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Does power shortage diminish firm CO_2 emissions? evidence from Chinese listed firms

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The power shortages directly affect the production behavior of firms. The study utilizes a city-specific index of power shortage and a comprehensive database of listed firms in China to investigate the correlation between power shortages and firm CO_2 emissions. Empirical results indicate a significant positive relationship between power shortages and firm CO_2 emissions, alongside a noted decline in the extent of technological innovation among listed firms and a negative impact on their resource allocation. Further analysis shows that power shortage significantly contributes to the CO_2 emissions of non-state-owned firms, non-heavily polluting firms and firms located in areas with high carbon-intensive energy use and fiscal expenditure pressure. These findings are robust across various sensitivity analyses and address concerns regarding endogeneity. Hence, policymakers are advised to take into account the influence of power shortages on CO_2 emissions of listed firms, beyond their traditionally recognized adverse effects on economic operations. As frontrunners in China's low-carbon transition, listed firms should strengthen risk resilience while driving technological innovation and resource optimization, thereby establishing operational paradigms for small and medium - sized firms to emulate.

KEYWORDS

power shortages, CO_2 emissions of listed firms, carbon-intensive energy, dual carbon goals, low-carbon transition

1 Introduction

The provision of electricity supply is a crucial aspect of infrastructure and an essential input for production in most firms. Nevertheless, in emerging economies, a vast number of individuals and firms continue to endure frequent power shortages and fluctuations in voltage due to insufficient capacity and inadequate infrastructure (Farquharson et al., 2018). Data from the World Bank indicates that more than 30% of firms identify the stability of power provision as the paramount factor influencing their manufacturing processes (World Bank, 2021). Furthermore, over 13.6% of firms surveyed between 2006 and 2017 reported power shortages, which have been estimated to cost businesses in developing nations up to $82 billion in annual losses (Asiedu et al., 2021). Existing research indicates that power supply interruptions cause at least $4.5 billion (1.7% of Pakistan's GDP) in losses annually (Samad and Zhang, 2018). Power shortages exerted substantial macroeconomic impacts, manifesting as a 7% contraction in real GDP growth and a 48% depreciation in fixed capital formation relative to baseline projections in Nepal (Timilsina and Steinbuks, 2021). Even in a developing country like China, which has achieved notable success in the electricity sector, the issue of power shortages has re-emerged in recent years (Guo et al., 2023). Since the beginning of the 21st century, China has encountered three distinct phases of power shortages, with each additional power supply interruption resulting in economic losses up to 1.44 billion yuan (Chen et al., 2022). The 2022 power shortages across China's Chongqing, Sichuan, Hubei, Anhui and Zhejiang provinces, municipality resulted from three primary drivers, supply-demand imbalances, policy decisions and structural constraints in generation capacity. Meteorological extremes, particularly record-breaking summer heatwaves and prolonged drought, critically compromised regional electricity supply systems during peak demand periods (Guo et al., 2023).

China has repeatedly faced incidents of power shortages, hindering the progress of its "dual carbon" goals. Emissions of greenhouse gases such as CO_2 have caused environmental issues that have attracted global attention. Being the globe's predominant source of carbon emissions, China has clearly delineated a strategy to reach its peak carbon output and attain carbon neutrality. Electricity supply's reliability and accessibility are pivotal to fostering superior economic growth, bolstering societal wellbeing, and promoting a transition to a low-carbon energy system (Lin, 2022). As core enablers of socioeconomic progress, investments in electrical grids and energy utilization dynamics significantly stimulate industrial expansion and technological innovation. Concurrently, maintaining grid stability and ensuring uninterrupted electricity provision emerge as vital prerequisites for achieving sustainable economic restructuring, optimizing public service systems, and accelerating ecological civilization construction (Shi et al., 2021).However, the escalating grid integration of renewable energy sources, coupled with intensifying extreme meteorological phenomena and climate change-induced extreme output deficit scenarios in climate-vulnerable wind-solar hybrid systems (Zheng et al., 2024), have collectively compromised the operational stability of China's power networks, precipitating regional electricity supply-demand imbalances. In the first half of 2021, China experienced the most severe electricity crisis in nearly a decade, with Over half of the nation's provinces are experiencing electricity allocation measures. Scholarly investigations have systematically categorized CO_2 emission determinants into three operational dimensions, technological parameters encompassing innovation capacity and infrastructure modernization (Li et al., 2011), (Ganda, 2019); structural determinants involving energy mix composition and sectoral economic distribution (Sun and Huang, 2022), (Zhao et al., 2022); scale-related elements covering macroeconomic output and demographic expansion (Dong et al., 2018). Current empirical analyses predominantly concentrate on multi-tier examinations across national, provincial, municipal, and industrial levels. As the main participants in carbon emissions, research on the micro-level of listed firms is relatively limited.

Although previous research has analyzed the effects of power shortages on firm performance (Bao et al., 2024), their influence on listed firm low-carbon energy transition remains uncertain (Allcott et al., 2016). Confronted with power shortages, some listed firms may augment their reliance on carbon-intensive energy sources or procure backup generators to maintain uninterrupted production through self-generation. It is anticipated that listed firms' strategies in response to power shortages will affect their CO_2 emissions, a concern that is escalating in significance within the context of most developing nations where grid reliability often correlates with industrialization stages. Our study is driven by the need to assess the potential and manner in which power shortages might impact CO_2 emissions of listed firms, extending prior single-country analyses to comparative institutional frameworks.We initially utilized an annual indicator of power shortages in China constructed by Guo et al. (2023). Furthermore, due to data availability, we merged this indicator with information from the listed firms database in China. Beyond establishing correlation between power shortages and CO_2 emissions at the firm level through instrumental variable analysis, this study further examines the hypothesized mechanisms underlying this relationship.

The aim of this study is to emphasize the environmental impacts of power shortages and to highlight the environmental factors that listed firms, as "pioneers" of economic development, should prioritize, thereby setting an example for other small and micro firms. We initiate our analysis with an annual city-level index of power shortages in China. Subsequently, we integrate this index with data from the China Listed Firms Annual Report Database spanning 2000 to 2020 due to the data constraints. Beyond pinpointing the correlation between power shortages and firms' CO_2 emissions utilizing an instrumental variable method, we also explore the potential mechanisms. Despite this study being rooted in China's unique institutional context, it is globally relevant for three key reasons. Firstly, as the world's second-largest economy, China is undergoing a critical transformation in carbon emission governance, providing an ideal institutional laboratory for research on firm carbon emissions. The government's "dual carbon" commitment has created a unique policy environment where practical power shortages and institutional top-down carbon emission governance interact, offering insights for both developed and emerging markets. Secondly, China has over 5,300 A-share listed companies and the second-largest total market value globally, and their carbon emission performance has a significant impact on the global market. Thirdly, as power shortages are a common challenge faced by developing countries, China's remedial experience based on its local power shortage situation can provide transferable lessons for other developing countries.

