

Yu, Hongwei et al.

**Working Paper**

## The Impact of the Energy Conservation Law on Enterprise Energy Efficiency: Quasi-Experimental Evidence from Chinese Firms

GLO Discussion Paper, No. 1339

**Provided in Cooperation with:**

Global Labor Organization (GLO)

*Suggested Citation:* Yu, Hongwei et al. (2023) : The Impact of the Energy Conservation Law on Enterprise Energy Efficiency: Quasi-Experimental Evidence from Chinese Firms, GLO Discussion Paper, No. 1339, Global Labor Organization (GLO), Essen

This Version is available at:

<https://hdl.handle.net/10419/278822>

**Standard-Nutzungsbedingungen:**

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

**Terms of use:**

*Documents in EconStor may be saved and copied for your personal and scholarly purposes.*

*You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.*

*If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.*

# **The Impact of the Energy Conservation Law on Enterprise Energy Efficiency: Quasi-Experimental Evidence from Chinese Firms**

Hongwei Yu,<sup>1</sup> Wenjin Chen,<sup>2</sup> Xinyi Wang,<sup>2</sup> Laurence Delina,<sup>2</sup>  
Zhiming Cheng,<sup>3</sup> and Le Zhang<sup>3</sup>

## **Abstract**

We employ a regression discontinuity design (RDD) to investigate the causal effect of China's Energy Conservation Law (ECL) on the energy efficiency of Chinese firms. Using data from the 2018 China Employer-Employee Survey (CEES), we find that the energy regulation has a positive impact on enterprise energy efficiency. Furthermore, we observe that the effects of the regulation vary across industries, ownership types, and firm ages. We also find that energy management system (EnMS) and technological innovation are mechanisms through which the energy regulation helps improve enterprise energy efficiency. These findings underscore the importance of well-designed and effectively implemented energy regulations in fostering energy efficiency and reducing carbon emissions in the industrial sector. They also highlight the need to consider the heterogeneity of the regulatory impact when designing energy-saving policies.

**Keywords:** Energy Conservation Law; energy regulation; energy efficiency; China; regression discontinuity design

**JEL Classifications:** K32; Q56; Q58

---

<sup>1</sup> Wuhan University, Wuhan, China

<sup>2</sup> The Hong Kong University of Science and Technology, Kowloon, Hong Kong

<sup>3</sup> Macquarie Business School, Macquarie University, Sydney, Australia & GLO

Corresponding author: Wenjin Chen. Email: wenjinchen@ust.hk

## 1. Introduction

In 2022, global carbon dioxide (CO<sub>2</sub>) emissions resulting from energy consumption and industrial processes reached a new annual record high, surpassing 36.8 billion tons (IEA, 2023). One effective approach for the industrial sector to reduce emissions is to enhance its energy efficiency. Improved energy efficiency enables enterprises to achieve greater economic output while consuming less energy, reducing energy costs and mitigating environmental pollution (Patterson, 1996). However, enterprises frequently lack the motivation to prioritize energy efficiency improvements due to concerns regarding the associated costs, a lack of awareness about energy-saving opportunities, and inadequate attention at the managerial and organizational levels (Yemelyanov et al., 2023; Kostka et al., 2013; Cagno et al., 2013; Blumstein et al., 1980). Therefore, government regulations could play a crucial role in intervening and regulating enterprises to enhance their energy efficiency.

Energy regulations typically impose uniform, mandatory, rigid, and certain requirements on industries, leaving them with limited discretion and flexibility to comply (Nabitz et al., 2016; Tanaka, 2011). Various countries have implemented regulatory instruments to promote energy efficiency, often involving mandatory energy audits and management practices (Nabitz et al., 2016). For instance, the European Commission introduced Article 8 of the Energy Efficiency Directive, which compels large companies in the European Union (EU) to conduct energy audits (Nabitz & Hirzel, 2019). In certain EU countries such as Romania and Italy, additional energy thresholds have been established to regulate enterprises exceeding a specific level of annual energy consumption, ensuring that they undergo these audits (Nabitz & Hirzel, 2019; Nabitz et al., 2016). Under the Energy Conservation Act, Japan requires companies consuming over 1,500 kiloliters of crude oil equivalent to systematically manage their energy usage (Kimura & Noda, 2014). Turkey's Energy Efficiency Law requires companies consuming more than 1,000 tonnes of oil equivalent (toe) to adopt energy management applications (Nabitz et al., 2016; Ates & Durakbasa, 2012). Similar regulations have also been implemented in other countries, including Australia, India, and China (Nabitz et al., 2016).

There has been limited research on the causal impact of energy regulations on firm outcomes. For instance, Yajima & Arimura (2022) investigate the effects of Japan's Emission Reduction Program on CO<sub>2</sub> emissions in the manufacturing sector and find that the energy regulation effectively reduces CO<sub>2</sub> emissions. Chen et al. (2020) examine the causal impact of China's energy regulation during the 11th Five-Year Plan period (2006-2010) on firms' energy intensity and structure, revealing that stricter energy regulation leads to lower energy intensity and a shift toward a cleaner energy structure. However, Yajima & Arimura (2022) do not assess the impact of the energy regulation on enterprise energy efficiency, while Chen et al. (2020) focus solely on a relatively short-term energy regulation.

This paper provides one of the first analyses of the causal impact of long-standing energy regulations on industrial energy efficiency. We employ a regression discontinuity design (RDD) to investigate the causal effect of China's Energy Conservation Law (ECL) on enterprise

energy efficiency, drawing on data from the China Employer-Employee Survey (CEES). China serves as a distinctive research context that enables an examination of the causal impact of an energy regulation on enterprises using the RDD method. The ECL explicitly targets specific firms based on a clearly defined threshold of annual energy consumption within this unique regulatory framework, making the RDD methodology applicable and effective.

We find a positive impact of implementing the ECL on enterprise energy efficiency. Specifically, we observe a notable 15-percentage-point increase in the total value added per unit of energy consumption due to the ECL regulation. Furthermore, our research identifies the adoption of energy management system (EnMS) and technological innovation as the key mechanisms through which the energy regulation positively influences enterprise energy efficiency. These findings remain robust even after subjecting them to a series of rigorous sensitivity analyses.

Our study makes four important contributions to the literature. First, it adds to the literature concerning the empirical connection between government energy regulations and enterprise energy efficiency. While some studies analyze and assess the characteristics, classifications, advantages, and disadvantages of energy regulations in enhancing enterprise energy efficiency (e.g., Nabitz & Hirzel, 2019; Nabitz et al., 2016; Kimura & Noda, 2014; Duzgun & Komurgoz, 2014), empirical evaluations exploring the impact of these regulations on enterprise energy efficiency have been limited, likely due to a lack of enterprise energy consumption data. We overcome this limitation by utilizing a comprehensive firm-level survey dataset that includes data on enterprise energy consumption, allowing us to quantify the causal effects of a government regulation on industrial energy efficiency. Our findings indicate that regulated enterprises demonstrate a higher propensity to adopt advanced energy management practices and invest more in technological innovation, both of which significantly enhance their energy efficiency.

Second, we contribute to the literature on government policy instruments aimed at enhancing enterprise energy efficiency. While prior research explores the effects of environmental policies, taxes, subsidies, and minimum wage regulations on energy intensity and efficiency (e.g., Peng et al., 2022; Zhou et al., 2022; Zhang, 2023; Zhao & Mao, 2022; Capozza et al., 2021; García-Quevedo & Jové-Llopis, 2021; Zhang et al., 2020; Curtis & Lee, 2019), very few studies have focused specifically on understanding the effects of energy regulations on firm outcomes, as discussed above.

Third, in terms of methodological rigor and the robustness of the results, we place particular emphasis on establishing a causal relationship between energy regulations and enterprise energy efficiency. The implementation of a regulation can potentially be endogenous to enterprise conditions, the measurement of government policies is often a subject of debate, and the impact of a regulation may be confounded by various other factors. To address these

concerns, we employ the RDD approach. Doing so enables us to distinguish treatment and control groups of enterprises based on their annual energy consumption, just above and just below the 10,000 tons of coal equivalent (TCE) threshold stipulated by the government energy regulation. This approach effectively mitigates the endogeneity issue. Subsequently, we compare the energy efficiency of enterprises regulated by the ECL with those unaffected by the regulation.

Fourth, our paper contributes to the literature by examining the influence of China's ECL on enterprise energy efficiency over the long term. The ECL, enacted in 1997, serves as a critical legal foundation for institutionalizing improvements in industrial energy efficiency (Sinton et al., 1998). However, an empirical assessment of the impact of the ECL has been lacking in the literature. Prior empirical studies on China's energy policies and regulations concerning industrial energy efficiency have predominantly focused on short-term policy programs, such as the Top-1,000 Energy-Consuming Enterprises Program during the 11th Five-Year Plan period (2006-2010) (e.g., Ai et al., 2021; Chen et al., 2020; Ma & Liang, 2018; Price et al., 2008) and the Ten Thousand Enterprise Energy Conservation Program during the 12th Five-Year Plan period (2011-2015) (e.g., Zhang et al., 2022; Lo et al., 2015).

