total output and installed capacity of the thermal plants above 6 MW in 2005 were 2,030 Terawatt hours (TWh) and 381 GW, respectively, accounting for 99.3% and 97.4% of total thermal output and capacity of that year. The shares of the above 6 MW plants were even closer to 100% by the end of 2014, attributable to the phase-out of small plants.

We exclude observations where key information (e.g., capacity) is missing, utilization hours are larger than 8,760 h, or plant electricity consumption rate is less than 0. Additionally, we drop outliers and inconsistent data, referring to power plants whose output does not equal to the product of utilization hours and installed capacity. Ultimately, 2,220 thermal power plants are included in our sample. Table D.3 in Supplementary Materials presents the annual distributions of our samples after the

[8] Data are from annual issues of the *Compilation of statistics of the China electric power industry*. We choose data from 2005 to 2012 for the following reasons. First, there was a power reform in 2002, which might have induced significant changes in many areas. Second, a boom in coal power investment, initiated in 2014 because of the decentralization of investment approval power, might also interfere with our results. Some provinces switched back to equal-share dispatch around 2014, which is difficult to identify. Third, data are missing in 2013.

exclusions.

Our key outcome variable is the annual electricity output of power plants, which is directly affected by the allocation rule. Generation output (in megawatt-hours) is determined by installed capacity and utilization hours. For the policy effects on investment, we use capacity added one year after ESGD implementation because time is needed to adjust plant structure and equipment. We also construct a capacity redundancy variable, which is equal to the difference between potential generation (capacity multiplied by number of hours in the year) and actual generation. Another important outcome is standard coal consumption per unit of electricity supply, which is the amount of standard coal used to supply one kWh to the grid. In contrast to the coal consumption rate of power generation used in the literature (Ma and Takeuchi, 2020), the rate per unit supplied includes the plant's own electricity consumption, which is a more complete measure of energy efficiency.

Table 1 Definitions and summary statistics of variables

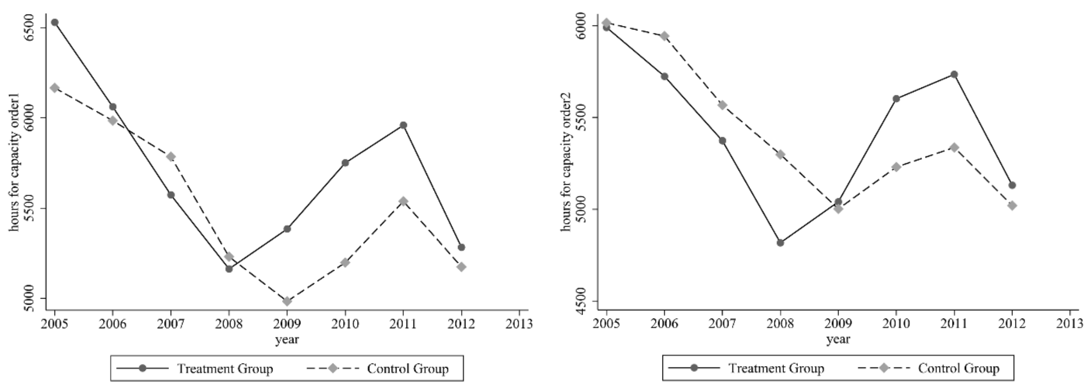
Variables	Definition	Obs	Mean	SD
Panel A. Key outcome variables				
Output	Power generation (10MWh)	10131	171987	289661
Hours	Annual utilization hours	9988	4779.7	1916.4
Coal rate	Standard coal consumption rate of power supply (g/kWh)	10136	400.5	119.75
Capacity redundancy	Capacity ×365 ×24 –output	9949	110174	181339
Capacity added the next year	The new installed capacity in the second year compared with the current year (MW)	8030	326.0	540.0
Panel B. Other plant level variables				
Capacity	Installed capacity at the end of the year (MW)	9953	325.0	523.6
Self cons	Self-consumption percentage of a power plant generation.	9857	8.17	3.99
Coal_gen_rate	Standard coal consumption rate of power generation (g/kWh)	10136	366.4	101.2

Note: Our sample includes observations for coal-fired power plants with an installed capacity of 6 MW and higher from 2005 to 2012. Self-owned power plants are not included because they are not subject to the unified grid dispatch.

Other power plant-level variables include installed capacity, the percentage of a power plant's self-consumption in power generation, and standard coal consumption per unit of electricity generated. The electricity self-consumption rate is the percentage of self-consumption in a plant's power generation. The variables at the provincial level are collected from the China Statistical Yearbook, China Electric Power Yearbook, the Compilation of Statistical Materials of Electric Power Industry, and government documents. Although only total plant capacity data are available, and not those for unit capacity-level data, a separate data set with unit level information (Global Energy Monitor, 2022) indicates that in plants with more than one unit, the units are often the same size.[9]

Detailed definitions and summary statistics of variables are given in Table 1, including key outcomes in Panel A and other plant level variables in Panel B.

We then divide the sample into capacity groups to determine whether there are differences in behavior: <100, 100–200, 200–600, 600–1000, and 1000+ MW. Fig. 1 shows the annual hours of treatment and control groups for each capacity order (class).[10] For power plants with capacity larger than 200MW, after 2009, the annual hours of the treated group are higher than the hours of the non-treated group (after 2010 for the 200–600 MW class). By contrast, the differences in annual hours between treated and non-treated samples are relatively small for plants with capacities smaller than 200 MW, especially within the <100 MW category.[11] The findings suggest that the effect of the reform likely varies across different capacity groups, with larger power plants experiencing more noticeable changes in annual hours following the implementation of the ESGD policy than those of smaller plants.



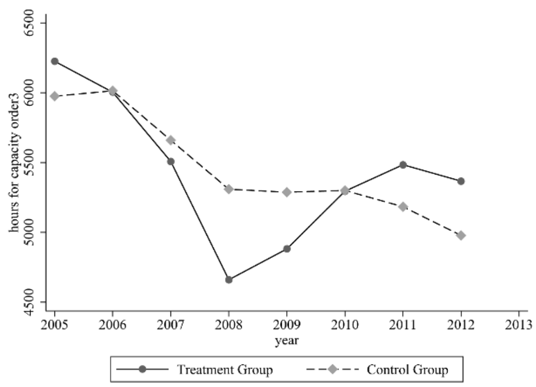
(a) Hours of plants, 1000+ MW

(b) Hours of plants, 600–1000 MW

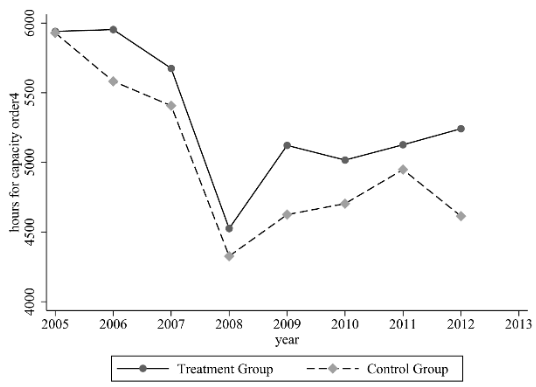
[9] We obtain unit information from "Global Coal Plant Tracker, Global Energy Monitor, July 2022 release." It includes coal-fired generating units 30 MW and larger.

[10] The power reform is a series of shocks where different provinces started ESGD at different times. Here we only divide each capacity group into treatment and control groups for each year, depending on when a province started ESGD.

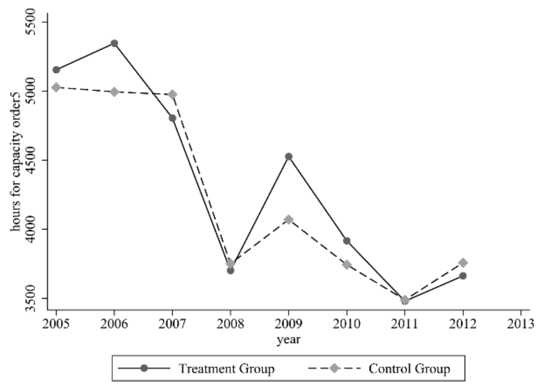
[11] Owing to the operation of new thermal power units, coupled with the abundant hydropower, the thermal power utilization hours in Guangxi, Sichuan, Hunan, Yunnan and other provinces decreased significantly in 2008. See news report (in Chinese): http://www.p5w.net/news/cjxw/200901/t2135556.htm.



(c) Hours of plants, 200–600 MW



(d) Hours of plants, 100–200 MW



(e) Hours of plants, <100 MW

Fig.1 Hours change between treatment and control groups for different capacity classes

Notes: Figure shows the average annual utilization hours of treatment and control groups for each capacity order (class). The treatment group in each year is the provinces that have implemented ESGD in that year.

3.2. Econometric model and identification strategy

To accurately evaluate the effects of the dispatch reform, we use an event study design that exploits the staggered timing of ESGD adoption for coal-fired power plants. We have the first implementation of ESGD in the five pilot provinces mentioned in a 2007 government document, later adoption by the three remaining provinces in the China Southern Power Grid in 2011, and staggered expansion to other provinces regulated by the State Grid Corporation.[12]

[12] Provinces are either in the State Grid or the Southern Grid. After the announcement of the ESGD pilot, several provinces regulated by the State Grid Corporation began implementing similar dispatch reforms. These provinces include Shaanxi, Fujian, Shandong, and Tianjin in 2008, Hebei in 2010, Ningxia in 2011, and Shanghai in 2012. Appendix A.2 in Supplementary Materials provides more details.

We construct a difference-in-differences (DD) framework, using power plants in provinces without dispatch reform to estimate counterfactual outcomes after adjusting for common shocks and time-invariant differences. The baseline DD estimation equation is as follows:

$$y_{ipt} = \beta ESGD_{pt} + \rho policy_{ipt} + \delta_i + \lambda_t + \eta_{gt} + \varepsilon_{ipt} \tag{1}$$

where y_{ipt} represents the technical and economic outcomes of power plant i in province p, region g, and year t. The outcomes include the logarithm of output, hours, installed capacity, and standard coal consumption rate for power supply. The $ESGD_{pt}$ equals 1 if province p officially implements the dispatch reform program in year t and 0 otherwise; δ_i is the plant fixed effect, λ_t is the time fixed effect, and η_{gt} is the region year-level fixed effect.[13] We cluster the standard errors at the province level.