The marginal contributions of this paper are delineated below: Firstly, this study leverages a unique dataset of listed firms' operational and emissions records to empirically examine the understudied link between power shortages and firm CO_2 emissions. By focusing on China's "prioritizing large firms" environmental policy, we provide systematic evidence that institutional selectivity strengthens the reliability of emissions assessments in regulated firms. Secondly, the identification strategy innovatively addresses endogeneity concerns by employing the number of high-temperature days (D_High_Tem) and cooling degree days (CDD) as instrumental variables. These climate-driven instruments capture exogenous variations in regional power grid stress, isolating the causal effect of electricity shortages from confounding policy interventions. Lastly, the heterogeneity framework systematically disentangles how institutional and structural factors mediate firm responses. The study develops a novel stratification approach that jointly examines firm-level characteristics (ownership type, pollution intensity) and regional disparities (energy structure and fiscal capacity). This methodology reveals how power shortages interact with China's unique institutional landscape to produce divergent emission trajectories, providing a template for analyzing energy-environment nexuses in regulated firms.

The ensuing organization of this manuscript is as follows: Section 2 establishes the theoretical framework and formulates research hypotheses; Section 3 outlines the methodological framework; Section 4 describes the selection of variables and sources of data; Section 5 conducts an empirical examination; Section 6 deepens the analysis with supplementary explorations; and Section 7 synthesizes the conclusions and the evidence-based policy recommendations.

2 Theoretical review and research hypotheses

2.1 Theoretical review

As electricity serves a pivotal role in firm production processes, power shortages are likely to have profound consequences on the manufacturing activities of firms (Freeman et al., 2020). An expanding corpus of studies have delved into the repercussions of power shortages on firm efficiency and the strategies employed by businesses to manage inconsistent electrical availability across different nations (Grainger and Zhang, 2019). These studies have revealed that power shortages exert negative influences on firm performance across several key metrics, including productivity (Abdisa, 2018), sales (Allcott et al., 2016) through disrupted supply chain coordination, employees (Alby et al., 2013) via reduced shift scheduling flexibility, and financial metrics such as revenues and profits (Hardy and McCasland, 2021) owing to emergency energy procurement costs. Notably, Guo et al. (2023) constructed a city-level power shortage index in China, revealing a significant adverse effect on firms' overall efficiency. Discovered that firms encountering power shortages faced a substantial reduction in the probability of engaging in export activities due to compromised compliance with international delivery timelines, with firms experiencing power shortages being 9%–13% less likely to enter the export market. Allcott et al. (Allcott et al., 2016) demonstrated the substantial effects of power shortages on Indian manufacturers' critical business metrics, revealing 5%–10% contractions in both revenue streams and producer surplus. Parallel observations emerge from Southeast Asia, where Elliott et al. (Elliott et al., 2021) quantified the economic repercussions of grid instability in Vietnam, identifying a linear relationship where each 1% increment in service interruptions corresponds to 0.73% manufacturing revenue decline amplified by foreign investor risk aversion. Empirical data from Bhattacharyya et al. (2021) demonstrate that a 1% increment in electricity supply deficits across U.S. power systems during the 1997-2019 period manifested as quantifiable macroeconomic impacts, inducing GDP losses valued at USD 11.6 billion. Concurrently, Growitsch et al. (Growitsch et al., 2015) conducted systematic economic impact quantification of German power infrastructure failures, revealing an average hourly economic damage of EUR 430 million per outage event.

Although the the effects of power shortages on firm operational outcomes and strategic responses have received considerable scholarly attention, the influence on firms' environmental performance, such as the impact on carbon dioxide emissions, remains overlooked in the existing literature. Current research has examined the factors influencing firm CO_2 emissions from various perspectives, including both internal and external dimensions. Internally, (Wang Z. et al., 2023) examined that a firm's political ties have a positive influence on its aggregate CO_2 emissions. Alam et al. (2019) using large datasets from the G6 countries discovered that firms' investments in eco-friendly research and development particularly in clean production technologies are correlated with a reduction in CO_2 emissions. Lee and Min (2015) conducted systematic analyses leveraging comprehensive firm-level datasets spanning corporate entities across G6 nations and Japan, demonstrating that green research and development (R&D) investments exhibit a statistically significant mitigating effect on CO_2 emission intensity. Externally, (Yu J. et al., 2021) observed that firms in China tend to rely on inexpensive and polluting fossil fuels as a strategy to address escalating economic policy uncertainty, consequently enhancing their CO_2 emissions. Zhou et al. (2022) assessed the efficacy of China's low-carbon pilot city initiative on firm energy conservation practices through mandated energy audits and smart grid investments, discovering that it led to a notable decrease in firm coal usage. Liu et al. (2021) conducted empirical analysis on how China's evolving sustainability policy framework influenced firm environmental practices. Their study revealed that institutionalizing emission control benchmarks within strategic planning documents combined with cross-ministerial enforcement mechanisms induced measurable decarbonization effects, with carbon intensity metrics declining by 2.37 percentage points across domestic firms during the 2008-2011 period.

However, research on firm carbon emissions has overlooked the unique institutional realities of listed firms in regulated economies such as China. As the "pacesetters" among numerous Chinese firms, the CO_2 emissions of listed firms will significantly impact the achievement of China's "dual carbon" goals. China's environmental regulation of listed firms is in line with its "focus on the big, leave the small" approach. Piotroski et al. (2015) argued that China's unique economic system endows listed firms with inherent political advantages particularly in accessing green financing through state-owned banks' carbon transition funds. Compared to small and micro firms, listed firms face greater pressure to reduce carbon emissions. Qu et al. (2013) believed that to ensure the stable operation of the national economy amid energy security constraints, listed firms may be prioritized for rectification as environmental governance issues become increasingly important. For example, the majority of firms on the national key supervision list are listed firms. Du and Li (2020) analyzed industrial decarbonization trajectories through comprehensive firm-level data, identifying significant CO_2 mitigation effects from China's pollution control frameworks. This consensus, however, faces theoretical challenges from the "green paradox" hypothesis (Sinn, 2008), which posits counterproductive outcomes from premature climate interventions like accelerated fossil extraction before policy enforcement. Smulders et al. (2012) argued that imposing a carbon tax would lead to the "green paradox" effect, stimulating firms to consume fossil fuels and increase carbon emissions during the transition period. Zhang et al. (2021a) empirically validated this phenomenon within China's regulatory context, identifying persistent green paradox manifestations in current policy implementations.

Although existing literature has extensively analyzed both the operational impacts of power shortages and the determinants of firm CO_2 emissions, critical blind spots remain at their intersection. Prior studies overlook how electricity constraints interact with China's unique regulatory framework, specifically the "focus on the big, leave the small" environmental governance paradigm, to shape emission trajectories of listed firms. These firms face a dual institutional reality: stringent emissions monitoring and coal usage restrictions contrast with preferential access to grid resources, creating adaptation strategies distinct from those of small firms. The research gap is evident where prior investigations into the drivers of Chinese listed firms' CO_2 emissions have overlooked the potential influence of power shortages. To address this gap, we utilize a city-level index of power shortages in China to examine the effects on Chinese Listed firm CO_2 emissions. This paper seeks to broaden our understanding of the additional adverse consequences of power shortages in developing economies and emphasizes the necessity for policymakers to ensure a stable power supply.

2.2 Hypotheses

Reviewing previous studies (Farquharson et al., 2018), (Guo et al., 2023), (Yu J. et al., 2023), we find that power shortages can affect the decision-making of listed firms in various aspects. The resulting performance and strategies further influence the CO_2 emissions of listed firms. Although no study has directly examined the direct impact of power shortages on the CO_2 emissions of listed firms, based on previous research, we can still propose several pathways through which power shortages affect the CO_2 emissions of listed firms.