## **2. Energy regulations and enterprise energy efficiency**

The existing body of literature on energy regulations and their impact on enterprise energy efficiency presents varying conclusions, spanning from the successful enhancement of efficiency and energy management due to regulations (Zhang et al., 2018; Thollander et al., 2007; Hepbasli & Ozalp, 2003) to a limited influence on the tangible energy-saving activities of companies (Kimura & Noda, 2014; Liu et al., 2014; Suk et al., 2013). These divergent findings can be attributed to the challenges in accurately estimating the causal effect of energy regulations while isolating their impact from other confounding factors. In this field of study, causal inference techniques have been underutilized, and finding a suitable 'quasi-experimental' design for causal inference remains challenging.

Regarding the mechanisms through which energy regulations influence enterprise energy efficiency, the literature highlights two potential pathways. The first crucial mechanism involves energy management practices, encompassing energy audits, monitoring energy consumption, conducting analysis and simulation, and building energy management teams (Johansson & Thollander, 2018; Schulze et al., 2016; Lo et al., 2015). Nabitz et al. (2016) identified several countries that have implemented energy regulations targeting energy audits and management systems in enterprises to enhance energy efficiency, emphasizing the significance of energy management as a mechanism influenced by energy regulations.

The second potential mechanism is technological innovation, a traditional approach employed by policy instruments to promote energy efficiency. As illustrated by Birol & Keppler (2000), an improvement in energy efficiency is a manifestation of enterprise technological innovation.

Government interventions are essential to reduce market barriers and increase opportunities for the implementation of new technologies to enhance energy efficiency (Kiss & Neij, 2011). Therefore, most traditional energy efficiency policies have focused on investing in energy-efficient technologies and solutions (Bertoldi, 2022).

### **3. China's Energy Conservation Law**

With rapid industrialization and urbanization, China's escalating energy demand has exerted significant pressure on its energy supply. Insufficient electric power and frequent power cuts have hindered the country's industrial growth (De Gouvello, Taylor, & Song, 2021). Consequently, enhancing industrial energy efficiency has become imperative to achieve more with less. Simultaneously, as the market began to play a central role in resource allocation, numerous new enterprises emerged and operated under market principles. This proliferation necessitated the establishment of a legal framework to regulate the burgeoning number of enterprises and promote improvements in energy efficiency.

In response to these challenges, China introduced the ECL in 1997, and it entered into force the following year. The ECL was designed with the following primary objectives: to promote energy conservation, improve energy efficiency, and protect the environment. Encompassing a spectrum of regulatory, voluntary, economic, and supportive energy conservation policies and measures across various industrial sectors, the ECL stands as a foundational legal framework institutionalizing policies, programs, measures, and incentives aimed at enhancing industrial energy efficiency in China (Yuan et al., 2011; Sinton et al., 1998).

The ECL defines 'key energy-using enterprises' as those consuming over 10,000 TCE per year or those designated by provincial governments consuming between 5,000 and 10,000 TCE per year (NPC, 2018; NPC, 1997). Throughout the 12th Five-Year Plan period (2011-2015), an estimated 17,000 key energy-using enterprises were identified, collectively constituting 60% of China's total energy consumption (TEC).

According to the provisions of the ECL and its related measures (NPC, 2018; NPC, 1997; National Energy Administration, 2011), key energy-using enterprises are subject to several requirements. These include appointing energy managers with expertise in energy savings, practical experience, and technical certifications. Additionally, these enterprises must conduct energy audits and implement measures to enhance their energy efficiency based on the audit findings. They are also expected to adhere to national standards for energy measurement, monitoring, and management. Moreover, these enterprises are obligated to submit annual reports on their energy usage, encompassing details on energy consumption, energy efficiency, progress toward energy conservation goals, analysis of energy conservation benefits, and information on the energy-saving measures implemented.

The ECL incorporates mandatory features that entail rewards and fines formulated by all levels of government for key energy-using enterprises and related individuals. Failure to comply with the requirements results in administrative and economic penalties under energy-saving

supervision (National Development Reform Commission, 2018; National Energy Administration, 2011). Therefore, the ECL strongly regulates key energy-using enterprises to improve their energy efficiency. Since its inception, the ECL has been revised three times – in 2007, 2016, and 2018 – while the definition of key energy-using enterprises has remained unchanged. This long-lasting energy regulation under the ECL provides a unique opportunity to examine its impact on enterprise energy efficiency.

#### **4. Data**

Our empirical analysis is based on firm-level data from the 2018 CEES, a comprehensive and high-quality dataset based on a survey of both manufacturing enterprises and workers across China. In contrast to prior studies that predominantly examined publicly listed and large-scale enterprises when analyzing Chinese enterprises' environmental and energy management (Qian et al., 2022; Chen, Chen, Jin, & Lu, 2020; Wang, Wu, & Zhang, 2018; Liu, Shadbegian, & Zhang, 2017), our research focuses on nonlisted enterprises of various sizes, enhancing the representativeness of our study within China's manufacturing sector.

The 2018 CEES utilized the 2016 Annual Report Database collected by the State Administration for Market Regulation as the sampling frame. The survey employed a two-stage probability proportional-to-size sampling method for both employers and employees, with size being defined as the number of employees in the manufacturing sector.

In the first stage, the CEES randomly selected twenty county-level districts in each province, with probabilities proportionate to the level of manufacturing employment in each district. In the second stage, approximately 25 manufacturing enterprises were randomly selected in each district, again with probabilities proportionate to the level of manufacturing employment in each enterprise. As a result, the firm sample obtained through this process is reasonably representative of China's manufacturing firms.

This study utilizes the 2018 firm-level CEES data because 2018 was the year when enterprise energy consumption data were collected. The sample includes 1,835 manufacturing firms from 100 districts/counties across sixty prefecture-level cities in Guangdong, Hubei, Jiangsu, Sichuan, and Jilin Provinces. The CEES gathered information on the consumption of electricity, natural gas, gasoline, diesel, and coal, and this information was then used to calculate each enterprise's TEC.

We focus on comparing enterprises with TEC volumes around the 10,000 TCE cutoff. Consequently, we restricted our sample to enterprises having TEC volumes between 5,000 and 15,000 TCE. Applying these criteria results in a final sample consisting of 764 firms. These enterprises are distributed across 58 different counties in China and represent 29 diverse manufacturing industries. In terms of ownership, private enterprises, foreign-invested enterprises, and state-owned enterprises (SOEs) account for 78.7%, 9.8%, and 11.5% of the sample, respectively.

## 5. Methods

We employ an RDD to estimate the causal impact of the ECL on firm energy efficiency. An RDD leverages the fact that whether a subject receives treatment is based on whether certain eligibility criteria surpass a predefined cutoff within the distribution of possible values. In our context, the ECL governs energy-intensive enterprises based on their TEC. Specifically, enterprises with a TEC of 10,000 TCE or above (or other firms consuming between 5,000 and 10,000 TCE per year, as determined by the provincial government) are subject to regulatory measures, while those falling below the TCE threshold remain unaffected. In this study, the enterprise itself constitutes the subject, adherence to the ECL constitutes the regulatory treatment, TEC serves as the eligibility variable, and the critical cutoff stands at 10,000 TCE.

Our research question aligns with the essence of the RDD, as Chinese firms are mandatorily subjected to the ECL based on a known assignment rule (i.e.,  $TEC \geq 10,000$  TCE). Consequently, firms fall into two distinct groups based on a dichotomous treatment variable, indicating whether they are subject to the ECL. The RDD can manifest in two forms: a sharp RDD and a fuzzy RDD. In our analysis, the probability of being subject to the ECL is deterministic at the 10,000 TCE threshold, as firms must strictly comply with the law's regulatory provisions. Therefore, we employ a sharp RDD.

Figure 1 portrays the correlation between energy regulation and a firm's energy efficiency, denoted as the natural logarithm of the ratio of gross value added (GVA) to TEC, within the -5 to 5 range, equivalent to  $\pm 5,000$  TCE of energy consumption. The cutoff point at 10,000 TCE is indicated by zero. The figure conspicuously illustrates that energy efficiency exhibits a notable increase among regulated firms compared to their unregulated counterparts around the cutoff. Consequently, based on visual inspection, employing RDD analysis appears justified.