To control for any possible contamination of related policies or external shocks, $policy_{ipt}$ is included as an explicit control in the DD estimation, where $policy_{ipt}$ = {FGD_{it}, $small\_shut_{it}$, $earthquake_{pt}$, $BOG08_{pt}$, $drought_{pt}$}. FGD_{it} is a dummy variable that equals one if power plant i has desulfurization facilities in operation in year t based on the National Coal-fired Unit Desulfurization Facility List.[14] $small\_shut_{it}$ is a dummy variable that equals one if power plant i in year t is listed in the First Batch of the Shutdown of Small Thermal Power Units and Shutdown Schedule.[15] $earthquake_{pt}$ equals one for Sichuan Province in 2008 to account for the earthquake that caused massive destruction and 69,000 deaths and zero otherwise. $BOG08_{pt}$ captures the effects of the 2008 Beijing Olympic Games, which are discussed by He et al. (2016) and Ma and Takeuchi (2020), among others.[16] The variable has the value of one if the province p belongs to Beijing and its neighboring provinces Tianjin, Hebei, Shandong, Shanxi, and Inner Mongolia and t equals 2007 or 2008 (He et al., 2016; Ma and Takeuchi, 2020). $drought_{pt}$ captures the shock of the 2010–2011 drought, which affected some provinces in the south with substantial hydro sources. For a convenient summary, a timeline of the major events and policy changes is provided in Figure C.1 in Supplementary

[13] We divide the provinces into six regions, which are generally the same as the six regional power grids. The Northeast region covers Liaoning, Jilin, and Heilongjiang; the Northwest region covers Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, and Tibet; the North China region includes Inner Mongolia, Beijing, Tianjin, Hebei, and Shandong; the East China region covers Shanghai, Jiangsu, Zhejiang, Anhui, and Fujian; the Central China region includes Henan, Sichuan, Chongqing, Hubei, Jiangxi, and Hunan; and the South China region covers Guangdong, Guangxi, Yunnan, Guizhou, and Hainan.

[14] This list is given at the Ministry of Environment and Ecology: https://www.mee.gov.cn/gkml/hbb/bgg/201407/W020140711581927228220.pdf.

[15] The schedule is given at the National Energy Administration: http://www.nea.gov.cn/2011-08/17/c_131053127.htm.

[16] To meet the air quality targets set for the 2008 Beijing Olympic Games in October 2007, the State Council of China issued the "Measures to Ensure Good Air Quality in the 29th Beijing Olympics and Paralympics". Some measures are aimed at power plants, including adopting clean coal, shutting down small thermal power plants, retiring outdated production facilities, and installing desulfurization equipment. Ma and Takeuchi (2020) find that the 2008 Beijing Olympic Games improved the energy efficiency of thermal power plants.

Materials.

Recent studies identify the pitfalls of a standard two-way fixed-effects (TWFE) estimator with multiple treatment times (Borusyak et al., 2021; Callaway and Sant'Anna, 2021; De Chaisemartin and d'Haultfoeuille, 2020; Sun and Abraham, 2021). To address these pitfalls, we also apply the approach by De Chaisemartin and d'Haultfoeuille (2022).

The DD strategy compares the output and hours of power plants in pilot provinces with those in nonpilot provinces, before and after the policy. Our approach also provides an opportunity to empirically estimate the allocation effects for power plants of different characteristics, because the rules state that generating units with higher energy efficiency should be allocated more hours. Therefore, the output of a power plant is determined by three sources of variation: 1) province variation in reform coverage, 2) temporal variation pre- and post- reform, and 3) capacity and coal rate variation. We leverage these variations in a triple differences framework to examine whether the allocation rule was strictly implemented. Identification relies on the assumption that differences in outcomes between plants of different capacities (i.e., plants with higher energy efficiency versus those with lower efficiency) in pilot provinces versus nonpilot provinces would follow the same trend in the absence of reform shocks, conditional on covariates.

The estimating equation for the outcomes of plant i under a fixed effects framework is as follows:[17]

$$y_{ipt} = \sum_{o\in\{1,2,3,4\}} \beta_o ESGD_{pt} \times Order_{it}^{o} + \rho policy_{ipt} + \eta_{pt} + \delta_i + \omega_{ot} + \varepsilon_{ipt} \tag{2}$$

where $ESGD_{pt}$ and δ_i are as in Eq. (1). $Order_{it}^{o}$ equals one if plant i falls in order bin o in year t and zero otherwise. Table 2 shows definitions of the two orders following Shi and Yang (2012), one based on capacity size and one on coal consumption rates. The interaction term $ESGD_{pt} \times Order_{it}^{o}$ is the variable of interest, and β_o measures the treatment effect of dispatch reform on power plants of order o compared with plants of order 5 (the omitted order). We consider Order–year and province–year fixed effects, absorbed by ω_{ot} and η_{pt}, respectively, to filter out unobserved factors that may be confounding with generation output. ε_{ipt} is an unobserved error term.

In Table 2 , which details the order definitions, the top panel is based on the coal

[17] The fixed-effects triple estimator is an extended version of the two-way fixed-effects estimator in the differences-in-differences regression. Although the framework in triple differences is widely used in recent research, we still need to consider the presence of staggered policy adoption and heterogenous treatment effects (De Chaisemartin and d'Haultfoeuille, 2022). We discuss this identification concern in Section 4.1 and show regression results using alternative estimators.

consumption rate (grams of standard coal/kWh). We categorize our data into five bins, ranging from the most efficient to the most inefficient. In the bottom panel, the five bins for installed capacity are provided. Table D.4 in Supplementary Materials presents the base year distributions of the coal rate and capacity orders.

Table 2. Definitions of power plant coal rate order and capacity order

Panel A CoalRateOrder	Std. coal consumption rate; from efficient to inefficient
CoalRateOrder1	0-290g/kWh bin
CoalRateOrder2	290-320g/kWh bin
CoalRateOrder3	320-365g/kWh bin
CoalRateOrder4	365-410g/kWh bin
CoalRateOrder5	Over 410g/kWh bin
Panel B Capacityorder	Installed capacity; from large to small
capacityorder1	Over 1000MW bin
capacityorder2	600-1000MW bin
capacityorder3	200-600MW bin
capacityorder4	100-200MW bin
capacityorder5	0-100MW bin

Notes: These are the classifications of the variable Order in Eq. (2). We employ two distinct categorizations, CoalRateOrder for coal consumption rates in Panel A and Capacityorder in Panel B.

4. Results

4.1. Main results

The overall effect of dispatch reform (Eq. 1) on output, utilization hours, and investment in new generation capacity (investment after 1 year) is presented in Table 3. We find no significant ESGD effect on plant power generation, which is determined by installed capacity and utilization hours. The estimates also indicate that the capacity and hours in pilot provinces are not significantly affected by the policy. Compared with plants in nonpilot provinces, the policy failed to have a statistically significant effect on power plants regulated in pilot provinces.

Because our empirical specification employs a staggered-event study design, it can be subject to multiple identification problems as noted by De Chaisemartin and d'Haultfoeuille (2022). To address this concern, we apply the method proposed by De Chaisemartin and d'Haultfoeuille (2022) to reestimate Eq.1, and present the estimations for average treatment effects in Panel B of Table 3.[18] Consistent with the conventional

[18] In the estimation of staggered DD, the average treatment effect (ATE) obtained from the two-way fixed-effects (TWFE) model may be biased if the treatment effect varies across time points and between groups. The heterogeneity

two-way fixed-effects estimates in Panel A, none of the coefficients are statistically significant. Furthermore, we also employ this method to estimate the dynamic effects of ESGD (Fig. 2). Irrespective of pre- or post-treatment, all coefficients are centered around zero and display no statistical significance. This lack of significance suggests that the overall effect of ESGD on power generation remains negligible, even when accounting for the various identification problems associated with staggered-event study designs.

Table 3. Overall effects of dispatch reform (Eq. 1)

	(1)	(2)	(3)
VARIABLES	ln(output)	ln(hours)	ln(NewCapacity $_{t+1}$)
	Panel A: OLS		
ESGD	-0.0914	-0.0824	-0.0376
	(0.0684)	(0.0510)	(0.143)
Observations	9,764	9,625	6,762
R-squared	0.945	0.663	0.252
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Region×Year FE	Yes	Yes	Yes
	Panel B: De Chaisemartin and d'Haultfoeuille (2022)		
ESGD	0.0931	-0.0873	-0.116
	(0.133)	(0.0761)	(0.237)
Observations	4,196	4,142	2,950
Year FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Region×Year FE	Yes	Yes	Yes

Notes: The dependent variables are logarithm of output (column 1), logarithm of utilization hours (column 2), and the capacity added 1 year after policy change (column 3). Energy-Saving Generation Dispatch (ESGD) is a binary indicator to represent whether a power plant has implemented ESGD policy. The estimates in Panel A are obtained by two-way fixed-effects (TWFE) DD regressions, whereas in Panel B, a heterogeneity robust DD framework is used. Robust standard errors for coefficients clustered at the province level are reported in parentheses; ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

robust DD estimator proposed by De Chaisemartin and d'Haultfoeuille (2022) can be applied to staggered binary or discrete treatments and generalized to staggered continuous treatments or nonbinary treatments. By calculating a weighted average of the different treatment effects, an unbiased estimate of the ATE can be obtained.

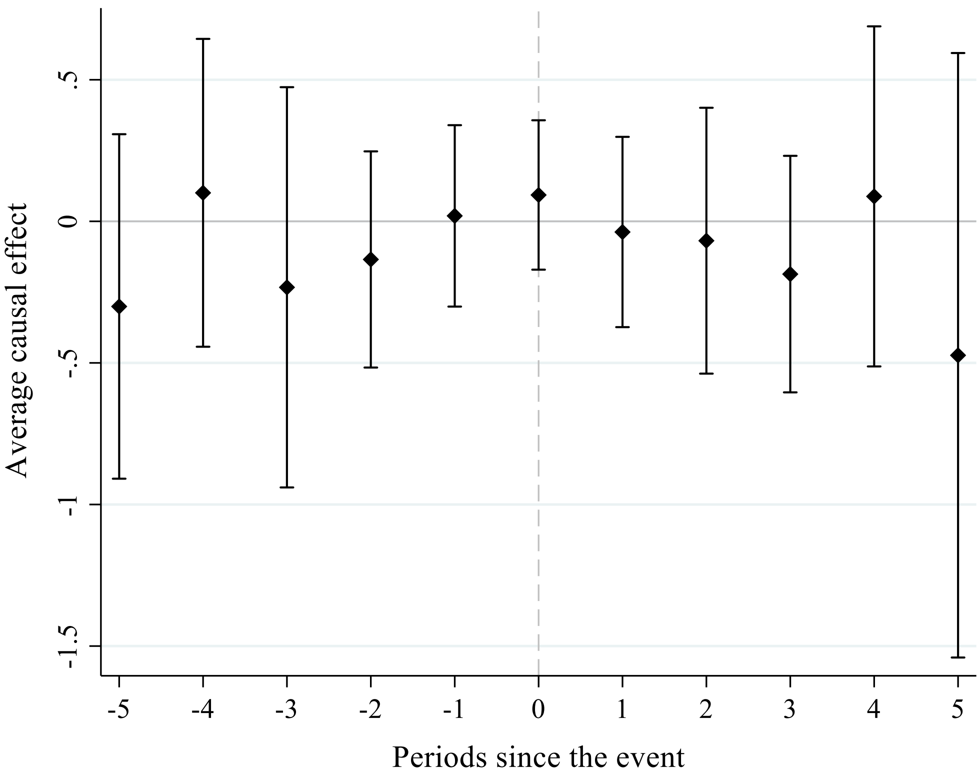


Fig. 2. DD estimation of ESGD effects on output applying the heterogeneity robust approach of De Chaisemartin and d'Haultfoeuille (2022)

Note: The figure shows the event study results on output following De Chaisemartin and d'Haultfoeuille (2022). The horizontal axis is the relative time since the policy shock, and the vertical axis represents the regression coefficients. We set the last year before the treatment time as the reference group.