The impact of power shortages on energy usage has attracted significant scholarly interest and has been scrutinized across diverse national settings. Driven by power shortages, businesses have turned to supplementary fossil fuels such as coal, petroleum and natural gas. The combustion of coal for electricity production is relatively more carbon-intensive than that of natural gas or petroleum. Consequently, this leads to reduced efficiency in firm energy consumption and increased CO_2 emissions. Qiu et al. (2021) utilized a panel data set from urban areas in China spanning from 2003 to 2017 applying difference-in-differences analysis on low-carbon pilot cities to evaluate the efficacy of policies in reducing urban emissions. Their research revealed that energy consumption is a pivotal factor in the mechanisms underlying emission reductions. Abbasi et al. (2022) analyzed the interaction between fossil fuels, renewables and GDP from 1980 to 2018 using cutting-edge ARDL and Frequency Domain methods to disentangle long-run cointegration versus short-term adjustments. Their data show that fossil fuels notably boost CO_2 emissions, with cost-effective fossil fuels being a key factor in emission increases particularly in deregulated energy markets. Yu et al. (2021a) used CTSD data from 2008 to 2011 to explore firms' emission reduction mechanisms. They concluded that the reliance on inexpensive fossil fuels significantly drives carbon emissions, with energy-intensive operations directly increasing environmental impacts. Alam et al. (2022) revealed U.S. firms with greater cash reserves demonstrate lower emissions, as enhanced financial capacity enables renewable energy adoption and carbon mitigation investments rather than reliance on high-emission energy sources. Zhang et al. (2021b) analyzed China's 2016 Energy Consumption Permit Trading Scheme's efficacy using 2006–2019 panel data from 30 provinces.Their research indicates that curtailing energy consumption with high carbon emission is a critical pathway to meeting carbon emission reduction targets. Following the preceding analysis, we introduce our initial hypothesis:

Hypothesis 1: Power shortage has a significant positive impact on listed firm CO_2 emissions.

Empirical evidence suggests that power shortages have a detrimental effect on firms' financial performance, leading to credit constraints among affected firms as reflected in increased loan rejection rates from commercial banks. Based on liquidity theory, it is hypothesized that increased credit constraints could reduce a firm's capacity for innovation, compromise its market competitiveness, and diminish production efficiency. Consequently, firms may confront funding deficiencies that impede investment in technological advancements, creating a self-reinforcing cycle of energy inefficiency (Zhang et al., 2017). However, studies have also shown that increased investment in technology innovation particularly through public-private R&D partnerships has a positive impact on reducing CO_2 emissions in both developed and developing countries (Ma et al., 2022). Specifically, technological advancements in low-carbon emissions contribute to the optimization of industrial production and environmental quality through the reduction of CO_2 emissions (Hailemariam et al., 2022). Zhang et al. (2024) analyzed China's CO_2 emission trends from 2000 to 2013, finding that key environmental regulations effectively reduced industrial carbon outputs. In a provincial-level study covering 2000-2016, (Huang et al., 2020) quantified how technological upgrades in pollution control systems decreased CO_2 emissions across manufacturing sectors. Their research indicates that environmental technological innovations in adjacent regions significantly contribute to the reduction of CO_2 emissions. Ouyang et al. (2020) explored the effects of environmental regulation on firm innovation applying patent citation network analysis. The study indicates that firms can lower pollution costs by enhancing their engagement in technological innovation. Liu et al. (2021) used data from the Chinese Tax Survey Database between 2008 and 2011 and identified that augmented investment in technological innovation measured by software copyright acquisitions serves as a sustainable strategy for firms to attain energy efficiency and reduce CO_2 emissions. Petrović and Lobanov (2020) found that between 1981 and 2014, for every 1% increase in R&D investment, CO_2 emissions in Organisation for Economic Co-operation and Development countries decreased by an average of 0.09%–0.15% with stronger effects in energy-intensive industries.In the United States, recurring electricity supply deficits have compelled numerous corporations to reconfigure production strategies or procure standalone generation equipment. Empirical studies substantiate that enterprise adoption of independent power generators not only elevates operational costs and diminishes profit margins, but also induces statistically significant crowding-out effects on R&D investments (Reinikka and Svensson, 2002), thereby constraining innovation capacity and productivity enhancement.

Hypothesis 2a: Power shortages can influence Listed firms' CO_2 emissions through the technological innovation.

The "Porter Hypothesis" suggests that promoting technological innovation or adopting advanced technologies can ultimately enhance a firm's productivity, compensating for environmental investment costs while improving market profitability. Empirical evidence shows that power shortages substantially reduce total factor productivity (TFP), which is one of a critical determinant of CO_2 emission reduction, as technological progress enhances energy efficiency and pollution control capabilities. Ladu and Meleddu (2014) demonstrate that higher TFP optimizes resource allocation and decreases energy consumption in Italy from 1996 to 2008. Amri (2018) identifies TFP growth as a key mechanism for curbing CO_2 emissions on Tunisia from 1975 to 2014. In emerging economies, (Altinoz et al., 2021) analyses reveal dynamic relationships between digital technologies, TFP, and carbon emissions. The analysis results show that increased total factor productivity has a negative effect on total CO_2 emissions. Yu et al. (2023a) and Yu et al. (2023b) have illustrated that the effects of the energy trilemma on TFP markedly enhance the potential for fostering collaborative low-carbon economies and the advancement of sustainable energy practices. Zhang et al. (2024) argue that both total factor productivity and green total factor productivity positively influence the transition to clean energy. In advanced economies, the beneficial effect of TFP on the transition to clean energy exceeds that of TFP. Their longitudinal analysis of OECD countries reveals that while conventional TFP improvements predominantly enhance energy efficiency, GTFP specifically drives renewable technology adoption. Ansari et al. (2022) indicate that a slowdown in TFP growth may increase output that results in higher CO_2 emissions, a phenomenon particularly evident in developing economies where environmental regulations are less stringent. Yang et al. (2022) have demonstrated that enhancements in total factor productivity within a specific region can exert a notably significant suppressive impact on CO_2 emissions. Therefore, when facing power shortages firms may escalate their reliance on fossil fuels as a proxy for electricity, consequently augmenting CO_2 emissions through the mechanism of energy intensity. Wang et al. (2023a) employed a GMM model to assess the correlation between electricity usage and TFP among Belt and Road Initiative (BRI) nations over the period 2000-2021. Since electricity is an essential factor of production, power shortages will decrease a firm's TFP. Fried and Lagakos (2020) demonstrated that electricity shortages exert significant negative effects on enterprise productivity in both short-term and long-term contexts, with the long-term adverse impact being five times greater than the short-term consequences. Based on the findings of recent studies, the following hypothesis is proposed:

Hypothesis 2b: Power shortages can influence firms' CO_2 emissions through the total factor productivity (TFP) channel.

The logic diagram of this paper is illustrated in Figure 1.