**[Figure 1 here]**

For the RDD approach to be valid, the critical assumption that firms do not strategically manipulate their energy consumption in the vicinity of the cutoff must be satisfied. This assumption could be rendered problematic if firms deliberately adjust their energy consumption to fall precisely below the 10,000 TCE threshold, solely to evade compliance with the ECL. However, in practice, we contend that such strategic behavior, wherein firms meticulously control their energy consumption for regulatory avoidance, is unlikely. While determining their energy consumption real-world firms are confronted with a plethora of considerations, including the imperative to maintain optimal output levels, fully utilize production capacity, and secure a larger market share for their products. No existing empirical evidence supports the assertion that the ECL is the sole determinant influencing a firm's energy consumption decisions.

To further assuage concerns regarding the potential manipulation of energy consumption by firms to evade the regulation, we adopt the method proposed by McCrary (2008) to conduct a density test to verify the continuity around the 10,000 TCE threshold. The density test seeks



to detect any anomalous clustering of TEC just below the threshold, indicating potential manipulation. However, as evidenced in Figure 2, our density test reveals no discernible jump in TEC at the cutoff point. Furthermore, the calculated discontinuity test statistic (Cattaneo. et al., 2020) is statistically nonsignificant (P value=0.4780, the hypothesis that the sample sizes on both sides near the breakpoint are approximately equal cannot be rejected.). Thus, we do not find any evidence to suggest that enterprises manipulate their TEC solely to evade policy regulations.

**[Figure 2 here]**

We employ both parametric and nonparametric approaches to estimate the impact of the ECL. The parametric RDD model is as follows:<sup>1</sup>

$$EE_i = \alpha_0 + \alpha_1 ER_i + \alpha_2 f(TEC_i) + \theta X_i + \rho_r + \gamma_t + \varepsilon_i \quad (1)$$

The energy efficiency ( $EE_i$ ) of a firm is defined as the natural logarithm of the ratio of the firm's GVA to its TEC. This definition of energy efficiency is in accordance with the framework proposed by Patterson (1996), which conceptualizes energy efficiency as the ratio of output to energy input within a process. To compute the GVA for each firm, the income approach is employed. The income approach considers both the gross operating surplus of the enterprise and the consumption of fixed capital, following the methodology outlined by Albu et al. (2020). Table 1 presents the summary statistics.

The variable  $ER_i$  is a binary variable that indicates whether a firm is subject to the ECL regulation. It takes the value of one if a firm's total energy consumption ( $TEC_i$ ) is 10,000 TCE or above and zero otherwise. This binary variable categorizes firms into those regulated by the ECL (with  $ER_i = 1$ ) and those not subject to the regulation (with  $ER_i = 0$ ).

$f(TEC_i)$  is a polynomial function of the forcing variable  $TEC_i$ , which measures a firm's TEC encompassing various sources, such as electricity, natural gas, gasoline/diesel, and coal. To facilitate a unified comparison, all energy consumption quantities are converted into standard coal equivalent units based on the standards stipulated in the Management Measures of Energy Conservation for Key Energy-Using Enterprises. Subsequently, total energy consumption  $TEC_i$  is calculated by summing all energy consumption quantities in their standard coal equivalents. The total energy consumption variable  $TEC_i$  is then normalized so that the value is zero when a firm's TEC is exactly 10,000 TCE.

Among the remaining variables,  $X_i$  constitutes a vector of control variables that capture various firm-level characteristics. These include firm size, firm age, the ownership structure, financial performance indicators, capital input, the average years of employees' schooling, the proportion of high-skilled employees, and the presence of government research and development (R&D) subsidies. By incorporating these control variables, the analysis aims to

---

<sup>1</sup> In later analysis, we use both linear and quadratic functions.

account for potential confounding factors and other firm-specific characteristics that may influence the energy efficiency outcomes.  $\rho_r$  is industry fixed effects based on the two-digit standard industrial classification code.  $\gamma_c$  is city fixed effects.  $\varepsilon_i$  is the error term.

Another crucial assumption of the RDD is that there should be no discontinuities in the independent variables that are correlated with the outcome variables, provided that the running variable (in this case, energy consumption  $TEC_i$ ) has not been manipulated. As depicted in Figure 3, the analysis reveals that the independent variables employed in this study satisfy the continuity requirement. Specifically, either no discontinuities or only nonsignificant small jumps are observed at the regulatory cutoff point (10,000 TCE). These results support the validity of the RDD approach and reinforce the confidence in interpreting the estimated treatment effect of the ECL regulation on energy efficiency.

[Table 1 here]

[Figure 3 here]

In our approach to selecting the optimal bandwidth for parametric estimates in the RDD, we employ two established methods: the mean squared error (MSE) and coverage error rate (CER) techniques, as proposed by Calonico et al. (2017, 2019). The MSE-optimal method is designed to ensure the most accurate point estimation of treatment effects, while the CER-optimal method focuses on achieving optimal confidence intervals, as outlined by Cattaneo et al. (2019).

For nonparametric estimates, which do not rely on specific functional forms, we utilize three distinct kernel estimators: triangular, Epanechnikov, and uniform. These kernel estimators effectively smooth the data around the cutoff point, providing a flexible approach for estimating the treatment effect. This flexibility is particularly advantageous when the relationship between the forcing variable and the outcome variable exhibits nonlinearity.

## 6. Main results

Table 2 displays the regression results of the parametric estimations. Model 1 presents the findings from a linear interaction model, indicating that the energy regulation leads to a 15-percentage-point increase in energy efficiency for key energy-using enterprises. Models 2 and 3 employ a linear interaction model and a quadratic interaction model, respectively, and both demonstrate that the energy regulation leads to a substantial 19-23-percentage-point increase in energy efficiency among these enterprises.

[Table 2 here]

Table 3 presents the results based on nonparametric methods. It displays the outcomes of different kernel estimates, specifically triangular, Epanechnikov, and uniform, all computed under optimal bandwidth selection. The findings in Table 3 align consistently with the results obtained from the parametric estimations presented in Table 2. The nonparametric analyses also reveal a significant and consistent positive effect of the energy regulation on enterprise energy efficiency, corroborating the results obtained from the parametric estimation. This convergence in results across different estimation techniques lends further credibility to the

robustness of the identified impact of the energy regulation on enhancing energy efficiency among the enterprises under study.

[Table 3 here]

## 7. Robustness checks

To ensure the robustness of our findings, we conducted a series of robustness checks. First, we examined the sensitivity of our results to variations in the bandwidth size for both the parametric and nonparametric models. For the parametric models, we replicated the analysis using different bandwidths that were either larger or smaller than the baseline window of  $[-5, 5]$ . Specifically, we explored bandwidths within the range of the optimal bandwidth  $\pm 0.1$ ,  $\pm 0.2$ , and  $\pm 0.3$ . Additionally, we tested the robustness of the results under both linear and quadratic interaction models. Table 4 presents the outcomes of these robustness checks. The results demonstrate that the effect of the energy regulation on enterprise energy efficiency remains robust across different bandwidth selections, except the  $-0.2$  bandwidth. In this particular case, the estimated coefficient under the quadratic interaction model is not statistically significant, which could be attributed to the smaller sample size resulting from the bandwidth selection. Nevertheless, the estimates consistently suggest that the energy efficiency of key energy-using enterprises is approximately 14-22-percentage-points higher than that of their unregulated counterparts.

[Table 4 here]

Second, we perform a bandwidth sensitivity test for the nonparametric models. Specifically, we re-estimated the coefficients at multiple bandwidths ranging from 20% to 200% of the optimal bandwidth, with increments of 10%. The results, depicted in Figure 4, reveal that the estimated coefficients consistently fall within the range of 10-30 percentage points. Remarkably, all estimated coefficients are statistically significant at the 5% level, indicating that our estimations remain robust and are not sensitive to changes in bandwidth.

[Figure 4 here]

Third, we investigate the sensitivity of our findings to different placebo cutoff points. While our main analysis utilizes the 10,000 TCE threshold in accordance with the energy regulation, we acknowledge that other unobservable factors might lead to placebo impacts on enterprise energy efficiency. For instance, provincial governments have the authority to independently designate enterprises with TEC between 5,000 and 10,000 TCE as key energy-using enterprises, potentially introducing placebo effects. To address this concern, we examine multiple placebo cutoffs at 20% ( $\pm 0.2$ ), 40% ( $\pm 0.4$ ), 60% ( $\pm 0.6$ ), 80% ( $\pm 0.8$ ), and 100% ( $\pm 1.0$ ) on both sides of the original cutoff point, which we normalize to zero in our main analysis. Figure 5 graphically depicts the results of this placebo analysis and suggests that at these placebo cutoff points, the energy regulation has no discernible treatment effect on enterprise energy efficiency. This finding reaffirms the robustness of our baseline result. The absence of any significant treatment effects at these placebo cutoffs provides evidence that our initial findings are not

driven by spurious associations or unobservable factors, further strengthening the validity and credibility of our conclusions.