Next, we use triple differences (DDD) to examine the compositional effect for the two different orders within the affected areas (Eq. 2). The ESGD reform aims to reduce the fossil fuel consumption of China's electricity sector by allocating more power generation to plants with relatively high coal efficiency. As such, the reform initially stipulated that power in the pilot provinces should be dispatched based on standard coal consumption rate. To explore this aspect of reform, we use the order of coal consumption rate, the *CoalRateOrder*, as another source of variation to test whether power plants with lower annual average coal consumption rate accrue more generation hours in the pilot provinces (i.e., represented as the variable *Order* in Eq. 2). Table 4 presents the estimates of the effects of dispatch reform on power plant output and hours allowing for different annual average standard coal consumption rates. The bins in columns (1) and (2) are based on standard coal consumption rate in year *t–1*, whereas bins in columns (3) and (4) are based on the coal consumption rate in year *t*. Both are updated and dynamically adjusted. We find that the coefficients are generally not significant, which indicates that DOs in the pilot provinces did not allocate power generation hours according to the actual annual average coal consumption rate.

Table 4. Effects of dispatch reform for different coal rate classes

VARIABLES	(1) using order(t-1) ln(output)	(2) using order(t-1) ln(hours)	(3) using order(t) ln(output)	(4) using order(t) ln(hours)
ESGD×CoalRateOrder1	-0.0104	0.0725	-0.0841	-0.0425
	(0.114)	(0.106)	(0.123)	(0.109)
ESGD×CoalRateOrder2	0.0419	0.103	0.00316	0.0216
	(0.0844)	(0.0801)	(0.105)	(0.0938)
ESGD×CoalRateOrder3	0.00374	0.0646	-0.00466	-0.00164
	(0.0848)	(0.0802)	(0.109)	(0.0978)
ESGD×CoalRateOrder4	-0.0298	0.0374	-0.00298	0.0201
	(0.0817)	(0.0759)	(0.113)	(0.101)
Observations	7,101	7,050	9,757	9,618
R-squared	0.962	0.732	0.949	0.691
Year×Province FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Order×Year FE	Yes	Yes	Yes	Yes

Note: The dependent variable is the logarithm of output in columns (1) and (3) and the logarithm of hours in columns (2) and (4). Energy-Saving Generation Dispatch (ESGD) is a dummy variable indicating the implementation of dispatch reform. CoalRateOrder1 to CoalRateOrder4 are dummy variables indicating the order listed in Table 2. Columns (1) and (2) assign the *CoalRateOrder* based on the coal consumption rate in the previous year, whereas columns (3) and (4) are based on the consumption rate in the current year, The estimates are obtained by fixed-effects triple-differences regressions. Robust standard errors for coefficients clustered at the plant level are reported in parentheses; ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

We then consider whether electricity generation in the reform provinces is dispatched based on a fixed coal consumption rate order instead of being updated annually. In 2007, the State Council disclosed that the merit order of coal-fired power plants was temporarily based on nameplate coal consumption level of the unit provided by the equipment manufacturer and that it would gradually change to real-time measured values.[19] However, some papers have pointed out that the dispatch order of power generators followed the nameplate energy efficiency provided by the manufacturers, not real-time monitoring data (Ding and Yang, 2013; Dong et al., 2015; Kahrl et al., 2013).

[19] State Council General Office (2007), No. 53, "Interim Measures for Energy-Saving Generation Dispatch." Available from: https://www.gov.cn/gongbao/content/2007/content_744115.htm.

In Table D.5 in Supplementary Materials, we report the estimation results using a fixed coal consumption rate, in contrast to the dynamically adjusted rates in Table 4. *CoalRateOrder* bins in columns (1) and (2) are measured by the median coal consumption value of each power plant from 2005 to 2012.[20] Bins in columns (3) and (4) are measured by the rate of the power plant in the first year of the period before the dispatch shock. The estimated coefficients are not significant, which suggests that a fixed value of measured coal consumption was also not the basis for dispatch.

Possibly due to the stalled progress in allocating power generation based on actual coal consumption rates[21], many treated provinces began to dispatch electricity generation according to nameplate rates when ESGD was expanded. To probe the potential for dispatch by capacity, we interact the ESGD treatment variable with an order variable assigned using the median value (over 2005–2012) of installed plant capacity.[22]

Table 5. Effects of dispatch reform for different capacity classes

	(1)	(2)	(3)
VARIABLES	ln(output)	ln(hours)	ln(capacity redundancy)
ESGD×capacityorder1	0.259***	0.288***	-0.314***
	(0.0742)	(0.0579)	(0.0739)
ESGD×capacityorder2	0.374***	0.328***	-0.376***
	(0.0911)	(0.0650)	(0.0712)
ESGD×capacityorder3	0.281***	0.224***	-0.0278
	(0.0873)	(0.0681)	(0.0738)
ESGD×capacityorder4	0.153	0.231**	-0.0640
	(0.127)	(0.0984)	(0.116)
Observations	9,757	9,618	9,501
R-squared	0.949	0.691	0.946
Year×Province FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Order×Year FE	Yes	Yes	Yes

[20] The variance in annual coal consumption rate of power plants is large, so we use the median of the sample period as a proxy of what the dispatcher used. We also run a regression treating the median coal consumption rate value as a continuous variable, instead of assigning it to five bins, and obtain a small and insignificant coefficient.

[21] Although the policy documents issued by the central government require that the coal consumption rate data should progressively transition from parameters provided by equipment manufacturers to real-time measured values, progress has been slow. According to available data, the development of the online coal consumption monitoring system in the pilot provinces has lagged. Guizhou began the research and construction of this system in 2008. However, owing to the complexity, only 13 coal-fired power plants had installed a monitoring system by 2010. Guangdong Province did not initiate the promotion of online monitoring systems until 2011. By 2013, only 31 coal-fired power plants had incorporated the system, which might have led some provinces to dispatch power according to nameplate consumption rates when the ESGD was expanded (further discussion in Supplementary Materials Appendix A.2).

[22] It is important to note again that we have only the total plant capacity, not unit-level data, and that the dispatch rule is based on unit characteristics.

Note: The dependent variable is the logarithm of output in column (1), the logarithm of utilization hours in column (2), and the logarithm of capacity redundancy in column (3). The independent variables are the interactions of the Energy-Saving Generation Dispatch (ESGD) dummy and *capacityorders* as given in Table 2. *Capacityorder* is assigned based on the median value of a plant's capacity over 2005–2012. The estimates are obtained by fixed-effects triple-differences regressions. Robust standard errors for coefficients clustered at the plant level are reported in parentheses; ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

Table 5 shows the DDD estimates based on Eq. (2) using capacity order. Here, the results are statistically significant. Compared with plants in the lowest capacity bin, plants with larger capacity obtained more generating hours and produced more output, thus improving equipment utilization efficiency. The two largest capacity orders have approximately 30% more hours; but the differences in coefficients between them are not statistically significant. The third order (200–600 MW) has approximately 20% more hours. The changes in hours result in a 26% increase in output for order 1 and 37% for order 2; a difference that might be attributable to ramping differences. For power plants in the 100–200 MW bin, there is no significant generation difference from that in the smallest class. Only two coefficients in the capacity redundancy regression (column 3) are significant.

The benchmark triple-differences regression (Eq. 2) uses a staggered-event study design, which may be subject to potential bias in estimation and inference because of negative weights and heterogenous treatment effects (De Chaisemartin and d'Haultfoeuille, 2022; Strezhnev, 2023). To address these concerns, we re-estimate the policy effects on power plants of different installed capacities with robust estimators. To our knowledge, despite the rapid recent progress in two-way fixed effects studies, a well-defined estimate for treatment effects in a triple-difference design with multiple treatment groups has not been established. The imputation method proposed by Borusyak et al. (2021) can be applied to a triple-difference system but does not accommodate multiple treatments. Therefore, to apply this method, we consider a simplified setting with only two groups: one with capacities above 100 MW and the other with capacities below 100 MW, using the latter as the reference group. We also implement a triple-difference version of the interaction-weighted estimator proposed by Sun and Abraham (2021). For a further robustness check, we estimate this model with the standard fixed effects estimator.

Results for the three different estimators are given in Appendix Table A.1. The significantly positive effects for all three estimators indicates the robustness of our baseline design, notwithstanding the possible estimation bias due to the staggered empirical design. The heterogeneity robust estimators exhibit larger quantitative effects while showing a similar pattern: larger power plants were allocated more generation when the ESGD policy was introduced.

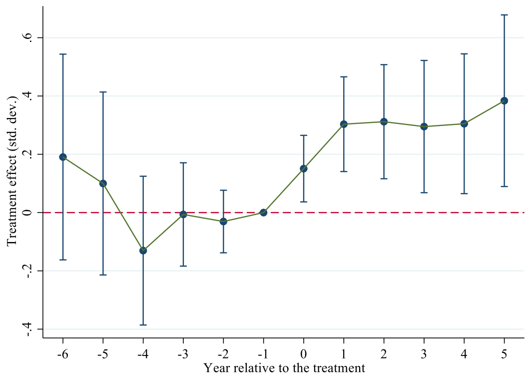
4.2. Robustness checks for validity of the triple-difference design

It is assumed that power plants of the same capacity order across pilot and nonpilot provinces would exhibit similar time trends in electricity generation in the absence of the reform. To examine this assumption, the following regression was run with leads and lags:

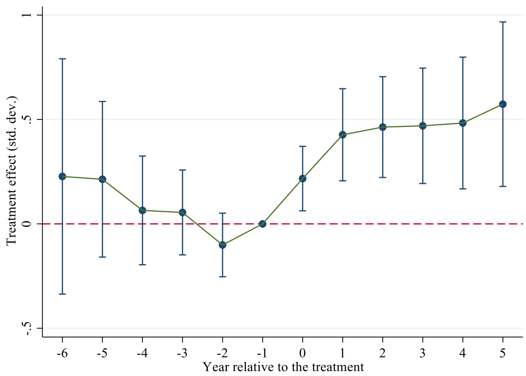
$$y_{ipt} = \sum_{k=-6}^{5} \sum_{o\in\{1,2,3,4\}} \beta_o^k ESGD_{t_{p0}+k} * Order_i^o + \rho policy_{ipt} + \eta_{pt} + \delta_i + \omega_{ot} + \varepsilon_{ipt} \quad (3)$$

where $ESGD_{t_{p0}+k}$ is a dummy variable that has the value one in year $t_{p0}+k$ for pilot province p and zero otherwise and t_{p0} denotes the year when province p implemented the dispatch reform. We use $k = [-6, 5]$ to indicate the event-time relative to the first year of treatment, $k = t - t_{p0}$. For example, $k = -1$ denotes the final year of the pretreatment period and $k = 0$ represents the first year of treatment. In the regression model, we consider electricity generation in the year prior to the instigation of ESGD reform in each province as the reference group, and the coefficients represent changes in generation relative to that year.