3 Methodology

To identify the causal effect of power shortages on listed firm CO_2 emissions, this study employs a two-way fixed effects panel regression model, which controls for unobserved heterogeneity across firms and time-invariant confounders. The baseline specification is formalized as Equation 1:

$$Ln\,CO_{2,it} = \alpha + \beta ES20_{it} + \gamma X_{it} + u_i + \delta_t + \varepsilon_{it} \qquad (1)$$

where i represents the firm and t represents the year, respectively. $Ln\,CO_{2,it}$ denotes the CO_2 emission of firm i at time t. The core variable $ES20_{it}$ is the power shortage index of firm i at time t. X denotes a vector of control variables, including return on total assets (roa), financial debt ratio (Finlev), cash flow (cflow), shareholding ratio of the largest shareholder (top1), cash holdings (cash), cash substitutes (liqui), current asset ratio (cr), asset structure (tang), and proportion of intangible assets (itang). u_i signifies firm-fixed effects that varies across different firms i. δ_t is year-fixed effects that varies with time t, which captures the impact of macroeconomic shocks. ε_{it} is a random error term.

4 Variable selection and data sources

4.1 Variable selection

Explained variables: The explained variable in this study is the natural logarithm of firm CO_2 emissions ($LNCO_2$). We handle CO_2 emissions as follows.

First, we obtain the total CO_2 emissions of each firm by multiplying each firm's actual consumption of various types of energy (such as oil, coal, and electricity) by their respective emission factors.

Electricity emission factors fluctuated between 0.797 and 1.278 $kgCO_2/kg$ during 2008–2015, reflecting annual adjustments in regional power grid structures documented by China's National Bureau of Statistics, while fixed factors were used for coal (1.9003 $kgCO_2/kg$) and oil (3.0202 $kgCO_2/kg$) (Qian et al., 2021). Second, we employ the log-transformed total CO_2 emissions as the primary dependent variable to mitigate scale effects in regression analysis.

Core explanatory variables:The key explanatory variable is the city-level power shortage index based on 20 text analysis keywords (PS20), constructed using the methodology proposed by Guo et al. (2023), Yu et al. (2023b).

The city-level power shortage index is constructed through the following steps:

(i) Collect news reports from city-specific daily newspapers across China.
(ii) Identify 20 representative technical phrases across four domains[1], covering five operational dimensions, demand-side management, generation optimization, system reliability, operational interventions and infrastructure

1 The 20 critical terms consist of peak load management, electricity generation, thermal recovery generation, off-peak operation, grid isolation, demand-side rationing, circuit shutdown, optimized consumption, protective tripping, load shifting, supply interruption, industrial energy usage, phased peak reduction, emergency load shedding, power failure incidents, capacity overloading, feeder switching, grid reliability, consumption curtailment, and energy redistribution.

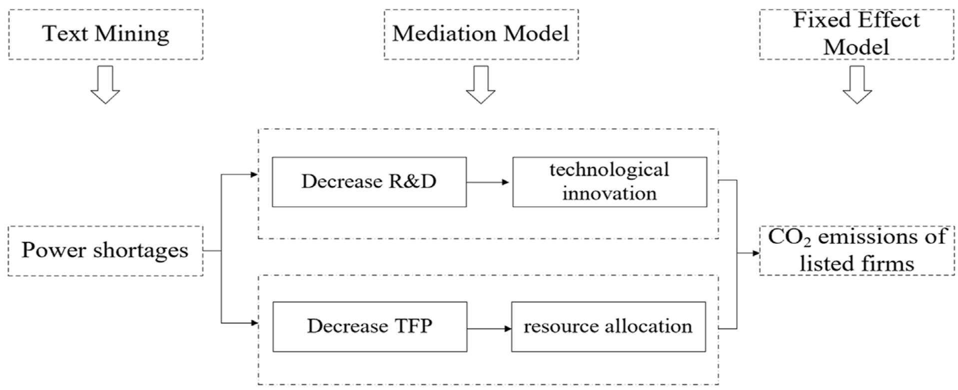

FIGURE 1
Logic diagram of the impact of power shortages on CO_2 emissions of listed firms

contingencies, determined through keyword frequency analysis and expert validation.

(iii) Following the methods of Guo et al. (2023), Da et al. (2015), measure the occurrence rate for individual key phrases (k = 1,2,. . .,20) for each city (j) in year t, denoted as $YFI_{j,k,t}$. The rate of change for each key phrase is quantitatively analyzed using the methodology described by Equation 2:

$$\Delta YFI_{j,k,t} = ln\left(YFI_{j,k,t}\right) - ln\left(YFI_{j,k,t-1}\right) \tag{2}$$

(iv) Apply 1%–99% Winsorization to $\Delta YFI_{j,k,t}$ to minimize outlier distortion, followed by standardization to ensure comparability across indicators. This process generates adjusted standardized values $\Delta AYFI_{j,k,t}$ for each power shortage-related phrase.

(v) Aggregate $\Delta AYFI_{j,k,t}$ per city annually, ultimately deriving the city-level power shortage index (PS) through aggregation, using the Equation 3:

$$PS_{j,t} = \sum_{k=1}^{20} \Delta AYFI_{j,k,t} \tag{3}$$

Instrumental variables for power shortages, selected based on a natural climate perspective, include the number of high-temperature days (DHT) and cooling degree days (CDD), following the approach introduced by Yu et al. (2023b). The number of high-temperature days (DHT) is computed through multi-stage spatial processing. Initial data collection involves daily mean temperatures and latitude coordinates from 824 national meteorological stations. Spatial interpolation using inverse distance weighting creates rasterized temperature grids, followed by administrative boundary processing to generate municipal-level thermal datasets. Annual counts of days exceeding 30°C thermal thresholds per city are aggregated, which serves as the instrumental variable for electricity supply constraints, formally designated as high-temperature days (DHT). This study also adopts annual cooling degree days (CDD) as an instrumental variable. The calculation formulas for CDD are given in Equation 4.

$$CDD = \sum_{i=1}^{n} rd\left(T_i - T_b\right) \tag{4}$$

Specifically, CDD (cooling degree days) refers to the cumulative number of degrees above a base temperature for a given year, indicating the extent to which cooling is required due to increased temperatures. n represents the number of days in a year. T_i denotes the average daily temperature. The base temperature T_b, following Fisher-Vanden et al. (2015), is set at 18 degrees Celsius. rd is a dummy variable, which is recorded as 1 if the average daily temperature exceeds the base temperature, and 0 otherwise.

To account for potential confounding factors influencing firm productivity, multiple control variables were incorporated into the model, namely return on total assets, financial debt ratio, cash flow, dominant shareholder ownership percentage, cash holdings, cash substitutes, current asset ratio, asset structure, and proportion of intangible assets. Return on total assets (roa) represents a firm's net profit relative to its total asset base. The financial leverage ratio (Finlev) is calculated by dividing total liabilities by total assets. Cash flow (cflow) refers to the net operational cash generated through business activities. The largest shareholder's equity position (top1) quantifies the dominant shareholder's proportionate ownership in the firm. Cash holdings (cash) are the amount of cash held by the firm. Cash substitutes (liqui) are highly liquid assets that can be quickly converted to cash. The current asset ratio (cr) is equal to current assets divided by total assets. Asset structure (tang) is measured by the ratio of tangible assets. The intangible asset ratio (itang) corresponds to the percentage of intangible holdings. Definitions of the variables are reported in Table 1 and summary statistics are presented in Table 2.