**[Figure 5 here]**

Fourth, we use a donut RDD to rule out potential heaping-induced bias. Observations close to the regulation threshold may exhibit similar characteristics, making it challenging to discern a clear difference between regulated and unregulated enterprises (Valentim et al., 2021). This could result from unregulated enterprises with a TEC close to the threshold actively following regulated key energy-using enterprises to improve their energy efficiency. Additionally, government attention, such as energy use inspections, may be directed toward unregulated enterprises close to the threshold to assess potential regulation in the future. To mitigate these concerns, we implemented the donut RDD approach, which involves selectively excluding a portion of observations near the cutoff while preserving a sufficient number of observations on either side of the threshold (Barreca et al., 2011; Bajari et al., 2011; Barreca et al., 2016). Specifically, within the initial bandwidth of  $[-5, 5]$ , we removed 1% to 10% of the sample around the cutoff, creating a ‘donut’ shape. Subsequently, we re-estimated the treatment effect discontinuity based on the remaining sample. Figure 6 displays the results of the donut RDD analysis. Even after removing less than 4% of the sample, the estimated treatment effect remains statistically significant. These findings align consistently with our baseline results, providing robust evidence for the validity and reliability of our RDD analysis.

**[Figure 6 here]**

## **8. Mechanisms**

We investigate two potential mechanisms through which energy regulation influences energy efficiency. The first mechanism is energy management practices. According to the ECL and the Management Measures of Energy Conservation, key energy-using enterprises are required to establish and enhance their EnMS, form teams dedicated to energy conservation efforts, and adhere to national EnMS standards such as GB/T 23331 or ISO 50001, along with other relevant criteria (National Development Reform Commission, 2018). Strengthening energy management practices in regulated enterprises is likely a significant mechanism underlying the treatment effects of the energy regulation in promoting enterprise energy efficiency. Thus, we begin by examining the effects of the energy regulation on various energy management practices.

To assess these energy management practices, we dichotomously measure whether enterprises have implemented an EnMS, set energy management goals, conducted energy-related data analysis, and established a specialized energy management team. Based on the CEES data, we code enterprises with GB/T 23331 or ISO 50001 certifications or those with self-built energy standards as having an EnMS (coded as 1), while enterprises without such systems are coded

as 0. Likewise, we code enterprises with energy management goals as 1 and those without goals as 0. Furthermore, we code enterprises conducting energy-related data analysis manually, automatically based on information technology (IT), or through a hybrid approach as 1 and those lacking data analysis as 0. Finally, enterprises with specialized energy management departments are coded as 1, whereas those without such departments are coded as 0.

The results from both the linear and quadratic interaction models presented in Table 5 suggest that key energy-using enterprises exhibit a higher level of energy management compared to unregulated enterprises. These findings support the notion that the energy regulation stimulates the adoption of more robust energy management practices, contributing to the observed improvements in enterprise energy efficiency.

**[Table 5 here]**

The second mechanism we explore is technological innovation. As stipulated in the ECL, key energy-using enterprises are encouraged to focus on energy-related technological innovation. They are expected to adopt advanced energy-saving technologies and equipment, implement energy-saving practices, allocate funds for R&D and employee training, and engage in research collaboration with universities (National Development Reform Commission, 2018). Thus, enhancing technological innovation within regulated enterprises can serve as the second mechanism driving the effects of energy regulation. To investigate this mechanism, we estimated the treatment effect of the energy regulation on a range of enterprises' technological innovation activities.

The activities were measured using enterprise R&D expenditures, process innovation items (such as production methods, inventory management, packaging, storage and transfer, transportation, and maintenance), and whether the enterprise conducts product innovation. The estimation results are presented in Table 6. The findings indicate that the treatment effects on enterprise R&D expenditure are statistically significant for the linear interaction model but nonsignificant for the quadratic interaction model. However, the effects on process innovation are significant for both models, while the effects on product innovation are found to be nonsignificant. These results suggest that the energy regulation motivates key energy-using enterprises to invest more in R&D expenditures and engage in process innovation. This is in line with the well-known Porter hypothesis, which proposes that enterprises undertake technological innovation to reduce the costs associated with environmental constraint policies (Porter, Michael, 1996; Porter, Michael E. & van der Linde, 1995; Zhang et al., 2018).

**[Table 6 here]**

Collectively, the evidence supports the notion that the energy regulation has a positive impact on both energy management practices and technological innovation among regulated enterprises. These mechanisms work in tandem to foster higher levels of energy efficiency

within this group of enterprises, demonstrating the effectiveness of the energy regulation in promoting sustainable energy practices and contributing to achieving broader environmental conservation goals.

## **9. Heterogeneity analysis**

In this section, we first delve into the heterogeneity of the effects of the energy regulation on enterprise energy efficiency across different industries. Specifically, we examine enterprises in high-energy-consumption industries (HECIs) and compare them with those in other industries. According to the China Economic and Social Development Statistics Report 2010, the six major HECIs encompass chemicals, mineral products, petroleum, and electricity.

Table 7 presents the results for enterprises in the HECI group. The findings indicate that the treatment effect of the energy regulation on energy efficiency is significantly positive, demonstrating that the energy regulation effectively improves the energy efficiency of enterprises in these industries. For enterprises in other industries, the effects on energy efficiency are found to be nonsignificant under the quadratic interaction model. The explanation for this outcome is that the potential space for the energy efficiency improvement of HECI enterprises is greater. Moreover, the implementation of energy regulations on HECI enterprises may be more stringent because the government may focus on HECI enterprises. This highlights distinct patterns between enterprises in HECIs and those in other industries, indicating that the impact of the energy regulation varies across different industrial sectors.

**[Table 7 here]**

Scholars have already noticed that heterogeneity exists among enterprises with different ownership structures (e.g., Tang et al., 2020; Fang et al., 2019). We explore the heterogeneous impact of the energy regulation on enterprises with different ownership types. We divided the samples into SOEs, private enterprises, and foreign-invested enterprises (including enterprises from Hong Kong, Macao, and Taiwan). The estimated results are shown in Table 8.

For SOEs and private enterprises, the treatment effect on energy efficiency is positive and significant at the 5% level. However, for foreign-invested enterprises, the treatment effect is nonsignificant. The potential explanation is that foreign-invested enterprises may already have good energy management and a high level of technological innovation; thus, the effect of the regulation on them is not significant.

**[Table 8 here]**

Finally, we investigate the heterogeneous impact of the energy regulation on enterprises of different ages. We recognize that enterprises of varying ages may respond differently to the energy regulation due to differences in their capabilities and resources. As a result, we divided

our sample into two groups: new enterprises (aged less than three years) and older enterprises (aged three years and more). Table 9 presents the results of this analysis. Notably, for both older and new enterprises, their energy efficiency exhibits a significantly positive impact from the energy regulation. This result suggests that both older and new enterprises benefit from the energy regulation. However, further analysis finds that the coefficient of enterprise resource planning (ERP) of older firms is significantly larger than that of new firm (0.361 vs. 0.181). Older firms gain more energy efficiency improvement from the energy regulation than new firms. This happens because older enterprises, having accumulated considerable capabilities and resources, can leverage these advantages to improve their energy efficiency under the influence of the regulation. For new enterprises, due to their weaker firm capabilities or insufficient resources, the cost of learning to adapt to government regulations will be high, and the benefits may be low.

[Table 9 here]

## 10. Discussion and conclusions

Our study employed the RDD to investigate the effects of an energy regulation on the energy efficiency of key energy-using enterprises, utilizing firm-level data from the 2018 CEES. Our study has several major findings. First, the energy regulation has a significantly positive effect on enterprise energy efficiency. This result demonstrates that the energy regulation has effectively promoted energy conservation and improved energy efficiency among enterprises. The robustness checks confirm the stability of the baseline results under varying bandwidths and regulatory thresholds.

Second, the energy regulation facilitates improvements in energy efficiency through the adoption of high-level EnMS measures and technological innovation. Enterprises have established EnMSs, set energy management goals, analyzed energy-related data, and formed energy management teams, all contributing to enhanced energy efficiency. Moreover, enterprises have increased their R&D expenditure and engaged in process innovation, optimizing production methods and maintenance practices to decrease their energy consumption and enhance their competitiveness.

Third, the effects of the energy regulation on enterprises exhibit heterogeneity. Notably, the impact is significant for enterprises in HECIs but nonsignificant for enterprises in other industries. Furthermore, the energy regulation significantly influences both SOEs and private enterprises in terms of energy efficiency, with the effect on SOEs being more pronounced. In contrast, foreign-invested firms do not gain much energy efficiency improvement from this energy regulation. Additionally, the energy regulation significantly influences both new

enterprises (established within the last three years) and older enterprises in terms of energy efficiency. Compared with new firms, older firms benefit more from the regulation.