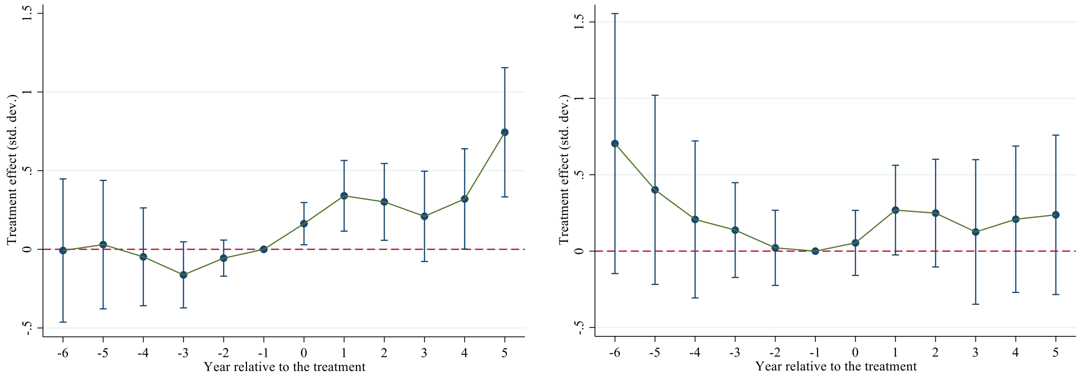
The estimated β_o^k values and associated 95% confidence intervals are illustrated in Fig. 3, with one plot for each capacity order. We find that the coefficients for the pretreatment period are not significant, corroborating the parallel trend assumption. After the policy change, power generation increased compared with that in the smallest plants, except for the smallest capacity class (100–200 MW).



(a) 1000+ MW



(b) 600–1000 MW



(c) 200–600 MW

(d) 100–200 MW

Fig. 3. Treatment effects of dispatch change on plant output by year for each capacity order

Notes: The event study plots are created by regressing plant output on a set of lead and lag indicators interacted with the Energy-Saving Generation Dispatch indicator, province–year fixed effects, plant fixed effects, order–year fixed effects, and the same controls as in baseline Eq. (2). For each capacity order, estimated effects are relative to plants of capacity <100 MW. Vertical bars are 95% confidence intervals.

The conventional parallel-trend examination in a staggered-event study design is prone to biases stemming from contamination across different treatment cohorts (Sun and Abraham 2021). To address this concern, we use the robust estimators proposed by Sun and Abraham (2021) and Borusyak et al. (2021) to examine the parallel-trend assumption with the triple-differences design (Appendix Table A.1). The estimated coefficients and 95% confidence intervals of the three estimators are presented in Fig. 4. Consistent with Fig. 3, we observe significantly positive coefficients for years following the ESGD reform and nonsignificant coefficients for years preceding the reform.

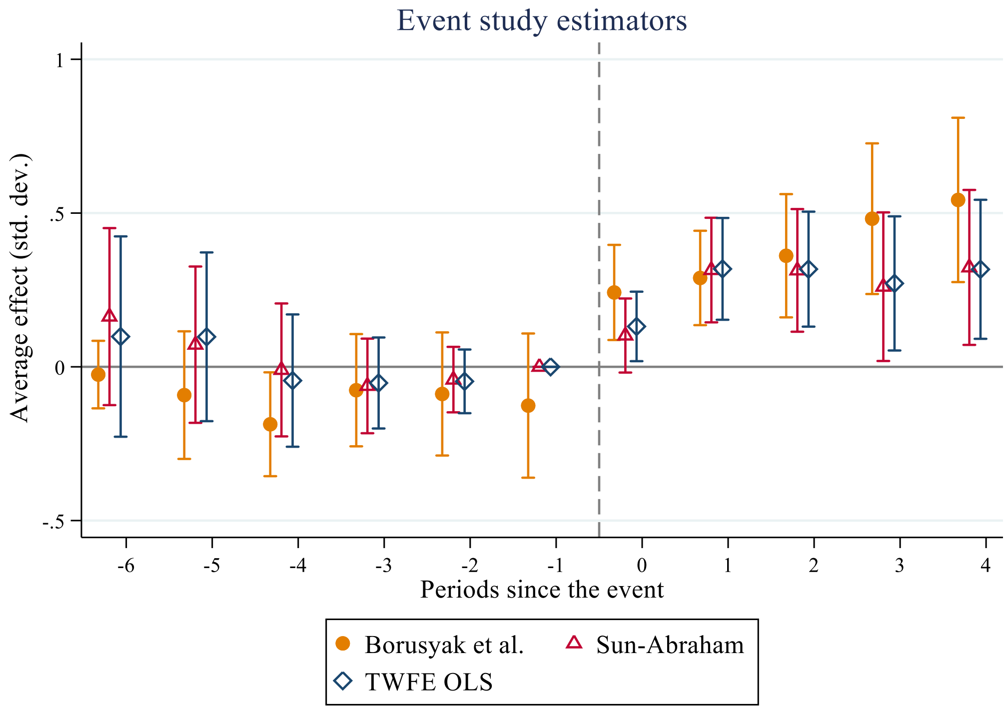


Fig. 4. Parallel-trend examination with robust estimators

Note: The figure shows the event study results on output using the fixed effects approach, the interaction-weighted (IW) approach proposed by Sun and Abraham (2021), and the imputation approach proposed by Borusyak et al. (2021). We estimate a cohort-specific dynamic treatment effect interacted with the indicator of large capacity orders (above 100 MW). The horizontal axis is the year relative to the policy shock, and the vertical axis represents the regression coefficients. We set the last year before treatment as the reference group. In the imputation approach, we are unable to estimate the coefficient for the fifth year following the introduction of Energy-Saving Generation Dispatch (ESGD) because of an insufficient effective sample size. Consequently, we retain only the first four periods post-ESGD shock for comparison.

To further verify our baseline DDD results by capacity order, a series of robustness checks are performed in Appendix B in Supplementary Materials.

4.3. Heterogenous effects by region

In China, provincial governments wield substantial authority, as discussed by Xu (2011) and Ho et al. (2017). During the top-down reform process, directives from the central government were broad and much of the detailed rules and implementation were entrusted to the provincial authorities (Davidson and Pérez-Arriaga, 2020; Pollitt et al., 2017). Provinces have marked disparities in terms of generation mix and electricity load, and thus, implementation of the ESGD policy is expected to vary across provinces. However, regional heterogeneity can be masked by the average effect obtained in the benchmark regression. For example, whether the nonsignificant effect by coal rate class is due to opposing positive and negative effects from different provinces is open to speculation. To examine possible masking effects, we employ subgroup regressions to explore the variations in policy effects among the original five pilot provinces.[23] In the application of DD regressions, management of control groups is of paramount importance. When conducting regression analysis for a particular pilot province, the samples from other provinces that implemented the ESGD reform during the same period (from 2005 to 2010) are excluded.

Table 6. Regional heterogeneity in output response to ESGD policy

VARIABLES	(1) Guangdong	(2) Guizhou	(3) Henan	(4) Jiangsu	(5) Sichuan
ESGD×capacityorder1	0.224*	0.378**	0.662***	0.159	0.523***
	(0.117)	(0.168)	(0.129)	(0.131)	(0.185)
ESGD×capacityorder2	0.163	0.294*	0.702***	0.0595	0.370
	(0.116)	(0.158)	(0.132)	(0.0909)	(0.265)
ESGD×capacityorder3	0.258**	0.406**	0.506***	-0.145	0.433
	(0.120)	(0.174)	(0.135)	(0.157)	(0.281)
ESGD×capacityorder4	0.130	0.180	0.519**	0.200	0.518
	(0.175)	(0.271)	(0.258)	(0.161)	(0.349)
Observations	3,937	3,698	4,123	4,664	3,801
R-squared	0.964	0.963	0.957	0.954	0.960
Year×Province FE	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes
Order×Year	Yes	Yes	Yes	Yes	Yes

Notes: This table shows the effect on output allowing for different capacity orders. Column (1) to column (5) report results of the subsample regressions for the five pilot provinces, corresponding to Guangdong, Guizhou, Henan, Jiangsu, and Sichuan, respectively. All results are obtained using fixed-effects triple-differences regressions.

Table 6 presents the heterogeneous effects for each pilot province interacting with capacity orders over the 2005–2010 period. The heterogeneity analysis also addresses the possibility that opposing provincial effects led to the nonsignificant results for coal rate order in Table D.5. We find that there are variations in the size of the policy effect among different provinces, with the most favorable policy effects in Henan. We also find significant positive policy effects in Guizhou and Sichuan. The results for Guangdong and Jiangsu are not significant, and one coefficient is negative.

It is useful to consider the differences in policy effectiveness in terms of the subjective efforts to implement the ESGD and the objective differences in material and

[23] The choice to focus on the five pioneering provinces stems from the availability of more comprehensive information and their designation as pilot areas under the central policy. We believe the choice provides the best chance at unraveling any provincial variation in policy implementation.

technical constraints.

First, according to our interviews with local regulators and information collected online, although all five pilot provinces primarily allocated generation based on installed capacity, there were variations in the regulation approaches. Guizhou allocated electricity in order of unit capacity size; when capacities were equivalent, allocation was then determined by coal consumption rate. The approach in Guangdong was purportedly based on nameplate coal consumption rate, and Sichuan allocated power according to different installed capacity classes, specifically 100/200/300/600 MW. Jiangsu mainly adopted trading of power generation rights, with larger units allocated more hours. It is shown that the difference in the annual power generation shares among large, small, and shut-down units in Jiangsu Province was relatively small.[24] Notably, Henan, the province with the most significant regression results, had a system where a (varying) share of generation remained under administrative planning and the remaining generation units faced market-based trading of generation rights. Regarding compensation mechanisms, we also observe regulatory heterogeneity, which is discussed in further detail in Section 5.1. Henan established a well-defined mechanism that compensated plants that were allocated fewer hours. Jiangsu used a market-based approach but for voluntary generation quota transactions which might not have been effective. Shi and Yang (2012) also notes that Jiangsu lacked an efficient and equitable mechanism for the distribution of benefits and compensation.