4.2 Data sources

This study investigates the impact of power shortages on CO_2 emissions of listed firms. In 2020, China proposed its "dual carbon" goals, demonstrating its nationally determined contribution to addressing global climate change and highlighting its responsibility and commitment as a major nation. Under this

TABLE 1 Definitions.

Variables	Definitions
PS20	City-level power shortage index, constructed based on methodology by Guo et al. (2023)
$LNCO_2$	Natural logarithm of listed firms' annual carbon dioxide emissions
roa	Return on assets, derived from net profit relative to total assets
Finlev	Financial leverage, expressed as total liabilities divided by total assets
cflow	Net monetary movement from core business activities
top1	Proportion of firm shares held by dominant shareholder
cash	Aggregate value of cash and equivalents possessed
liqui	Liquidity ratio, computed as highly liquid assets divided by total assets
cr	Current assets compared against total assets
tang	Tangibility ratio, defined as tangible fixed assets divided by total assets
itang	Intangible assets portion within total assets

grand goal, all industries are facing the urgent need for transformation, upgrading and green development. As an important part of China's economy, listed firms, with a market value accounting for 14.2% of the global market value, play a key role in the process of achieving the "dual carbon" goals and their carbon emissions have attracted wide attention. China's environmental regulation policies exhibit a "prioritizing large firms over smaller ones" characteristic, imposing greater carbon reduction pressure on listed companies. Therefore, this study employs A-share listed firms spanning the years 2001–2017 as the research sample. The independent variable, power shortage, utilizes data from the city-level power shortage index for 218 Chinese prefecture-level cities constructed by Guo et al. (2023). The dependent variable, firm CO_2 emissions, is calculated by multiplying actual energy consumption with corresponding CO_2 emission coefficients for each energy type. Firm-level control variables are obtained from the China Stock Market and Accounting Research database, while temperature datasets originate from the China National Meteorological Information Center.

TABLE 2 Summary statistics.

Variables	Obs	Mean	Std. dev	Min	Max
PS20	13,832	0.682	7.510	−17.41	24.07
$LnCO_2$	13,832	13.27	1.468	9.883	17.44
roa	13,832	0.0426	0.0514	−0.152	0.195
Finlev	13,832	0.436	0.258	0	0.915
cflow	13,832	0.0467	0.0736	−0.174	0.255
top1	13,832	38.13	15.63	9.090	77.97
cash	13,832	0.187	0.141	0.0128	0.684
liqui	13,832	0.0276	0.204	−0.489	0.524
cr	13,832	0.566	0.217	0.0720	0.964
tang	13,832	0.410	0.178	0.0540	0.827
itang	13,832	0.0444	0.0515	0	0.326

5 Empirical results

5.1 Baseline results

Table 3 presents the core regression analysis examining how power shortages affect listed firm CO_2 emissions, with consistent controls for firm and year fixed effects across specifications. In the Column (1), the PS20 variable reveals a positive coefficient reaching statistical significance at the 10% threshold, indicating that power shortages correlate with elevated CO_2 emissions. Specifically, the standard deviation shock in power shortages is estimated to increase firm-level CO_2 emissions by 0.725%. Introducing firm-level control variables in column (2) maintains the significant positive association for PS20 at the 5% level, with an estimated coefficient of 0.00103. This finding suggests that higher levels of power shortages are linked to elevated firm CO_2 emissions, potentially due to firms' inclination towards carbon-intensive energy sources like coal for self-generation during periods of shortage.

5.2 Instrumental variables regression

Although power shortages are considered an external shock (Cole et al., 2018), there may be endogenous issues of mutual causality between power shortages and CO_2 emissions of listed firms. Firms with lower carbon emissions alleviate local governments' restrictions on power supply and operational pressures on electricity infrastructure imposed to control coal-related energy consumption and emissions, thereby helping maintain local power stability. In contrast, firms with higher carbon emissions, characterized by high energy consumption, high pollution, substantial electricity demand, and accelerated infrastructure wear, are more likely to prompt governments to adopt compulsory measures such as electricity rationing,

TABLE 3 Baseline results.

VARIABLES	(1)	(2)
	$LnCO_2$	$LnCO_2$
PS20	0.000965*	0.00103**
	(0.001)	(0.001)
roa		2.249***
		(0.240)
Finlev		0.425***
		(0.074)
cflow		0.661***
		(0.127)
top1		0.00422**
		(0.002)
cash		−1.610***
		(0.172)
liqui		−0.998***
		(0.127)
cr		1.876***
		(0.218)
tang		0.109
		(0.115)
itang		0.654*
		(0.359)
Constant	13.29***	12.01***
	(0.000)	(0.143)
Firm FE	YES	YES
Year FE	YES	YES
Observations	13519	13519
Adj R^2	0.891	0.903

Note: Table 3 displays the foundational regression outcomes assessing the impact of Power shortage on Listed firm CO_2 emissions. Each column incorporates controls for both entity-specific and temporal fixed effects, with columns (2) including control variables.The suite of control variables includes return on total assets (roa), financial debt ratio (Finlev), cash flow (cflow), shareholding ratio of the largest shareholder (top1), cash holdings (cash), cash substitutes (liqui), current asset ratio (cr), asset structure (tang), and proportion of intangible assets (itang). The analysis applies firm-level clustering to standard errors for addressing intra-firm dependencies, with these adjusted estimates displayed in parentheses. Statistical significance thresholds are marked using ***, **, and * asterisks corresponding to 1%, 5%, and 10% probability levels.

exacerbating power shortages. To resolve the endogeneity concerns originating from the bidirectional causal relationship, this study employs an instrumental variable (IV) approach. An instrumental variable must satisfy relevance and exogeneity, it must correlate with the endogenous explanatory variable (PS20) and maintain independence from the with the error term. As demonstrated by Guo et al. (2023), rising temperatures significantly increase residential electricity demand, which crowds out industrial electricity consumption and intensifies firm power shortages. For relevance, local temperature and climatic conditions profoundly influence electricity usage patterns and power shortage severity. For exogeneity, neither academia nor industry has identified temperature as a direct determinant of firm carbon emissions. Thus, this research employs temperature-linked indicators as instrumental variables through the two-stage least squares methodological framework. The most commonly used variable in climate-economic impact research is temperature (Schlenker and Roberts, 2009). Accordingly, this paper adopts the number of high-temperature days (DHT) as the first instrumental variable. Additionally, cooling degree days (CDD), which reflect climate change impacts on building cooling needs and directly measure energy demand shifts under climate change, are used as the second instrumental variable.

TABLE 4 Results of instrumental variables regression.