Our study holds important policy implications for energy-saving policies and sustainable enterprise development. First, strengthening the foundation of the ECL and ensuring efficient legal enforcement for energy conservation are crucial. A strong legal foundation is vital for robust enforcement, as evidenced by the success of the energy regulation in the ECL. Governments and legal institutions should establish and support more judicial institutions to achieve energy conservation and enhance energy efficiency.

Second, providing guidance and financial support for enterprise energy management and technological innovation is essential. Enterprises have demonstrated improved energy efficiency through energy management and technological innovation. Governments should offer guidance to enterprises for establishing effective energy management measures, promoting technological innovation, and providing financial assistance.

Finally, supporting enterprises based on their characteristics and striving to achieve a win-win situation for environmental and energy efficiency benefits are important. The study reveals that firms characterized by different industries, ownership structures and ages are differently affected by an energy regulation. Government resource allocation should take into account the diversity of enterprises to obtain better outcomes.

In conclusion, our study sheds light on the positive impact of energy regulations on enterprise energy efficiency, with considerations of industry heterogeneity and enterprise characteristics. This research provides valuable guidance for policymakers in designing effective energy conservation policies and fostering sustainable development among enterprises.



## References

- Ai, H., Hu, Y., & Li, K. (2021). Impacts of environmental regulation on firm productivity: evidence from China's Top 1000 Energy-Consuming Enterprises Program. *Applied Economics*, 53(7), 830-844. 10.1080/00036846.2020.1815642
- Albu, N., Zubrzycki, K., Scholz, R., Ostwald, D. A., Somweber, K., & Haut, S. (2020). Direct Gross Value Added Calculation Method. Basel/Berlin/Darmstadt. 10.15405/epsbs.2017.05.02.133
- Ates, S. A., & Durakbasa, N. M. (2012). Evaluation of corporate energy management practices of energy intensive industries in Turkey. *Energy; the 24th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy, ECOS 2011*, 45(1), 81-91. 10.1016/j.energy.2012.03.032
- Bertoldi, P. (2022). Policies for energy conservation and sufficiency: Review of existing policies and recommendations for new and effective policies in OECD countries. *Energy and Buildings*, 264, 112075. 10.1016/j.enbuild.2022.112075
- Birol, F., & Keppler, J. H. (2000). Prices, technology development and the rebound effect. *Energy Policy*, 28(6), 457-469. 10.1016/S0301-4215(00)00020-3
- Blumstein, C., Krieg, B., Schipper, L., & York, C. (1980). Overcoming social and institutional barriers to energy conservation. *Energy*, 5(4), 355-371. 10.1016/0360-5442(80)90036-5
- Cagno, E., Ramirez-Portilla, A., & Trianni, A. (2015). Linking energy efficiency and innovation practices: Empirical evidence from the foundry sector. *Energy Policy*, 83, 240-256. 10.1016/j.enpol.2015.02.023
- Cagno, E., Worrell, E., Trianni, A., & Pugliese, G. (2013). A novel approach for barriers to industrial energy efficiency. *Renewable and Sustainable Energy Reviews*, 19, 290-308. 10.1016/j.rser.2012.11.007
- Calonico, S., Cattaneo, M. D., Farrell, M. H., & Titiunik, R. (2017). rdrobust: Software for regression-discontinuity designs. *The Stata Journal*, 17(2), 372-404.
- Calonico, S., Cattaneo, M. D., Farrell, M. H., & Titiunik, R. (2019). Regression Discontinuity Designs Using Covariates. *The Review of Economics and Statistics*, 101(3), 442-451. 10.1162/rest\_a\_00760
- Capozza, C., Divella, M., & Rubino, A. (2021). Exploring energy transition in European firms: The role of policy instruments, demand-pull factors and cost-saving needs in driving energy-efficient and renewable energy innovations. *Energy Sources, Part B: Economics, Planning, and Policy*, 16(11-12), 1094-1109.
- Cattaneo, M. D., Jansson, M., & Ma, X. (2020). Simple local polynomial density estimators. *Journal of the American Statistical Association*, 115(531), 1449-1455.
- Cattaneo, M. D., Idrobo, N. '., & Titiunik, R. ' i. (2019). A practical introduction to regression discontinuity designs: Foundations. Cambridge University Press.
- Chen, D., Chen, S., Jin, H., & Lu, Y. (2020). The impact of energy regulation on energy intensity and energy structure: Firm-level evidence from China. *China Economic Review*, 59, 101351.
- Curtis, E. M., & Lee, J. M. (2019). When do environmental regulations backfire? Onsite industrial electricity generation, energy efficiency and policy instruments. *Journal of Environmental Economics and Management*, 96, 174-194. 10.1016/j.jeem.2019.04.004
- De Gouvello, C., Taylor, R., & Song, Y. (2021). China: 40-Year Experience in Energy Efficiency Development-Policies, Achievements, and Lessons Learned.

- Duzgun, B., & Komurgoz, G. (2014). Turkey's energy efficiency assessment: White Certificates Systems and their applicability in Turkey. *Energy Policy*, 65, 465-474. 10.1016/j.enpol.2013.10.036
- Fang, J., Liu, C., & Gao, C. (2019). The impact of environmental regulation on firm exports: evidence from environmental information disclosure policy in China. *Environmental Science and Pollution Research*, 26(36), 37101-37113. 10.1007/s11356-019-06807-2
- García-Quevedo, J., & Jové-Llopis, E. (2021). Environmental policies and energy efficiency investments. An industry-level analysis. *Energy Policy*, 156, 112461. 10.1016/j.enpol.2021.112461
- Hepbasli, A., & Ozalp, N. (2003). Development of energy efficiency and management implementation in the Turkish industrial sector. *Energy Conversion and Management*, 44(2), 231-249. 10.1016/S0196-8904(02)00051-1
- IEA (2023), CO2 Emissions in 2022, IEA, Paris <https://www.iea.org/reports/co2-emissions-in-2022>, License: CC BY 4.0
- Johansson, M. T., & Thollander, P. (2018). A review of barriers to and driving forces for improved energy efficiency in Swedish industry— Recommendations for successful in-house energy management. *Renewable and Sustainable Energy Reviews*, 82, 618-628. 10.1016/j.rser.2017.09.052
- Kimura, O., & Noda, F. (2014). Does regulation of energy management systems work? A case study of the Energy Conservation Law in Japan. *Proceedings of the ECEEE Industrial Summer Study*, , 647-657.
- Kiss, B., & Neij, L. (2011). The importance of learning when supporting emergent technologies for energy efficiency—A case study on policy intervention for learning for the development of energy efficient windows in Sweden. *Energy Policy; Sustainability of Biofuels*, 39(10), 6514-6524. 10.1016/j.enpol.2011.07.053
- Kostka G, Moslener U, Andreas J. Barriers to increasing energy efficiency: evidence from small-and medium-sized enterprises in China 2013;57:59–68. <https://doi.org/10.1016/j.jclepro.2013.06.025>.
- Liu, X., Yamamoto, R., & Suk, S. (2014). A survey analysis of energy saving activities of industrial companies in Hyogo, Japan. *Journal of Cleaner Production*, 66, 288-300. 10.1016/j.jclepro.2013.10.011
- Liu, M., Shadbegian, R., & Zhang, B. (2017). Does environmental regulation affect labor demand in China? Evidence from the textile printing and dyeing industry. *Journal of Environmental Economics and Management*, 86, 277-294.
- Lo, K., Li, H., & Wang, M. (2015). Energy conservation in China's energy-intensive enterprises: An empirical study of the Ten-Thousand Enterprises Program. *Energy for Sustainable Development*, 27, 105-111.
- Ma, L., & Liang, J. (2018). The effects of firm ownership and affiliation on government's target setting on energy conservation in China. *Journal of Cleaner Production*, 199, 459-465. 10.1016/j.jclepro.2018.07.170
- McCrary, J. (2008). Manipulation of the running variable in the regression discontinuity design: A density test. *Journal of Econometrics; the Regression Discontinuity Design: Theory and Applications*, 142(2), 698-714. 10.1016/j.jeconom.2007.05.005
- Nabitz, L., & Hirzel, S. (2019). Transposing The Requirements of the Energy Efficiency Directive on Mandatory Energy Audits for Large Companies: A Policy-Cycle-based review of the National Implementation in the EU-28 Member States. *Energy Policy*, 125, 548-561. 10.1016/j.enpol.2017.12.016
- Nabitz, L., Hirzel, S., Rohde, C., Wohlfarth, K., Behling, I., & Turner, R. (2016). How can energy audits and energy management be promoted amongst SMEs? A review of policy instruments in the EU-28 and beyond. *Proceedings of the ECEEE Industrial Summer Study*, , 401-415.