The second reason for differences in policy effectiveness is that each province encountered distinct objective boundary constraints. Sichuan has a high share of hydropower and is heavily affected by seasonal streamflow, which can disrupt the real-time dispatch of thermal power plants. Thermal coal shortages can also limit dispatch capabilities. For example, in 2010, a coal crisis in Guizhou resulted in the shutdown of several major units. Both Jiangsu and Guangdong have high power loads. In the analysis of the power plant utilization hours from 2005 to 2010 (Table D.8 in Supplementary Materials), the highest utilization hours were in Jiangsu, followed by those in Guangdong, signaling a tight power supply. Furthermore, Jiangsu possessed the largest number of thermal units and the highest proportion of small, less efficient units and thus had the largest number of stakeholders to satisfy when dispatch was reformed.

5. Mechanisms

Thus far we have shown that nameplate indices were used as a substitute for real-

[24] We plot the changes in the utilization hours of power plants of different capacity classes in Jiangsu, and find that the differences between different-sized units are not large. In some years, there was even a serious inversion of utilization hours between large and small units.

time indices and the dispatch did not occur in a completely descending order even when sorted by capacity, deviating from the dispatch merit order. However, the factors that contributed to this imperfect implementation remain uncertain. Here we explore several potential mechanisms, including compensation for reduced operating hours, reliability and security of power systems, and considerations for local protection and pollution control, as well as imperfect information on real-time coal consumption rates.

5.1. Insufficient compensation for reduced utilization

The higher utilization of more efficient power plants results in corresponding reductions in less efficient plants, assuming total electricity demand remains constant. Under the feed-in tariff system with fixed prices, the reductions in hours allocated to less efficient plants would lead to decreases in revenues compared with those in the previous equal-share system. As a result, smaller and less efficient plants that suffer such revenue losses become an important force in opposing this change (Ding et al., 2023).

Although ESGD was initiated by the central government, provincial governments were granted the freedom to establish their own implementation plans as noted earlier. This freedom includes developing compensation schemes for plants experiencing reduced utilization. As a result, the pilot provinces executed distinct compensation strategies.

Notably, in the efforts to promote the implementation of ESGD, Henan and Guizhou created special funds to compensate power plants allocated fewer hours. The funds were obtained from penalties incurred for failing to meet power generation dispatch standards, as well as from fees paid by plants exceeding the established annual power generation hours. Power plants with utilization rates below those under the equal-share system received compensation from those funds.[25] Compensation in Sichuan was generally similar, and an administrative directive was used to establish a definitive beneficiary and a minimum compensation standard (Zhao, 2011).[26]

By contrast, Jiangsu and Guangdong did not establish a specific compensation scheme for ESGD but instead opted for measures such as voluntary generation quota

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[25] At the end of 2007, Henan formulated and developed the “Henan Province Energy-saving Power Generation Dispatch Peak, Frequency and Standby Compensation Measures (Draft for Comments)”. Provincial electric power companies handle settlements and compensation by considering the peak shaving and frequency modulation activities of generating units. Additionally, they established dedicated accounts for those funds.

[26] To implement the reform, the Sichuan government set the average utilization hours of generation units (3,000 h) and the compensation standard for the units with reduced allocation (0.06 yuan per kWh). The rate is subject to adjustment by the provincial ESGD office at the end of the year, depending on the funding situation. The required compensation funds are from the excess generation of hydropower during periods of abundant water and thermal power during periods of water scarcity.

transactions and auxiliary service compensation. However, those measures were likely not as effective as direct compensation funds, especially when the quota price was low or the market was inactive. Note that in the feed-in tariff system, the controlled electricity prices typically exceed the marginal production cost and are intended to cover fixed costs. Consequently, power plants in these provinces may continue seeking maximum utilization hours to protect their economic interests.

To test this conjecture, we explore the heterogeneous effects of ESGD in provinces with and without direct compensation mechanisms. We run regressions separately for the two groups, with Henan, Guizhou, and Sichuan with a direct compensation scheme and Guangdong and Jiangsu without one. The estimations are presented in columns (1) and (2) of Table 7. The regression coefficients of the group with direct compensation mechanisms with clear criteria are significantly positive. The results indicates that such compensation mechanisms effectively reduced opposition and allowed the ESGD reform to progress with substantial flexibility.[27]

By contrast, indirect market-based solutions had limited effect. In fact, the price in the voluntary generation rights market remained low and trading volume was minimal. This condition suggests that large power plants chose not to sign such contracts or opted out of contractual commitments (Kong et al., 2013; Zeng et al., 2013). Furthermore, the payment system for ancillary services remained in its early stages during the sample period. According to the summary of ancillary service compensation of Guangdong in 2010, the total revenue from ancillary services in Guangdong was only 0.17% of the generation revenues.[28] Additionally, small thermal power plants typically often have close relationships with local governments or are politically important as employers.[29] In the absence of adequate compensation mechanisms, they may lobby the government to adjust the ESGD policy (Xiang et al., 2023a).

As emphasized in a news article in the China Energy News on July 26, 2010, the government needs to conduct a thorough evaluation of the feasibility and effectiveness of adopting new dispatch methods in response to the demands from various stakeholders. Local governments are inclined to minimize adverse effects on the economy, ensuring that transitions are smooth and a reliable power supply is

[27] Regardless of the significant effects observed in provinces with direct compensation mechanisms, it is important to note that the sustainability of a low-limit compensation rate used in those provinces might be questionable. This is supported by the findings presented in Appendix Figure A.1, which illustrate that the treatment effects of the policy diminished in subsequent phases.

[28] Compensation statistics for Guangdong are from https://www.doc88.com/p-971177607603.html?s=rel&id=3. The total revenue from ancillary services was 199 million CNY. The average on-grid electricity price was 504 CNY per MWh, implying total revenue of 116 billion CNY.

[29] A more detailed discussion of the various interest groups is given in an opinion piece published by the China Society for Hydropower Engineering, available at http://www.hydropower.org.cn/sdkjj/showNewsDetail.asp?nsId=169.

maintained. [30] The null results in this study underscore the importance of implementing appropriate compensation mechanisms to effectively promote ESGD.

Table 7. Heterogeneous effects of dispatch reform by compensation system and profit margins

VARIABLES	(1) Direct compensation	(2) No direct compensation	(3) High-profit margins	(4) Low-profit margins
esg_capacityorder1	0.621***	0.102	0.396***	0.174
	(0.134)	(0.101)	(0.108)	(0.155)
esg_capacityorder2	0.647***	0.0501	0.400***	0.183
	(0.154)	(0.0856)	(0.108)	(0.302)
esg_capacityorder3	0.556***	0.0402	0.434***	0.0803
	(0.157)	(0.116)	(0.131)	(0.149)
esg_capacityorder4	0.593**	0.0941	0.141	0.215
	(0.257)	(0.135)	(0.153)	(0.181)
Observations	4,388	4,984	4,082	3,994
R-squared	0.956	0.956	0.979	0.925
Year×Province FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Order×Year FE	Yes	Yes	Yes	Yes

Notes: This table shows the effect on log output allowing for different capacity orders. Columns (1) and (2) report the subsample regressions for provinces with specific compulsory compensation schemes (Sichuan, Guizhou, Henan) and for those without (Guangdong, Jiangsu). Columns (3) and (4) present results of the subsample regressions for samples with high profits and for those with low profits. Those groups are defined by the median net profit per kWh of electricity produced by each power plant over the sample period. All results are obtained using fixed-effects triple-differences regressions.

A concern regarding the above heterogeneity analysis is that provinces with and without compensation funds may differ in various aspects beyond only compensation schemes. Hence, the distinct results observed may be influenced by factors other than compensation schemes. To alleviate this concern, we exploit time and regional variations in coal prices and feed-in tariffs, which are factors that directly influence generation profits. When coal prices are low, power plants costs decrease and profit margins for the recovery of fixed costs increase (because the output price is regulated and not adjusted often). Consequently, small plants may be less reluctant to reduce their utilization during periods of lower coal prices.

In Table 7, columns (3) and (4) explore this conjecture on the basis of heterogeneity analyses for periods of high versus low gross profits driven by variations

[30] The article can be found online at https://www.chinanews.com.cn/ny/2010/07-28/2430144.shtml.

in coal price and power tariff.[31] All coefficients for the low-profit sample, owing to high coal prices and delayed tariff adjustments, are not statistically significant, but the three coefficients for the high-profit group are significant at the 1% level. This contrast suggests that when elevated coal prices led to constrained corporate earnings, the effectiveness of the compensation schemes was greatly reduced. By contrast, in the sample of regions and periods with improved profit margins, local governments exhibited increased ability to effectively reduce the utilization hours of small power plants.

5.2. Security and reliability of the power system

The electricity sector is unique in its direct connection with all parts of society, including production units, households, and government. The sector not only serves as the backbone of modern infrastructure and economic activities but also has an indispensable role in daily life. Electricity blackouts can lead to substantial economic costs (Jha et al., 2023), which highlights the critical importance of the reliability and security of power systems. In fact, the stability of the power grid is the most crucial technical aspect of electricity dispatch (Joskow, 2008). In particular, the integration of intermittent renewable energy requires increased flexibility of conventional power units (Chen et al., 2020c; Oggioni et al., 2014), and nonintermittent units need to provide reserves and flexibility to maintain safe and reliable power system operation. There are very few gas units in China, and thus, the flexibility needs to be provided by coal-fired power plants (Li and Ho, 2022; Morales-España et al., 2021). Transmission constraints may necessitate the use of inefficient units when efficient ones are inaccessible.

To investigate this mechanism, we separately run regressions for provinces with a large share of renewable power consumption and for those with a low share in columns (1) and (2), respectively, of Table 8, with renewables including hydropower.[32] We also run the regression using renewable shares at the city level to exclude provincial confounding factors in columns (3) and (4).[33] The coefficients are smaller and less

[31] We determine the marginal profit of a power plant per unit of electricity produced using the formula provincial thermal feed-in tariffs minus the product of standard coal consumption per kWh and the coal price. The feed-in tariffs are sourced from the official pricing documents issued by The National Development and Reform Commission (NDRC). Coal prices are based on the provincial thermal coal price issued since 2014, combined with the extrapolation of the coal mining and washing industry ex-factory price indices of each province. To increase the robustness of the results, we perform identical profit computations and regressions using scraped power coal prices from a few available provinces as the reference for electricity coal price. The results are similar to those in columns (3) and (4) of Table 7.

[32] A large share of renewable energy in total electricity consumption in a province is defined as more than 30% in 2019.

[33] We calculate the proportion of the total installed renewable energy capacity in each city to the total installed power capacity every year. Then we define a city to have a large share of renewables if its median value of renewable proportion over the years is no less than 30 percent. We also run regressions where renewables include only wind and solar, excluding hydro, and the results are similar.

significant in the subsamples with high renewable shares than in those without, suggesting that those regions did not (or could not) strictly adhere to the dispatch rule. This result suggests a probable trade-off between reliable power supply and energy efficiency improvement in areas with more intermittent sources.