VARIABLES	(1)	(2)	(3)	(4)
	PS20	lnCO_2	PS20	lnCO_2
PS20		0.0194**		0.0325**
		(0.0096)		(0.0146)
DHT	0.0680***			
	(0.0084)			
CDD			0.0052***	
			(0.0008)	
Control_Var	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	8050	8050	13549	13549
Adj R^2	0.176	0.018	0.224	−0.058
F-statistic	7.8383	25.9801	5.2382	34.0515
Kleibergen-Paap rk LM statistic	59.0991***		35.0536***	
Kleibergen-Paap rk F statistic	65.3712		37.4125	

Note: Table 4 presents the instrumental variable (IV) regression results analyzing the effect of power shortages on listed firms' CO_2 emissions. Columns (1) and (3) report the first-stage regression estimates using the number of high-temperature days (DHT) and cooling degree days (CDD) as instrumental variables, respectively. Columns (2) and (4) report the second-stage regression outcomes analyzing the effect of power shortages (PS20) on CO_2 emissions at the firm level (lnCO_2). All specifications include controls for entity-specific fixed effects, temporal fixed effects, and the full suite of control variables: return on total assets (roa), financial debt ratio (Finlev), cash flow (cflow), shareholding ratio of the largest shareholder (top1), cash holdings (cash), cash substitutes (liqui), current asset ratio (cr), asset structure (tang), and proportion of intangible assets (itang). The analysis employs firm-level clustering for standard errors to address within-firm correlations, with these adjusted values appearing in parentheses. Statistical significance thresholds are indicated as *** (1%), ** (5%), and * (10%). Instrument validity is supported by two diagnostic metrics: the Kleibergen-Paap rk LM, statistic demonstrates identification strength by rejecting under-identification (rejecting under-identification at the 1% level), while the Kleibergen-Paap rk F statistic confirms instrument relevance through values surpassing Stock-Yogo critical thresholds. The F-statistics for both stages further confirm the robustness of the IV, specifications.

The estimation results from instrumental variable regression are detailed in Table 4. Columns (1) and (3) of Table 4 indicate a positive impact of the instrumental variables, namely the number of high-temperature days (*DHT*) and cooling degree days (*CDD*), on the explanatory variable.This indicates that extreme weather significantly intensifies power shortages, meeting the relevance condition for instrumental variables. Furthermore, columns (2) and (4) reveal a statistically significant positive effect of power shortages on firm CO_2 emissions at the 5% significance level. These results correspond with the primary regression outcomes documented in Table 3. The LM statistic's 1% significance level confirmation indicates the instrumental variables employed in this research are adequately identified. Furthermore, the Wald F statistics for both instruments surpass the critical values established by Stock and Yogo (2002), effectively mitigating concerns regarding weak instrument bias. In conclusion, having addressed the issue of endogeneity, the analysis reveals a direct positive link connecting power shortages with CO_2 emissions at the firm level, which strengthens the empirical validity of the study's core findings.

5.3 Robustness checks

Despite the instrumental variable regression outcomes detailed in Table 4, supplementary robustness checks are imperative to validate the reliability of this study's empirical conclusions. Firstly, the regressions were re-executed with a refined set of independent variables, narrowing down the power shortage index from 20 to only the top 5 keywords[2]. The outcomes in columns (1)-(2) of Table 5 confirm a significant positive correlation between power shortages and firm CO_2 emissions at 5% level, consistent with the baseline findings. Secondly, the 2008 financial crisis might have affected firms' operations and decisions. To avoid this impact on regression results, we exclude all 2008 observations and re-estimate the model. Table 5 columns (3)-(4) reveal that power shortage coefficients maintain significant positivity at the 5% level, confirming the core results' resilience against exogenous macroeconomic shocks. Thirdly, considering the temporal lag between the occurrence of power shortages and listed firms' adoption of energy-intensive alternatives along with production decision adjustments, this study introduces a one-period lag of the dependent variable into the regression model. The results

2 The construction of the PS5 variable employs a frequency-weighted methodology, prioritizing five predominant operational indicators in energy system optimization: peak load management, electricity generation, thermal recovery generation, off-peak operation, grid isolation.

TABLE 5 Robustness test.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	$LnCO_2$	$LnCO_2$	$LnCO_2$	$LnCO_2$	$LnCO_2$	$LnCO_2$	$LnCO_2$	$LnCO_2$
PS5	0.00434***	0.00352**						
	(0.002)	(0.001)						
PS20			0.00112*	0.00122**	0.00119*	0.00126**	0.00118**	0.00116**
			(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Control_Var	NO	YES	NO	YES	NO	YES	NO	YES
Firm FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Constant	13.29***	12.02***	13.30***	12.04***	13.23***	11.95***	13.32***	12.18***
	(0.001)	(0.143)	(0.000)	(0.141)	(0.000)	(0.167)	(0.000)	(0.152)
N	13528	13528	12768	12768	9922	9922	12895	12895
Adj R^2	0.891	0.903	0.892	0.904	0.901	0.908	0.898	0.908

Note: Table 5 presents robustness tests assessing the relationship between power shortages and listed firm CO_2 emissions. Columns (1)-(2) employ the refined PS5 index (constructed from five energy system optimization keywords), while columns (3)-(4) exclude 2008 observations to mitigate financial crisis effects. Columns (5)-(6) introduce a 1-year lagged dependent variable to account for temporal delays in firms' emission adjustment processes, with PS20 coefficients remaining statistically significant at 10% and 5% levels respectively. Columns (7)-(8) exclude pre-2005, data to align with China's post-Kyoto Protocol carbon accounting standardization, demonstrating persistent significance (5% level) of power shortage effects. All models incorporate firm and year fixed effects, with columns (2), (4), (6), and (8) incorporating additional control variables: return on total assets (roa), financial debt ratio (Finlev), cash flow (cflow), shareholding ratio of the largest shareholder (top1), cash holdings (cash), cash substitutes (liqui), current asset ratio (cr), asset structure (tang), and proportion of intangible assets (itang). Firm-level clustered standard errors are reported in parentheses. Asterisks (***, **, *) denote statistical significance at the 1%, 5%, and 10% levels, respectively.

presented in columns (5) and (6) of Table 5 demonstrate that the regression coefficients of PS20 are 0.00119 and 0.00126, showing statistical significance at the 10% and 5% levels respectively, consistent with the anticipated temporal hysteresis of firm carbon emissions. Finally, given the Kyoto Protocol's enforcement in 2005 and China's subsequent participation in the Clean Development Mechanism (CDM) with standardized carbon accounting methodologies, we exclude pre-2005 data to eliminate inconsistencies in emission measurement standards. As shown in columns (7) and (8) of Table 5, the PS20 coefficient remains significantly positive at the 5% level, indicating that the research conclusions remain unaffected by variations in carbon accounting standards.

6 Expansion analysis

6.1 Channel analysis

Building upon the theoretical framework and empirical evidence presented earlier, this study investigates the mechanisms through which power shortages exacerbate listed firms'CO_2 emissions, focusing on resource technological innovation and allocation efficiency. Following the methodological approach of Chen et al. (2020), we construct the following mediation model as shown in Equation 5:

$$Mech\_Var_{it} = \alpha + \beta ES20_{it} + \gamma X_{it} + u_i + \delta_t + \varepsilon_{it} \tag{5}$$

Where $Mech\_Var_{it}$ represents the mediating variables capturing technological innovation and resource allocation, while other variables remain consistent with those defined in preceding sections.

First, we conduct channel analysis through the technological innovation of listed firms. On the input side of innovation, this study employs the natural logarithm of R&D expenditure and the logarithm of R&D personnel headcount as proxy variables to explore their mediating role in the link between power shortages and CO_2 emissions. The regression results in columns (1) - (2) of Table 6 show that power shortages significantly reduce R&D expenditure and R&D personnel at the 5% level. Specifically, a one-unit increase in power shortages decreases firm R&D spending and R&D personnel by 0.29% and 0.33%, respectively. On the output side of innovation, we measure innovation performance using the logarithm of patent applications and the proportion of green invention patents to total patent filings within a year. Columns (3)-(4) of Table 6 reveal negative correlations between power shortages and both general technological innovation and green innovation at the 5% and 10% significance levels. These results confirm that technological innovation and green innovation serve as critical mediating channels through which power shortages exacerbate firm carbon emissions. These findings align with existing literature (Liu et al., 2021), (Ouyang et al., 2020) and substantiate Hypothesis 2a, demonstrating that enhancing innovation investments enables firms to adopt more efficient, productive, and environmentally sustainable production technologies.