- National Development Reform Commission. (2018). Management Measures of Energy Conservation for Key Energy-using Enterprises. <https://zfxgk.ndrc.gov.cn/web/iteminfo.jsp?id=18518>
- National Energy Administration. (2011). Management Measures for Energy Conservation of Key Energy-using Enterprises. [http://www.nea.gov.cn/2011-08/18/c\\_131057691.htm](http://www.nea.gov.cn/2011-08/18/c_131057691.htm).
- NPC. (1997, Nov 1.). Energy Conservation Law of the People's Republic of China (1997). [http://www.law-lib.com/law/law\\_view.asp?id=364](http://www.law-lib.com/law/law_view.asp?id=364)
- NPC. (2018, Nov 5.). Energy Conservation Law of the People's Republic of China. <http://www.npc.gov.cn/npc/c12435/201811/045c859c5a31443e855f6105fe22852b.shtml>
- Patterson, M. G. (1996). What is energy efficiency?: Concepts, indicators and methodological issues. *Energy Policy*, 24(5), 377-390. 10.1016/0301-4215(96)00017-1
- Peng, W., Lee, C., & Xiong, K. (2022). What shapes the impact of environmental regulation on energy intensity? New evidence from enterprise investment behavior in China. *Environmental Science and Pollution Research*, , 1-18.
- Price, L., Wang, X., & Yun, J. (2008). China's top-1000 energy-consuming enterprises program: reducing energy consumption of the 1000 largest industrial enterprises in China. Berkeley: Lawrence Berkeley National Lab.
- Qian, H., Ren, F., Gong, Y., Ma, R., Wei, W., & Wu, L. (2022). China industrial environmental database 1998–2015. *Scientific Data*, 9(1), 1-13.
- Schulze, M., Nehler, H., Ottosson, M., & Thollander, P. (2016). Energy management in industry – a systematic review of previous findings and an integrative conceptual framework. *Journal of Cleaner Production*, 112, 3692-3708. 10.1016/j.jclepro.2015.06.060
- Sinton, J. E., Levine, M. D., & Qingyi, W. (1998). Energy efficiency in China: accomplishments and challenges. *Energy Policy*, 26(11), 813-829. 10.1016/S0301-4215(98)00004-4
- Suk, S., Liu, X., & Sudo, K. (2013). A survey study of energy saving activities of industrial companies in the Republic of Korea. *Journal of Cleaner Production*, 41, 301-311. 10.1016/j.jclepro.2012.10.029
- Tachmitzaki, E. V., Didaskalou, E. A., & Georgakellos, D. A. (2020). Energy Management Practices' Determinants in Greek Enterprises. *Sustainability*, 12(1)10.3390/su12010133
- Tanaka, K. (2011). Review of policies and measures for energy efficiency in industry sector. *Energy Policy*, 39(10), 6532-6550. 10.1016/j.enpol.2011.07.058
- Tang, K., Qiu, Y., & Zhou, D. (2020). Does command-and-control regulation promote green innovation performance? Evidence from China's industrial enterprises. *Science of the Total Environment*, 712, 136362. 10.1016/j.scitotenv.2019.136362
- Thollander, P., & Ottosson, M. (2010). Energy management practices in Swedish energy-intensive industries. *Journal of Cleaner Production*, 18(12), 1125-1133. 10.1016/j.jclepro.2010.04.011
- Thollander, P., Danestig, M., & Rohdin, P. (2007). Energy policies for increased industrial energy efficiency: Evaluation of a local energy programme for manufacturing SMEs. *Energy Policy*, 35(11), 5774-5783. 10.1016/j.enpol.2007.06.013
- Wang, C., Wu, J., & Zhang, B. (2018). Environmental regulation, emissions and productivity: Evidence from Chinese COD-emitting manufacturers. *Journal of Environmental Economics and Management*, 92, 54-73.
- Yajima N., & Arimura T. H. (2022) Promoting energy efficiency in Japanese manufacturing industry through energy audits: Role of information provision, disclosure, target setting, inspection, reward, and organizational structure, *Energy Economics*, 114: 106253.

- Yemelyanov, O., Petrushka, I., Zahoretska, O., Petrushka, K., & Havryliak, A. (2023). Information support for managing energy-saving technological changes at enterprises. *Procedia Computer Science*, 217, 258-267. <https://doi.org/10.1016/j.procs.2022.12.221>
- Yuan, J., Kang, J., Yu, C., & Hu, Z. (2011). Energy conservation and emissions reduction in China—Progress and prospective. *Renewable and Sustainable Energy Reviews*, 15(9), 4334-4347. 10.1016/j.rser.2011.07.117
- Zhang, J. (2023). Assessing the impact of R&D Investments, government subsidies on energy efficiency: empirical analysis from the Chinese listed firms. *Environmental Science and Pollution Research*, 30(2), 3606-3620. 10.1007/s11356-022-22326-z
- Zhao, Y., & Mao, J. (2022). Energy effects of non-energy policies: Minimum wage standard and enterprise energy efficiency in China. *Resources Policy*, 79, 102953. 10.1016/j.resourpol.2022.102953
- Zhang, Y., Zhao, X., & Fu, B. (2022). Impact of energy saving on the financial performance of industrial enterprises in China: An empirical analysis based on propensity score matching. *Journal of Environmental Management*, 317, 115377. 10.1016/j.jenvman.2022.115377
- Zhang, Y., Li, X., Jiang, F., Song, Y., & Xu, M. (2020). Industrial policy, energy and environment efficiency: Evidence from Chinese firm-level data. *Journal of Environmental Management*, 260, 110123. 10.1016/j.jenvman.2020.110123
- Zhang, Y., Wei, Y., & Zhou, G. (2018). Promoting firms' energy-saving behavior: The role of institutional pressures, top management support and financial slack. *Energy Policy*, 115, 230-238. 10.1016/j.enpol.2018.01.003
- Zhou, Q., Cui, X., Ni, H., & Gong, L. (2022). The impact of environmental regulation policy on firms' energy-saving behavior: a quasi-natural experiment based on China's low-carbon pilot city policy. *Resources Policy*, 76, 102538.