Table 8. Heterogeneous effects of dispatch reform by renewable shares

	(1)	(2)	(3)	(4)
	Low province share	Large province share	Low city share	Large city share
VARIABLES	ln(output)	ln(output)	ln(output)	ln(output)
ESGD×capacityorder1	0.289***	0.158	0.290***	0.0830
	(0.0852)	(0.230)	(0.0783)	(0.282)
ESGD×capacityorder2	0.414***	0.292	0.382***	0.371
	(0.0980)	(0.276)	(0.0906)	(0.336)
ESGD×capacityorder3	0.208**	0.537**	0.283***	0.165
	(0.0968)	(0.257)	(0.0921)	(0.253)
ESGD×capacityorder4	0.165	-0.0455	0.292**	-1.139**
	(0.142)	(0.353)	(0.123)	(0.519)
Observations	8,210	1,547	7,568	2,152
R-squared	0.947	0.946	0.952	0.945
Year×Province FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Order×Year FE	Yes	Yes	Yes	Yes

Note: The fixed-effects triple-differences estimates for log output are displayed in each column. Column (1) has provinces with a low renewable energy share, whereas column (2) has those with a high renewable share sample. In columns (3) and (4), the share is defined at the city level. Robust standard errors for coefficients clustered at the plant level are reported in parentheses; ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

In addition, the total share of installed renewable capacity is not the only factor to affect dispatch flexibility, and in fact, fluctuations in net electricity load area are a more significant factor. To capture the effects of these fluctuations, we utilize the natural fluctuations in streamflow for hydropower, and in temperatures.[34] Following Eyer and Wichman (2018) and Heal and Park (2016), we employ cooling degree days (CDDs) to capture weather variations of extreme heat. In our study, CDD is calculated from county-level daily temperatures as a nonlinear measure of the deviation from an ambient indoor reference temperature, which is set at 26 °C:

[34] The net load curve is the amount of load remaining to be served by nonrenewable generation after loads have been served with all available renewable generation. Given the lack of access to direct electrical load data, we attempt to address this issue by examining two indirect sources: electricity demand and the load that thermal power must satisfy.

$$CDD = \sum_{i=1}^{n} \max(0, T_i - 26°C) \quad (4)$$

where n is the number of days in a year and T_i is the average temperature of the i th day.[35]

Further, we gather and process water runoff data at the 0.25° × 0.25° spatial resolution grid level.[36] A drought anomaly for runoff at the city level is defined as follows. The difference between each month's runoff value for city m and the historical long-term average for that month is computed. If the difference is negative, it indicates a relative drought in city m during that month. The cumulative drought anomaly for city m in year t is derived by summing all negative monthly differences and then taking the absolute value.

We divide the sample into two subgroups based on the median value of the CDDs, namely, into those subjected to heat shocks and those not. Similarly, for drought anomalies, we categorize the sample based on the median value of the annual anomaly, distinguishing between those subjected to drought shocks and those not. Columns (1) to (4) of Table 9 present the results of the subgroup regressions. The estimated coefficients reveal no significant variance in generation across coal-fired power plants of different sizes during hot or dry periods. Heat events increase electricity consumption because of the need for cooling, whereas droughts reduce water availability and heighten the necessity for thermal generation from all available coal plants. Such phenomena could be particularly prevalent during the sample period, because during that time, extreme weather events, especially heat waves and droughts, greatly intensified. These conditions extended the durations of short-term peak load, demanding increased flexibility and regulation from the power system. As a result, they significantly reduced the ability to dispatch by merit order.

To test the joint effects of hydropower availability and droughts, we further divide the sample into three groups: (1) regions without hydropower installations, (2) regions with hydropower installations but not suffering from droughts, and (3) regions with hydropower installations and experiencing droughts. Columns (5) – (7) of Table 9 show the estimations for the three subsamples. In regions with significant hydroelectric capacity and that experienced low runoffs (column 7), the ESGD policy did not lead to higher output for large-unit power plants. There is even a negative coefficient, although it is not significant. Because of droughts, smaller thermal power units are dispatched

[35] The temperature data come from the National Meteorological Information Center, from which we can obtain daily weather elements for 699 weather stations. We convert the data from station level to county-level.

[36] The water runoff data set is from the China Natural Runoff Dataset version 1.0 (CNRD v1.0) published by the National Tibetan Plateau Data Center (Gou et al., 2020; Gou et al., 2021; Miao et al., 2022).

with increased frequency to meet peak demands. Conversely, in regions with a stable hydropower supply, resource reallocation toward more efficient units seems effective. The reduced need for thermal generation likely led to more idling of the smaller thermal power units.

Table 9. Heterogeneous effects of dispatch reform by temperature and hydrological variations

VARIABLES	(1) Hot days	(2) Non-hot days	(3) Droughts	(4) No drought	(5) No hydro	(6) Hydro +_no drought	(7) Hydro + drought
ESGD×capacityorder1	0.104	0.409***	0.0922	0.362***	0.137	0.615***	-0.0377
	(0.113)	(0.112)	(0.115)	(0.107)	(0.106)	(0.152)	(0.165)
ESGD×capacityorder2	0.155	0.462***	0.322*	0.301**	0.248*	0.573***	0.0825
	(0.126)	(0.143)	(0.171)	(0.132)	(0.133)	(0.166)	(0.185)
ESGD×capacityorder3	0.0632	0.402***	0.0854	0.307***	0.389***	0.348**	-0.0333
	(0.135)	(0.120)	(0.159)	(0.115)	(0.132)	(0.138)	(0.217)
ESGD×capacityorder4	-0.00163	0.305	0.00128	0.228	0.0594	0.579***	-0.133
	(0.156)	(0.245)	(0.207)	(0.173)	(0.220)	(0.214)	(0.235)
Observations	4,790	4,663	4,367	4,334	4,196	2,321	2,845
R-squared	0.953	0.950	0.956	0.949	0.943	0.959	0.964
Year×Province FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Order×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: These are the fixed-effects triple-differences estimates for the effect on log output. Column (1) is based on the sample with above median cooling-degree days, and column (2) is based on the below median sample. Column (3) uses the drought group, and column (4) uses the no-drought group. Columns (5) to (7) have samples that correspond, respectively, to regions devoid of hydropower capacity, regions equipped with hydropower facilities but unaffected by droughts, and regions with hydropower capacity that experienced drought conditions. Robust standard errors for coefficients clustered at the plant level are reported in parentheses; ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

5.3. Considerations for local protection and pollution control

Numerous studies have highlighted the trade-offs among different policy targets assigned to agencies, noting that alternative priorities entail opportunity costs (Liang, 2018; Wenger et al., 2008). Under some circumstances, achieving some targets implies not meeting other targets (Zhang et al., 2022). The multiplicity of goals explains the intentional deviation in particular regulations. In the case of ESGD, factors such as local protection and pollution control are important considerations for governments when determining the scheduling sequence based on efficiency indicators.

Studies have also highlighted the added complexities in the implementation of power policies resulting from the structure of central–local government relations (Ho et al., 2017; Kahrl et al., 2013; Wei et al., 2018). These studies also note how local administrations wield considerable power and carry heavy responsibilities, which often leads them to prioritize local interests over top-down environmental goals, i.e., favoring less productive but local firms (Bulman et al., 2022; Kostka and Nahm, 2017). For local governments, inefficient, small thermal power plants exemplify the category of enterprises that bear the responsibility of sustaining local employment, revenues, and social stability and thus are supported regardless of efficiency levels.

By exploring variations in government regulation of firms with different ownership characteristics, we provide indirect evidence for deviating from the merit order to protect local interests when there is no effective compensation mechanism. State-owned enterprises (SOEs) remain prominent in China's power sector, owning a substantial share of generating assets (Ho et al., 2017). Among the power generation enterprises, many are affiliated with one of the five major power generation groups or other SOEs owned by the central government. Table A.2 in the Appendix provides the distribution by capacity class and shows that central SOEs have larger and more efficient coal-fired units compared with non- central SOEs.[37] Compared with central SOEs, enterprises belonging to local governments and other investors which are less efficient would likely suffer losses if the policy was fully implemented. We thus run separate regressions, one for power plants that are central SOEs or their subsidiaries and another for the noncentral SOE group.

Columns (1) and (2) of Table 10 show the DDD results using the two separate samples, which allow determination of whether provincial governments favored local enterprises. In the subgroup analysis, the coefficients and their statistical significance, are larger for central SOEs than for noncentral ones; there is only one significant coefficient in the allocation of generation quota among power plants not belonging to central SOEs. That is, the policy was likely modified to protect local plant interests.

[37] In China, power plants are broadly classified into two categories: those that are central enterprises and those that are noncentral enterprises. The former includes power plants affiliated with the five major power generation conglomerates: Huaneng, National Energy, Datang, Huadian, and State Power Investment groups. It also includes those associated with the four centralized corporations: Three Gorges, China Resources, and National Development and Investment groups and China General Nuclear Corporation. Any power plants not included in those classifications are designated as noncentralized enterprises in this study. To ascertain which power plants are part of central enterprises, two primary identification methods are employed. The first is name recognition. If a plant's name contains key terms such as "Shenhua" or "Datang", it is categorized under central enterprises. The second approach uses official website cross-references. We conduct a thorough search of the official websites of each central enterprise's headquarters and its branches. We also refer to the list of centralized power enterprises on public websites. If a power plant in the sample is in these lists, we also identify it as a centralized enterprise. The long list is available on request from the authors.

Table 10. Effects of dispatch reform on output for central state-owned enterprises (SOE) versus noncentral SOE plants

VARIABLES	(1) Central SOE	(2) Non-central SOE	(3) FGD sample	(4) Non-FGD sample
ESGD×capacityorder1	0.493***	0.0496	0.282**	0.318***
	(0.163)	(0.134)	(0.113)	(0.117)
ESGD×capacityorder2	0.488**	0.355***	0.377**	0.462***
	(0.189)	(0.115)	(0.147)	(0.127)
ESGD×capacityorder3	0.505***	0.0997	0.245	0.354***
	(0.188)	(0.104)	(0.149)	(0.105)
ESGD×capacityorder4	0.311	0.136	0.155	0.133
	(0.388)	(0.146)	(0.245)	(0.146)
Observations	2,799	6,937	2,700	7,026
R-squared	0.949	0.930	0.968	0.941
Year×Province FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Order×Year FE	Yes	Yes	Yes	Yes

Note: The dependent variable is the logarithm of output, and the estimates are obtained through fixed-effects triple-differences regressions. Robust standard errors for coefficients clustered at the plant level are reported in parentheses; ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

Another important target of the government is environmental protection, which in this case is air pollution control. To reduce sulfur dioxide emissions, many plants are required to install flue gas desulfurization (FGD) equipment. Although the basic merit order in Table D.1 does not consider emission control, the detailed ESGD instructions do prioritize plants with FGD equipment for a given unit type and coal rate. To examine how this affected the implementation of the policy, we divide the sample into FGD-equipped power plants, and non-FGD power plants, and the results are given in columns (3) and (4) of Table 10. The coefficients for non-FGD power plants in column (2) have mostly smaller standard errors and larger magnitudes than those of FGD-equipped power plants. This result indicates that for FGD power plants, there may be a small tendency for governments to relax the enforcement of dispatch regulation, prioritizing emission control over energy efficiency.