Second, this study examines the resource allocation channel. We measure firm resource allocation efficiency using two established total factor productivity (TFP) metrics: the Olley and Pakes (1996) and the Levinsohn-Petrin approach (Levinsohn and Petrin, 2003). Regression results in Columns (1)-(2) of Table 7 reveal statistically significant negative coefficients for the power shortage index (PS20) at the 5% level, indicating that power shortages substantially impair

TABLE 6 Mechanism test results (1).

VARIABLES	(1)	(2)	(3)	(4)
	R&D	R&D people	PAT	GPAT
PS20	−0.0029**	−0.0033**	−0.0022**	−0.0003*
	(0.001)	(0.002)	(0.001)	(0.000)
Constant	17.6324***	5.6742***	1.4876***	0.0094
	(0.185)	(0.214)	(0.120)	(0.019)
Control_Var	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
N	7,619	3,311	13,124	5,475
Adj R^2	0.842	0.912	0.737	0.427

Note: Table 6 displays the mechanism analysis examining how technological innovation mediates the connection between power shortages and CO_2 emissions in listed companies. Columns (1)-(2) assess innovation inputs through logarithmic R&D spending and research personnel data, with columns (3)-(4) evaluating outputs based on patent filings and green invention patent proportions. The PS20 power shortage index is used as the key explanatory variable. All models incorporate firm and year fixed effects while maintaining consistent control variables across specifications.The control variables include return on total assets (roa), financial debt ratio (Finlev), cash flow (cflow), shareholding ratio of the largest shareholder (top1), cash holdings (cash), cash substitutes (liqui), current asset ratio (cr), asset structure (tang), and proportion of intangible assets (itang). Standard errors clustered by firm are presented in parentheses. Significance levels are denoted by *** (1%), ** (5%), and * (10%).

TABLE 7 Mechanism test results (2).

VARIABLES	(1)	(2)	(3)
	TFP_OP	TFP_LP	GTFP
PS20	−0.0010**	−0.0009**	−0.0001***
	(0.000)	(0.000)	(0.000)
Constant	5.4586***	6.9318***	0.9944***
	(0.104)	(0.121)	(0.002)
Control_Var	YES	YES	YES
Firm FE	YES	YES	YES
Year FE	YES	YES	YES
N	11,642	11,632	12,094
Adj R^2	0.841	0.875	0.014

Note: Table 7 presents mechanism test results examining the resource allocation channel linking power shortages to firm CO_2 emissions. Columns (1)-(2) measure total factor productivity using the Olley-Pakes and Levinsohn-Petrin methodologies, while column (3) employs green total factor productivity (GTFP) data from Wu et al. (2022). The power shortage index serves as the core explanatory variable across all specifications. All regressions incorporate firm and year fixed effects, along with control variables including return on total assets (roa), financial debt ratio (Finlev), cash flow (cflow), shareholding ratio of the largest shareholder (top1), cash holdings (cash), cash substitutes (liqui), current asset ratio (cr), asset structure (tang), and proportion of intangible assets (itang). Standard errors clustered at the firm level are shown in parentheses. Asterisks indicate statistical significance levels, with *** representing 1%, ** 5%, and * 10% thresholds.

firms' TFP. Quantitatively, a one-unit increase in PS20 reduces TFP by 0.09%, demonstrating that energy constraints hinder firms' capacity to enhance productivity for carbon mitigation, thereby exacerbating CO_2 emissions. These findings validate Hypothesis 2b. Furthermore, since reduced carbon emissions signify firm green transition, we employ green total factor productivity (GTFP) data constructed by Wu et al. (2022) to assess its mediating role. Column (3) of Table 7 shows that power shortages significantly reduce GTFP at the 1% level. On the one hand, studies have revealed that in multiple countries, including China (Fisher-Vanden et al., 2015), India (Allcott et al., 2016), and Ethiopia (Abdisa, 2018), power shortages significantly impair firm performance and productivity. On the other hand, research indicates that firms with higher green total factor productivity have greater energy efficiency and lower CO_2 emissions (Cui et al., 2021), (Yu P. et al., 2021). We demonstrate that power shortages depress both conventional and green TFP, driving increased firm carbon emissions, thereby robustly supporting Hypothesis 2b.

6.2 Heterogeneity

Table 8 presents the heterogeneity regression results. In terms of firm characteristics, state-owned firms (SOEs), given their strategic

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TABLE 8 Results of heterogeneous analysis.

VARIABLES	(1)	(2)	(3)	(4)	(5)
	$lnCO_2$	$lnCO_2$	$LnCO_2$	$lnCO_2$	$lnCO_2$
PS20	0.000858	0.00127*	0.000621	−0.00494*	0.000651
	(0.001)	(0.001)	(0.001)	(0.003)	(0.002)
PS20×soe	−0.00260**				
	(0.001)				
soe	0.156***				
	(0.026)				
PS20×hvyp		−0.00247**			
		(0.001)			
hvyp		0.123			
		(0.108)			
PS20×Carbon			0.00686*		
			(0.004)		
Carbon			−0.191		
			(0.292)		
PS20×fiscal				0.00759**	
				(0.004)	
fiscal				0.104	
				(0.294)	
PS20×CPU					0.00158*
					(0.001)
CPU					0.0181
					(0.016)
Control_Var	YES	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES
N	13428	13519	12791	13549	13003
Adj R^2	0.902	0.902	0.905	0.902	0.896

Note: Table 8 presents heterogeneous analysis of power shortage impacts on CO_2 emissions across firm and regional characteristics. Columns (1)-(5) explore variations by ownership type (SOEs, vs. non-SOEs), industry pollution intensity (HPI, vs. non-HPI), regional carbon dependency (coal consumption share), fiscal pressure (provincial expenditure-revenue ratio) and climate policy uncertainty (CPU). All specifications include firm and year fixed effects, with consistent control variables: return on total assets (roa), financial debt ratio (Finlev), cash flow (cflow), shareholding ratio of the largest shareholder (top1), cash holdings (cash), cash substitutes (liqui), current asset ratio (cr), asset structure (tang), and proportion of intangible assets (itang). Firm-level clustered standard errors are shown in parentheses. Asterisks (***, **, *) denote significance at 1%, 5%, and 10% levels.

role in national economic security and prioritized access to energy supply guarantees, are endowed with more stable power allocation mechanisms, resulting in a lower probability of experiencing power shortages compared to non-SOEs. To test this hypothesis, we split the sample into SOEs and non-SOEs, using ownership type as a binary categorical variable (SOEs: soe = 1; otherwise soe = 0). As shown in Column (1) of Table 8, the interaction term between power shortages (PS20) and the SOE dummy is significantly negative, indicating that SOEs exhibit lower sensitivity to power shortage impacts. This is attributed to the priority given by the state grid to ensure power supply to state-owned firms, which are often integral to the national economy and public welfare. Furthermore, to assess industry-specific heterogeneity, we classify firms based on whether they operate in heavily polluting industries (HPIs). The sample is divided into HPI and non-HPI subsamples using a binary variable (hvyp = 1 for HPI firms; otherwise hvyp = 0). Column (2) of Table 8 reveals a significantly negative interaction term between PS20 and the HPI dummy at the 10% level, suggesting that non-pollution-intensive firms face greater emission increases under power shortages.