## Appendix

Figure 1. Total energy consumption and energy efficiency

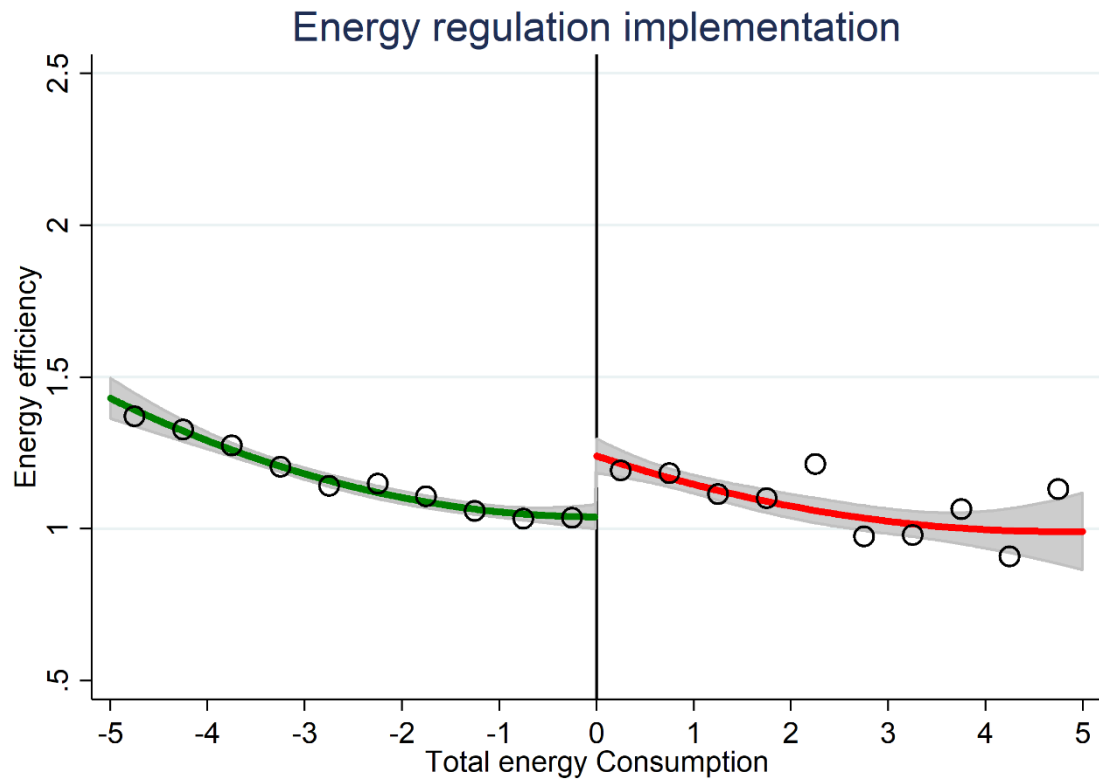


Figure 2. Manipulation test of total energy consumption

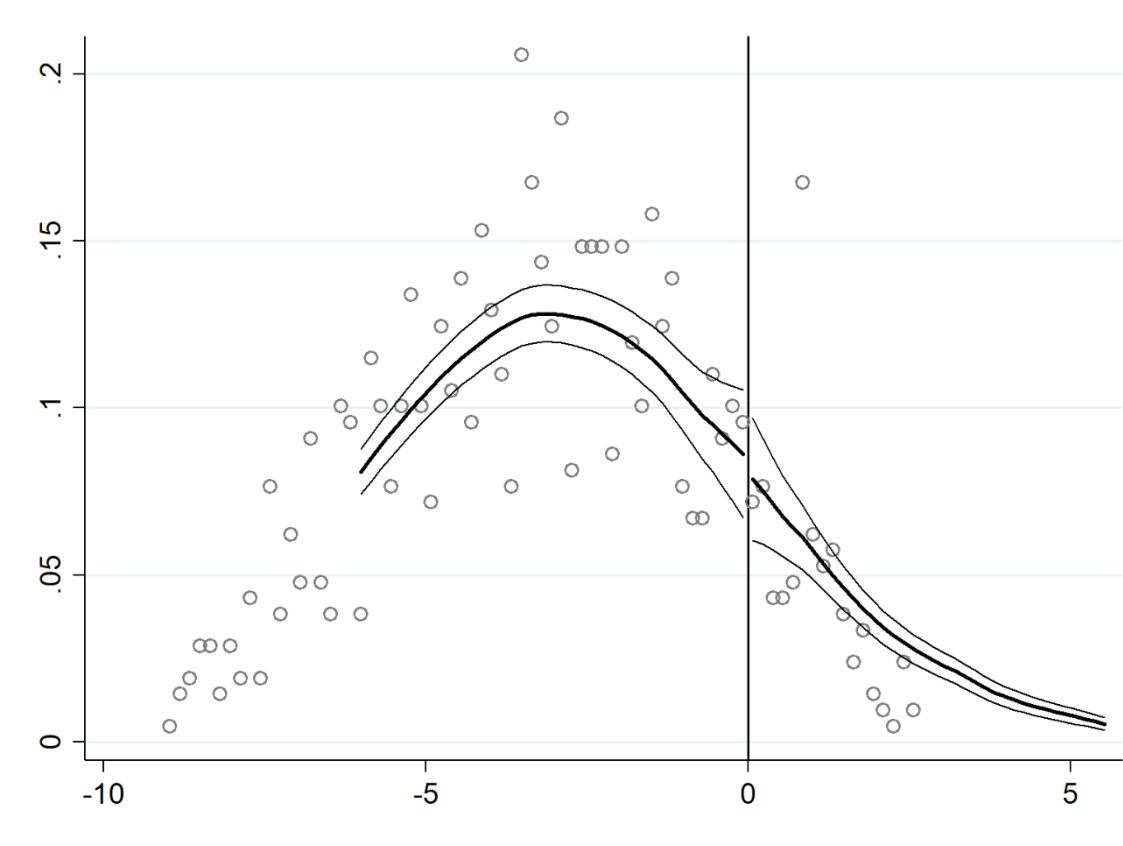


Figure 3. Covariate continuity test

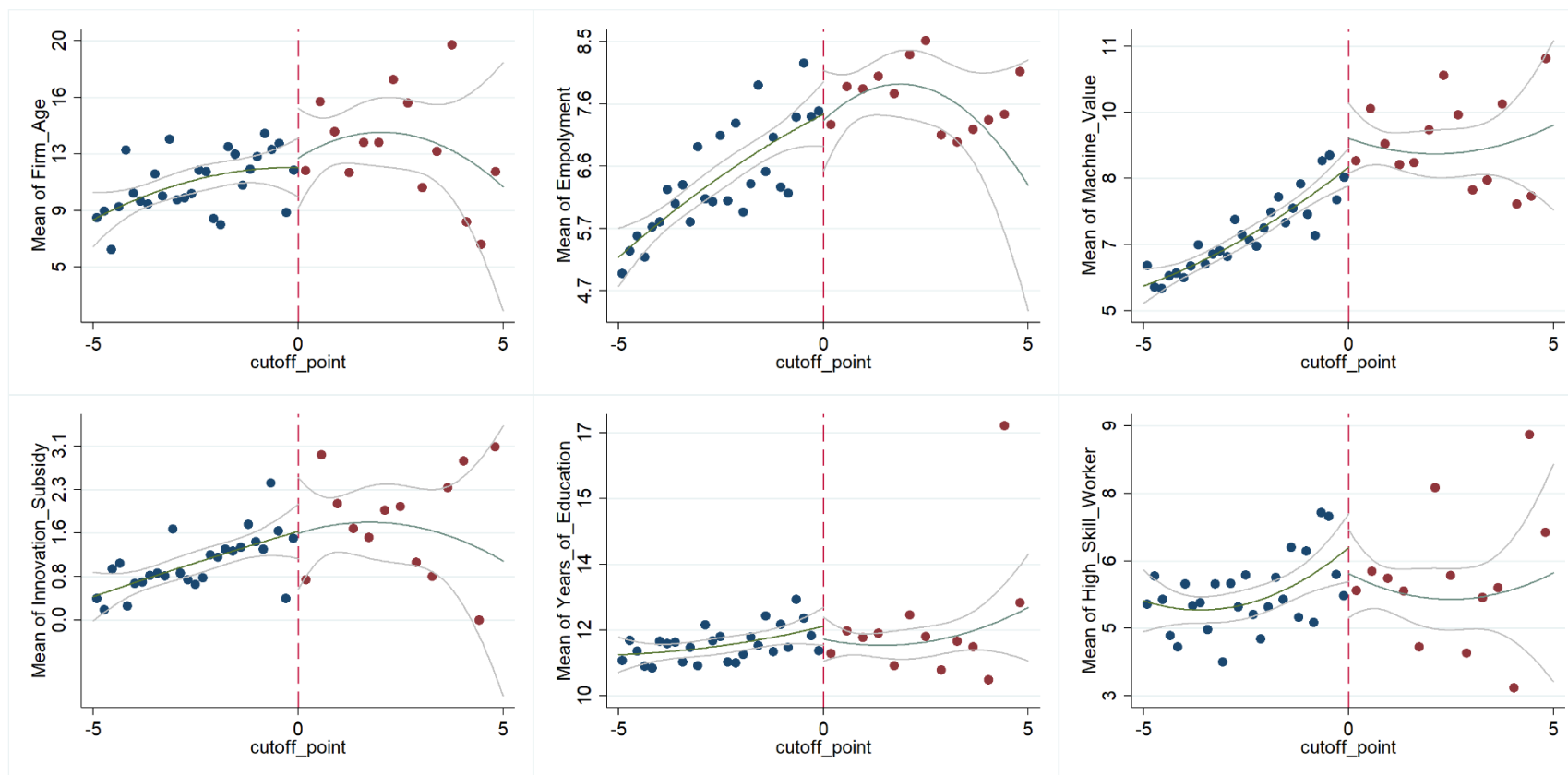


Figure 4. Bandwidth sensitivity test for nonparametric models

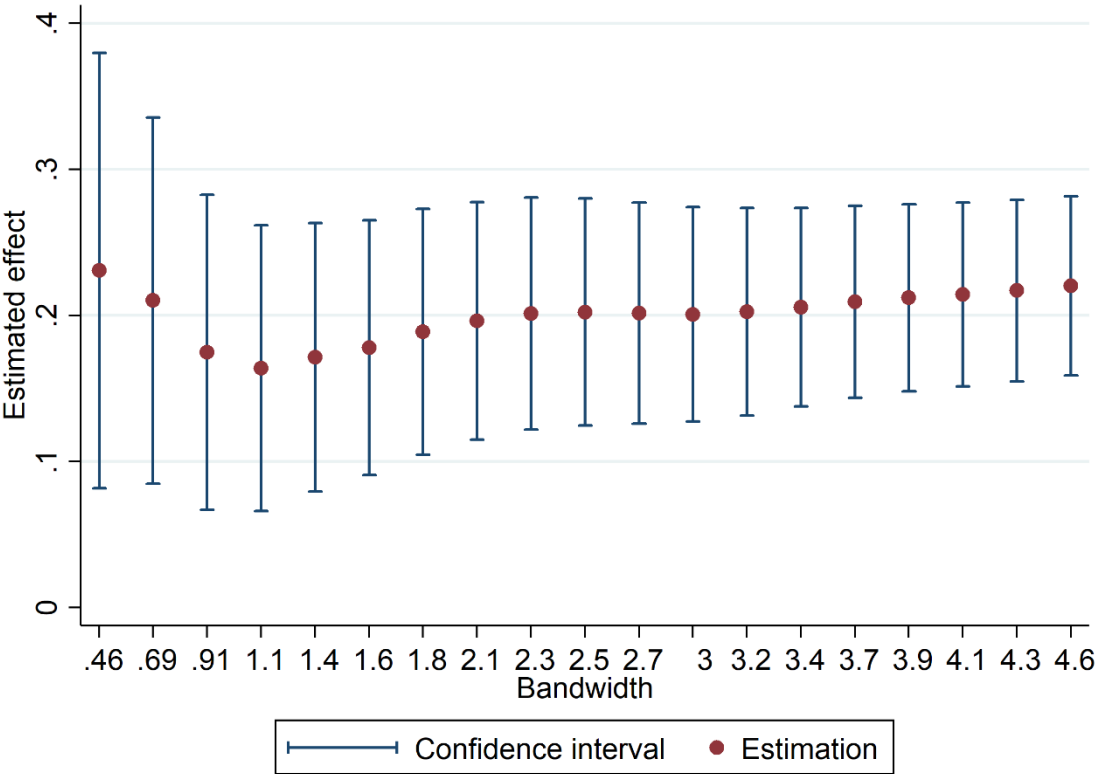




Figure 5. Results from different cutoff points for the regression discontinuity design