5.4. Imperfect information on real-time coal use

It was difficult to obtain real-time coal consumption rates providing ranking information during the 11th Five-Year Plan period, because many units were not connected to a real-time monitoring system (Ding and Yang, 2013). Furthermore, real-time coal consumption rates are volatile and vary greatly under different loads and operating conditions. Because authorities need a way to estimate "normal efficiency", a benchmark indicator is usually chosen for simplicity. Generally, the higher the capacity of a single unit is, the higher the efficiency of the boiler. The information cost to obtain capacity figures is low. Table A.3 reports the distribution of the size of the change, if any, in the coal consumption order and capacity order in the sample period of the study.[38] The coal consumption class changes in 53% of the plants, whereas 87% of the observations for capacity order are unchanged. The implementation of dispatch policy could increase the volatility of the coal consumption rate, increasing the difficulty for a dispatch agency to follow a real-time rule.

Table 11. Effect of ESGD policy on coal consumption rates by capacity class

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	1000+	600-1000	200-600	100-200	<100MW	all	all
ESGD	0.00341	0.00367	0.0528***	0.0158	0.00605	0.00468	
	(0.00276)	(0.00664)	(0.0176)	(0.0308)	(0.0315)	(0.0169)	
ESGD×capacityorder1							0.0199
							(0.0206)
ESGD×capacityorder2							0.0269
							(0.0225)
ESGD×capacityorder3							0.0625**
							(0.0297)
ESGD×capacityorder4							0.0290
							(0.0340)
Observations	1,172	1,144	1,277	763	5,410	9,766	9,759
R-squared	0.934	0.638	0.509	0.651	0.642	0.664	0.678
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year×Province FE							Yes
Region×Year FE	Yes	Yes	Yes	Yes	Yes	Yes	

Note: The dependent variable is the logarithm of coal consumption rate. The estimates from columns (1) to (5) are policy effects for each capacity class from 1000+ MW to <100 MW and are based on the two-way fixed-effects (TWFE) regressions. For column (6), the same method is used to estimate the effect for the full sample. Column (7) reports the triple-difference estimates for various capacity levels obtained by fixed-effects triple-differences regressions. Except for column (7), robust standard errors for coefficients clustered at the province level are reported

[38] For each power plant we observe the annual coal consumption rate for each year. Then we identify the highest and the lowest rates between 2005 and 2012 and determine their corresponding order. The difference between the two is *Order_change*, and the distribution of this change over the 2,220 plants is shown in the *CoalRateOrder* columns in Table 6. The change in capacity order is defined in the same way for the *CapacityOrder* columns.

in parentheses. Standard errors for coefficients in column (7) are clustered at the plant level.; ***, **, and * denote statistical significance at 1%, 5%, and 10%, respectively.

Table 11 shows the regression results of the ESGD effect on coal consumption rates for each capacity class in columns (1) to (5), whereas column (6) reports the results for all coal-fired power plants. Column (7) presents the triple-difference results based on the variation in capacity order for the whole sample. We find that, compared with power plants with the smallest capacity, power plants with larger capacities tended to increase their coal consumption rate, especially for order 3. This result provides some evidence that the new dispatch system led to changes in dispatch that increased coal rates in individual plants, despite the overall focus on reducing system-wide coal use. There might be two reasons for the increase. One reason is that the new dispatch policy changed the distribution of hours among plants within each capacity class, and the other is that the extra hours given to some capacity classes require increased frequency of ramping and thus increases in coal use.

6. Potential for energy saving and carbon emission reductions

Because the ESGD reform was not strictly implemented, the potential savings are estimated as if it was implemented as designed. We plot the coal consumption rate order distribution of separately for each capacity class, and Fig. 5 shows that the coal rate varies greatly within each class.

To determine what the coal consumption would be if dispatch agencies allocate strictly by merit order, we make a simple estimate of the total coal consumption based on plant coal consumption rate ranking while ignoring technical constraints.[39] We calculate that the coal consumption that could have been saved in 2010 is 25.9 million tonnes. The result implies a reduction of 63.6 (25.9 × 2.4567) million tonnes in CO_2 emissions and a social benefit of 1.526 (63.6 × 24/1,000) billion USD, based on a social cost of carbon of 24 USD/tonne CO_2 (Ricke et al., 2018).[40]

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[39] For simplicity, we assume that all power plants operate with a capacity factor of 0.9. We first sort all power plants according to their coal consumption rate, from low to high, in each province. Then we dispatch power plants in strict ascending order of coal consumption rate, and simulate the output of each power plant in this merit order. After summing over all power plants, we obtain the total coal consumption of each province under ideal conditions in each year. Based on provincial-level data, we calculate the actual total power generation and historical total coal consumption of each province. In this way, we can see how much total coal consumption could be saved if the power generation was redistributed strictly according to energy efficiency, ignoring constraints such as a lack of transmission capacity.

[40] The carbon emission coefficient of per tonnes of standard coal consumption is 2.4567 t CO_2/tce, given by the energy project team of the NDRC.

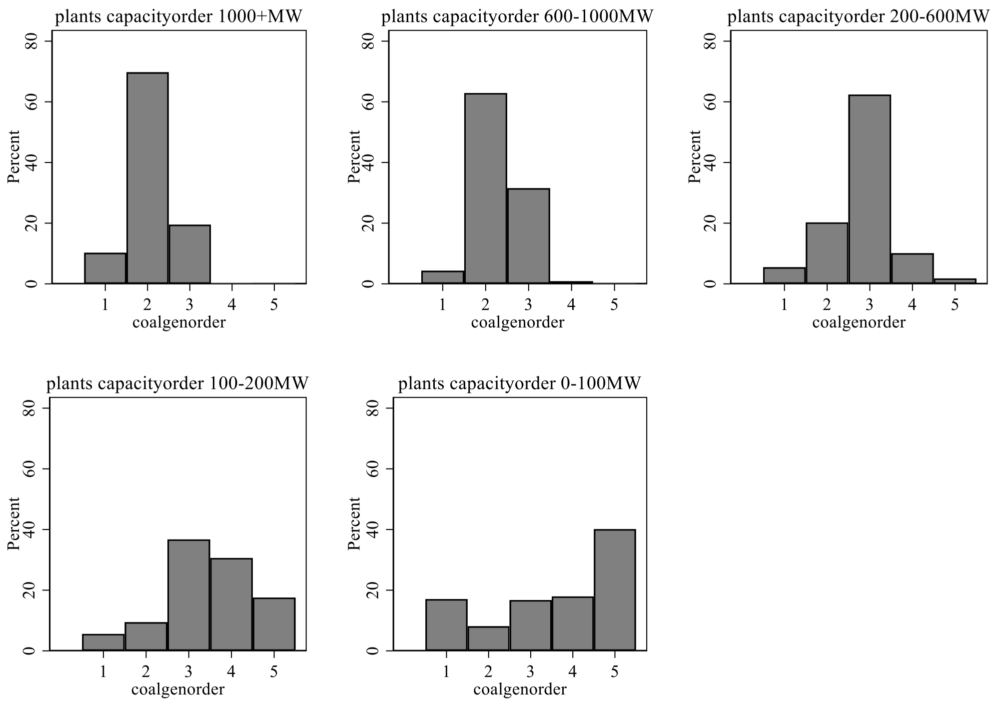


Fig. 5. Coal consumption rate order distribution of each capacity class

Notes: Figures show the distribution of the coal consumption rate over five bins in each of the five capacity classes. The coal generation orders are given in Table 2, with order 1 the most efficient.

Last, Jacobsen et al. (2020) propose an approach to measure the efficiency costs of imperfect regulation based on simple regression statistics. Applying this method, we evaluate the welfare loss from imperfect regulation. The approach is consistent with the framework presented by Jacobsen et al. (2020) in which tax policies depend on factors that are imperfectly correlated with externalities.[41] From regressions using average annual coal consumption rate on capacity class, an R^2 value of 0.40 is derived. Theoretically, this result suggests that the capacity proxy captures only 40% of the potential welfare gains for power plants, which could be realized with a merit order based on real-time coal consumption rates. Thus, there is substantial potential for welfare enhancement. Although this assessment relies on strong model assumptions, it does shed light on the welfare losses stemming from suboptimal regulation.

[41] The dispatch policy uses capacity class as an alternative merit order basis, primarily because of the prohibitive cost associated with directly targeting coal consumption rates. When contrasted with equal-share dispatch, the rule change can be interpreted as a shadow price imposed on power generation. Additionally, shadow taxes correspond to a linear function related to a plant's capacity class. Nevertheless, variations exist in unit lifetime, coal quality, and other factors, all of which affect the energy efficiency of power plants, leading to externalities.

7. Further discussion of electricity system reforms

The analysis in Section 6 reveals substantial potential reductions in fossil fuel consumption and carbon emissions with a change in China from the government-administered equal-share electricity dispatch to competitive electricity markets, with dispatch generation based on marginal cost. However, despite the considerable potential, the transition to electricity markets may be difficult. Our empirical analysis supports the contention that conflicts of interest among the parties hinder the promotion of ESGD. Although government compensation can reduce resistance to the reform, who should bear the costs of the compensation and how they should be organized remain to be decided. Electricity market reforms are likely to encounter similar resistance from existing stakeholders.

Owing to the failure of the earlier reforms to improve allocation efficiency and the integration of renewables, a new round of reform was launched in 2015 to further promote market-oriented changes (Davidson and Pérez-Arriaga, 2020). In September 2023, the National Development and Reform Commission and the National Energy Administration jointly issued the "Basic Rules for Electricity Spot Market (Trial)" to further clarify the development of electricity spot markets. The establishment of spot markets aims to use market mechanisms to efficiently allocate power generation resources. Generally, more efficient and cleaner units have lower operating costs, which is reflected in the prices of a competitive market (Borenstein et al., 2002). Under ideal conditions, the market mechanism will achieve balance between cost minimization and energy conservation (Guo et al., 2020).

However, electricity spot markets were only introduced on a pilot basis in 2018, and much of the electricity in the wholesale market is still traded through medium and long-term electricity contracts (Liu et al., 2022). Thus, an ambiguous link between contract settlement and dispatch remains. Without a mature spot market, short-term dispatch will be constrained by physical contracts that are settled monthly, weakening the dividend from electricity market reforms (Davidson and Pérez-Arriaga, 2020).