In examining the heterogeneity based on regional characteristics of firms, areas with higher coal consumption face a self-reinforcing "power shortage–coal dependency–emission surge" vicious cycle, driven by sluggish energy structure transition and insufficient grid flexibility.Firstly, this study evaluates regional energy consumption heterogeneity by measuring coal consumption share as a proxy for carbon-intensive energy use. As shown in Column (3) of Table 8, the significant positive interaction term between power shortages (PS20) and regional carbon intensity indicates that power constraints disproportionately escalate CO_2 emissions in coal-dependent regions. Secondly, we quantify fiscal pressure at the provincial level using the ratio of fiscal expenditure to revenue. Column (4) of Table 8 demonstrates a significantly positive interaction between PS20 and fiscal pressure, suggesting that regions with tighter fiscal conditions exhibit heightened vulnerability to power shortages. Thirdly, as global climate change intensifies, countries worldwide are addressing challenges by setting greenhouse gas reduction targets, implementing carbon emission trading systems, promoting renewable energy adoption, and improving energy efficiency. However, frequent adjustments to policy objectives, changes in policy tools, and interactions between policies (Le and Zak, 2005) make it difficult for businesses and society to predict the content, timing, intensity, and effectiveness of climate policies, resulting in Climate Policy Uncertainty (CPU). Therefore, this study adopts the Climate Policy Uncertainty Index constructed by Ma et al. (2023) to measure the uncertainty faced by firms in their respective regions. Column (5) of Table 8 presents the heterogeneous regression results examining the impact of climate policy uncertainty in firms' regions. The significantly positive regression coefficient of the interaction term between power shortages and regional climate policy uncertainty (PS20×CPU) indicates that power shortages exert a more pronounced effect on carbon emissions from listed firms in regions with higher climate policy uncertainty.

7 Conclusion

The stability of electricity supply is crucial for firm growth and operational continuity. However, power shortages prevalent in emerging economies pose significant challenges. While existing studies demonstrate that electricity constraints reduce firm productivity, few have focused on their impact on CO_2 emissions from listed firms in developing countries. This study employs a city-level power shortage index to examine its effect on CO_2 emissions of Chinese listed firms, revealing a significant positive correlation. Further analysis indicates that power shortages exacerbate firm carbon emissions by suppressing technological innovation and distorting resource allocation. The positive impact of power shortages on CO_2 emissions is particularly pronounced for non-state-owned firms, non-pollution-intensive industries, and firms located in regions with higher reliance on carbon-intensive energy use or greater fiscal revenue and expenditure pressures. These findings persist after controlling for endogeneity concerns and performing various robustness tests.

Given China's status as a major global carbon emitter and its commitment to dual-carbon goals, policymakers must carefully consider the environmental implications of power shortages in strategic planning. Governments should prioritize the construction and management of electricity infrastructure. Firstly, proactive efforts should be made to upgrade power infrastructure, particularly in regions with high electricity consumption intensity and significant climate policy uncertainty. This includes adopting smart grid technologies to dynamically balance supply-demand mismatches and deploying demand response systems to incentivize off-peak energy use. Against the backdrop of the digital economy's heavy reliance on electricity, timely modernization of grid systems is essential to enhance supply stability and reliability, reduce power shortage frequency, and provide robust energy security for firm operations and residential consumption. Secondly, governments should optimize regional electricity management by integrating actual energy transition progress with supply capacity. Establishing inter-regional coordination mechanisms could enable surplus renewable energy transfers from western provinces to eastern industrial hubs, rationing policies should be formulated based on firms' production characteristics and socioeconomic impacts to ensure policy feasibility, sustainability, and the protection of basic electricity needs for listed firms, thereby fostering a stable business environment. Thirdly, governments can guide firms to adopt clean energy through rational energy planning and the establishment of scientific energy systems. This may involve expanding carbon emission trading markets to internalize environmental costs and accelerate low-carbon technology adoption. This approach aims to reduce reliance on traditional high-pollution energy sources, promote diversification of the energy mix, increase the proportion of clean energy in power supply, and support firms in improving energy conservation and emission reduction efficiency. Finally, governments should refine regional electricity management by comprehensively evaluating the progress of energy transition and local power supply capabilities. Policies should be tailored according to firms' operational profiles and their socioeconomic influence to ensure practicality and sustainability.

Listed firms should strengthen risk resilience and improve technological innovation and resource allocation capabilities. In an increasingly volatile energy landscape, power shortages may occur unexpectedly. Beyond financial performance, listed firms should mitigate adverse environmental impacts by implementing targeted risk prevention, assessment, and response measures, such as optimizing production processes, advancing energy transition, and strengthening stakeholder engagement. Additionally, listed firms need to enhance technological innovation and resource allocation efficiency. Internally, firms should continuously accelerate digital transformation and information management, increase investments in digital transformation, and utilize technologies such as big data and artificial intelligence to enhance information processing efficiency and transparency. During power shortages, digital tools can be utilized to optimize energy management, accurately assess risks, and formulate effective response strategies. Externally, listed firms should explore diversified energy solutions, such as investing in distributed energy systems including biomass co-generation and hydrogen fuel cells to improve energy self-sufficiency and reduce dependence on external grids. Increased investment in R&D and adoption of energy-saving technologies such as waste heat recovery systems and pollution control equipment will enhance energy efficiency, reduce emissions, and improve environmental performance, setting benchmarks for smaller firms.

This study explores the relationship between power shortages and carbon emissions using CO_2 emission data from listed firms in China, offering practical insights for developing countries implementing carbon reduction strategies amid energy shortages. Moving forward, developing countries can strengthen public education and awareness-building efforts to enhance societal understanding of power shortages. First, through media campaigns, public welfare organizations, and other channels, governments should intensify efforts to educate the public on the impacts of power shortages on firms, raising awareness and recognition of corporate emission reduction initiatives. Second, leveraging the collaborative role of multinational organizations, countries can facilitate cross-border cooperation among firms to share successful experiences and technologies for addressing rising carbon emissions under power shortages. Collaborative research and development of energy-saving technologies, along with shared utilization of energy resources, should be promoted to collectively explore solutions, contributing to the achievement of carbon reduction goals in developing nations.

In future research, it can be further investigated the issue of carbon leakage that may arise from firms relocating their production to regions with ample and stable electricity supply due to chronic power shortages.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

YL: Conceptualization, Data curation, Writing – original draft. CN: Validation, Visualization, Writing – review and editing. BS: Formal Analysis, Investigation, Methodology, Project administration, Resources, Writing – original draft. GZ: Conceptualization, Data curation, Funding acquisition, Investigation, Software, Supervision, Validation, Writing – review and editing.

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Conflict of interest

Author CN was employed by AVIC China Aero-Polytechnology Establishment.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1590025/full#supplementary-material

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