Furthermore, even with the operation of wholesale and spot markets in some pilot provinces, electricity is still dispatched in part through administrative instructions rather than on the basis of price signals (Chen et al., 2020b; Pollitt, 2020). Such interventions prevent further reforms to marketize transactions (Hu and Jiang, 2022). The interventions are manifested in two main areas. First, compared with economic dispatch based on a merit order of costs in many developed countries, the government in China still allocates a large portion of electricity generation by setting quotas (Xiang et al., 2023b). Second, in setting quotas, local governments generally follow the egalitarian principle, preventing power plants from competing by costs (Yu et al., 2023). These features make the power market in China very different from more mature electricity markets in Europe and the US.[42] The current stage of reforms with only a few spot market pilots still leaves large misalignment of supply and demand. For example, electricity tariffs remained stable despite significant fluctuations in the supply–demand relation during the Covid pandemic (Hu and Jiang, 2022), and low fixed prices contributed to the shortages in summer 2022.

Many reasons can explain the slow electricity market reforms. The spot market pilots are very recent, and there are insufficient data to assess them using empirical methods. The problem of incomplete implementation in the post-2015 reforms is similar to the deviation in local government implementation of the ESGD policy. Government interventions in electricity market transactions continue to impede the success of current market-oriented reforms. The dispatch reform started in the 11th Five-Year Plan (2006–2010), as a historical transition policy, provides a natural experiment to uncover important concerns between government actions and the market. From the underlying mechanisms revealed in this study, lessons can be learned to improve the market-oriented structure.

Our study also extends beyond the current scope of China's electricity reform. Even in developed countries, existing spot markets face challenges such as unstable power supply due to integration of renewable energy and curtailment resulting from the intermittency of renewables. Such challenges may even escalate as more countries try to decarbonize their power systems. A difficult transition awaits all countries with established or developing power markets. As many have noted, simply having a spot market is insufficient, and there needs to be supplementary institutions such as capacity markets and auxiliary services markets. As revealed in the mechanism analysis in this study, ensuring sustainable compensation for ancillary service units and securing power supplies against unforeseen shocks are global concerns. A genuinely mature electricity market demands meticulous design and flexibility to adapt to increasingly complex circumstances. In particular, an efficient compensation mechanism is paramount to reduce opposition from existing stakeholders. On certain occasions, the government may have to intervene, but importantly, the intervention must not override underlying market incentives.

[42] See "Guiding Opinions on Accelerating the Construction of a National Unified Electricity Market" issued by the NDRC which can be found at https://www.ndrc.gov.cn/xxgk/zcfb/tz/202201/t20220128_1313653.html.

8. Conclusion

In the transition to an economy where markets play a key role, China continues to use many measures inherited from the planning era. Does this type of mixed-resource allocation lead to inefficiencies, and what are the reasons for keeping the old measures?

This paper investigates electric system reform that changed the dispatch order of coal-fired power plants, a reform providing a unique setting in which to compare different allocation mechanisms. It allows us to discuss the nature of imperfect regulation and its causes. Exploiting a micro-level dataset of national power plants, we first use the Difference-in-Difference strategy to identify the overall effect of the reform from equal-share dispatch toward one based on energy efficiency. We find that the mandatory change in dispatch did not affect the generation of power plants in regulated regions compared with those under equal-share dispatch.

Then we further evaluate the compositional effects for power plants in different classes by using a triple-differences framework. We observe a significant output increase in power plants with larger capacity compared to plants with smaller capacity. This indicates that the government regulation to save energy did mitigate resource misallocation compared to the previous equal-share dispatch system.

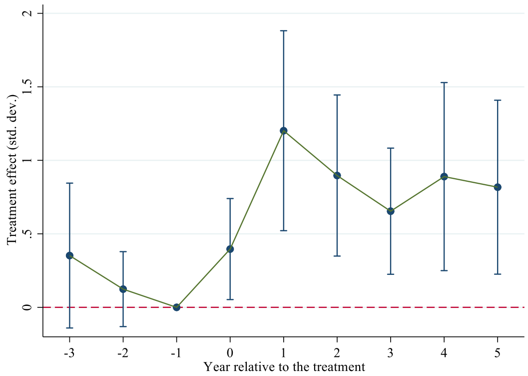
However, plants with low real-time energy consumption rates did not always increase relative output after the dispatch reform, which was not completely consistent with the new ESGD dispatch. Thus, power plants were not dispatched based on real-time coal consumption rates, but instead, agencies allocated generation hours according to capacity size. Moreover, the new merit order was not strictly sorted by capacity. The estimates show that the policy did not significantly change the power generation allocation for small plants in the 100–200 MW and <100 MW classes (compared with plants in nonpilot regions).

We find that the deviation from perfect regulation is the result of several factors. First, the absence of proper compensation schemes leads to deviation from strict capacity order. Not every region established specific compensation funds or enforced them rigorously, and the effectiveness of such compensation systems could be compromised by soaring coal prices. The lack of supporting mechanisms led small power plants to oppose the policy, fearing loss of profits after the reform. For governments, ensuring a safe and stable supply of electricity is the highest priority, and technical requirements for grid stability requires some sacrifice in energy efficiency. Special arrangements for local enterprises with social responsibilities and pollution control also affects policy implementation. Thus, the above factors account for intentional departures from the strict capacity order. Additionally, we have examined the information channel, which results in the use of capacity as a proxy for real-time metrics. The information cost of obtaining real-time coal consumption rate is very high, and real-time rates are volatile, affected by many factors. When the government cannot obtain accurate information, dispatch must be based on alternative information.

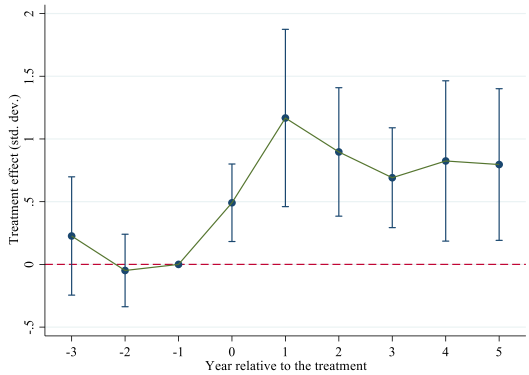
Compared with the equal-share dispatch rule, the new dispatch improved resource allocation. However, in our coal-saving analysis using an estimate of perfect regulation, we find there is still much room for improvement.

The inefficiencies that we find suggests that the role of compensation mechanisms, harmonizing the myriad interests of stakeholders, and coordinating different targets of governments are of obvious importance in regulatory policy making. Such inefficiencies also indicate that accelerated introduction of spot markets and other auxiliary markets is needed. The micro-level evidence of dispatch reform is not specific to the short historical period examined in this study or to China. Our findings shed light on underlying obstacles to dispatch reform and indicate the future directions for constructing an efficient electricity market in developing countries. Pollution control may also benefit from the use of markets.

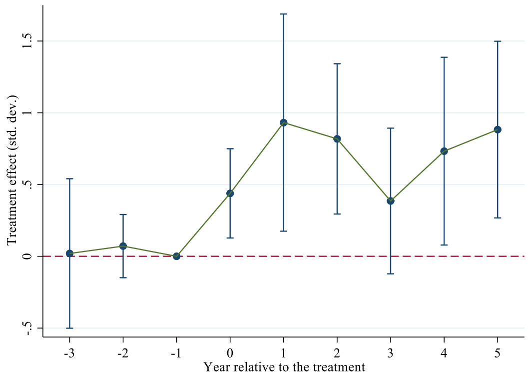
Appendix A



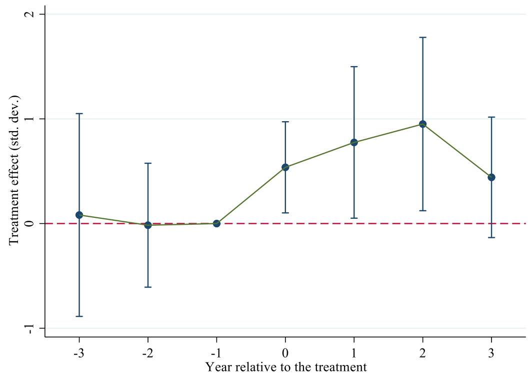
(a) 1000+ MW



(b) 600–1000 MW



(c) 200–600 MW



(d) 100–200 MW

Figure A.1. Treatment effects on plant output by year for each capacity order in provinces of China with clear compensation programs

Notes: These plots are created by regressing plant output on a set of lead and lag indicators interacted with the *Energy-Saving Generation Dispatch* indicator, province–year fixed effects, plant fixed effects, order–year fixed effects, and the same controls as in baseline Eq. (2). Our objective is to evaluate the policy effects in Henan, Guizhou, and Sichuan, the three provinces that distinctly implemented low-limit compensation rate programs. Consequently, we've excluded other provinces that introduced similar dispatch reforms during our sample period (2005–2012). For each capacity order, estimated effects are relative to plants of capacity <100 MW. Vertical bars are 95% confidence intervals.

Table A.1. Heterogeneity robust estimators for triple differences allowing for different capacities

	(1)	(2)	(3)
VARIABLES	Fixed effects	IW	imputation
ESGD×largeorder	0.268***	0.294*	0.382***
	(0.0663)	(0.153)	(0.0823)
Year×Province FE	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes
Order×Year FE	Yes	Yes	Yes

Notes: These regressions use heterogeneity robust estimators of the Energy-Saving Generation Dispatch (ESGD) effect, with *largeorder* a dummy for plants larger than 100 MW. In column (1), the fixed effects estimator is applied, which is used in Eq. (2). In column (2), the interaction-weighted (IW) estimator of Sun and Abraham (2021) is applied, and in column (3), the imputation approach of Borusyak et al. (2021) is applied.

Table A.2. Capacity order distribution for central and noncentral state-owned enterprises (SOEs)

capacityorder	Freq.	Percent	Cum.	Freq.	Percent	Cum.
	Central SOE			Non-central SOE		
1	840	28.88	28.88	377	5.22	5.22
2	768	26.4	55.28	429	5.94	11.15
3	658	22.62	77.9	652	9.02	20.17
4	134	4.61	82.5	647	8.95	29.13
5	509	17.5	100	5,122	70.87	100
Total	2,909	100		7,227	100	

Notes: "Freq." is the frequency of occurrence, "Percent" is the percentage of each order, and "Cum." is the cumulative percentage.

Table A.3. Volatility of coal consumption rate

Order_change	CoalRateOrder			CapacityOrder		
	Freq.	Percent	Cum.	Freq.	Percent	Cum.
0	1,039	46.8	46.8	1,922	86.58	86.58
1	531	23.92	70.72	104	4.68	91.26
2	269	12.12	82.84	61	2.75	94.01
3	144	6.49	89.32	30	1.35	95.36
4	237	10.68	100	103	4.64	100
Total	2,220	100		2,220	100	

Note: The distribution of *order_change* is for the 2,220 plants in the study. *Order_change* is defined as the difference between the highest and lowest coal consumption classes over the sample period and as the difference between the largest and smallest capacity classes.

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