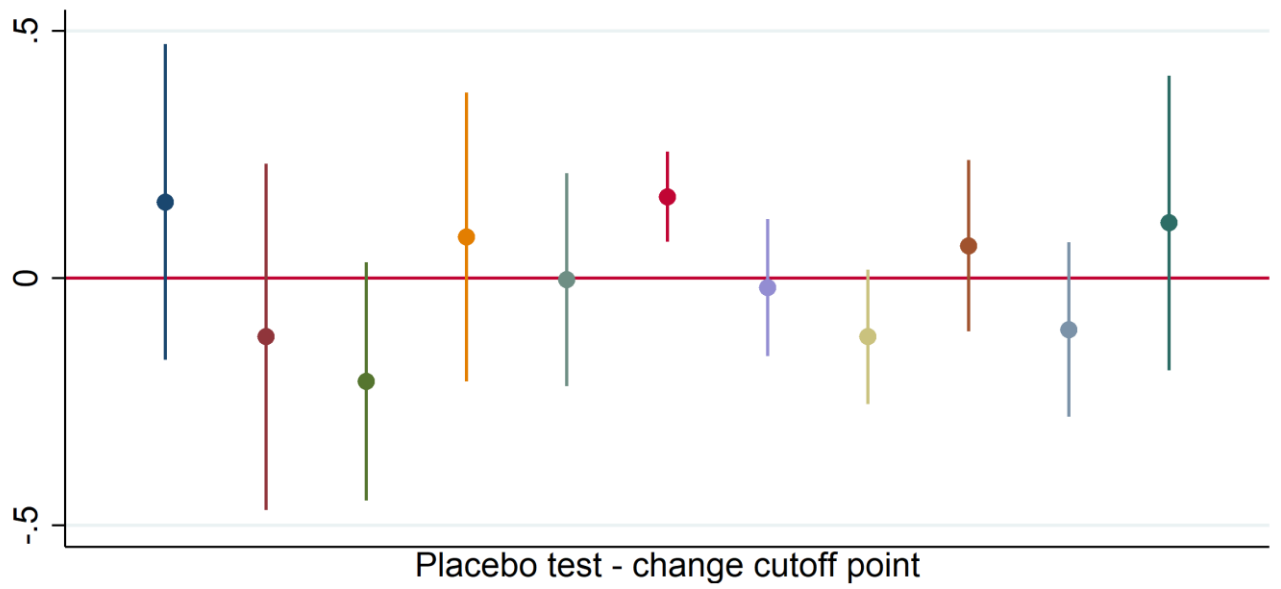
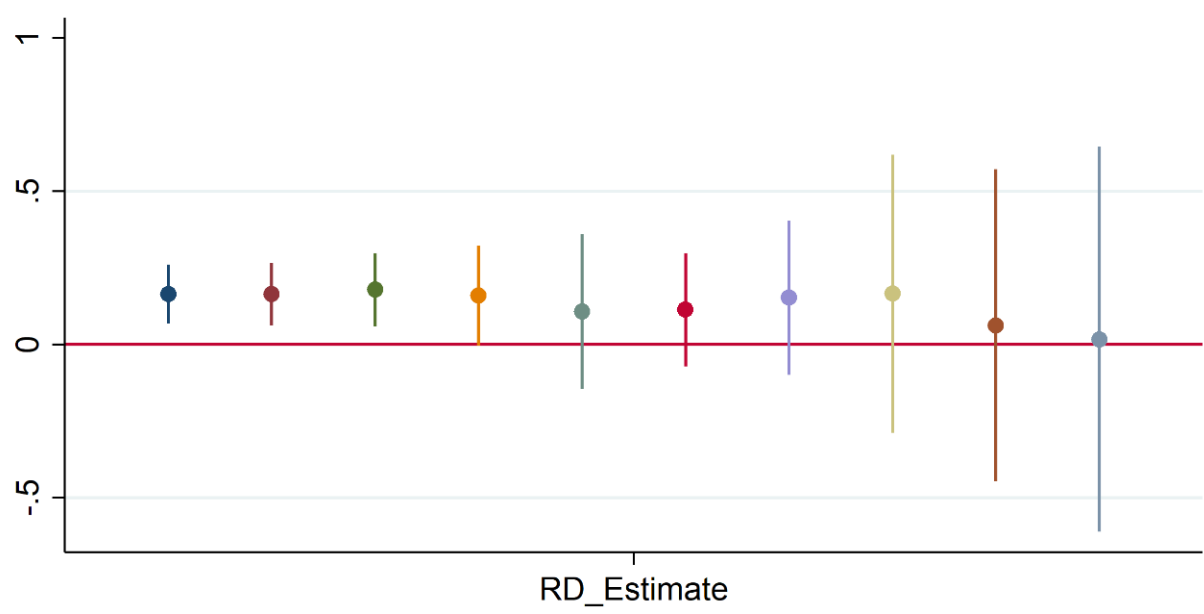


Figure 6. Results from the donut regression discontinuity design



**Table 1. Descriptive statistics**

Variable	Obs.	Mean	Std. Dev.	Min	Max
Energy efficiency (ln ln)	764	1.151	0.260	0.511	3.389
TEC	764	8.209	2.102	5.000	14.997
Number of employees (ln)	764	6.597	2.135	2.500	18.202
Added value (ln)	764	8.810	2.010	2.342	19.345
Firm age (year)	823	13.803	8.765	0	81
Machine value (ln)	764	6.996	2.159	1.313	17.371
R&D subsidy (ln)	764	1.117	2.260	0.000	13.978
Years of education of employees	764	11.360	2.119	6.354	36.730
Proportion of high-skilled workers (%)	764	5.204	3.074	0.000	24.500
Ownership	764	-	-	-	-
State-owned	88	-	-	-	-
Private	601	-	-	-	-
Foreign-invested	75	-	-	-	-

**Table 2. Parametric estimates of the effect of the energy regulation on energy efficiency**

	(1)	(2)	(3)
ER	0.150*** (0.020)	0.232*** (0.040)	0.190*** (0.061)
TEC	Yes	Yes	Yes
ER×TEC	No	Yes	Yes
TEC <sup>2</sup>	No	No	Yes
ER×TEC <sup>2</sup>	No	No	Yes
Control variables	Yes	Yes	Yes
Industry fixed effects	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes
Adjusted R <sup>2</sup>	0.963	0.971	0.971
N	764	764	764

Notes: \* p < 10%, \*\* p < 5%, \*\*\* p < 1%. Standard errors clustered at county and sector level in parentheses. See Table 1 for a full set of control variables.

**Table 3. Nonparametric estimate of the effect of the energy regulation on energy efficiency**

	(1)	(2)	(3)	(4)	(5)	(6)
ER	0.181*** (0.034)	0.182*** (0.033)	0.179*** (0.033)	0.209*** (0.044)	0.192*** (0.040)	0.190*** (0.039)
Covariates	Yes	Yes	Yes	Yes	Yes	Yes
Bandwidth calculation	MSE	MSE	MSE	CER	CER	CER
Best bandwidth	[-0.877,0.877]	[-1.136,1.136]	[-1.120,1.120]	[-0.629,0.629]	[-0.815,0.815]	[-0.804,0.804]
Kernel method	Uniform	Triangular	Epanechnikov	Uniform	Triangular	Epanechnikov
N	764	764	764	764	764	764

Notes: Standard errors in parentheses, \* p < 10%, \*\* p < 5%, \*\*\* p < 1%. Covariates include firm-level control variables, industry and city fixed effects.

**Table 4. Bandwidth test for the parameter estimate of the effect of the energy regulation on energy efficiency**

	Best bandwidth							
	-0.1		+0.1		-0.2		+0.2	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ER	0.186*	0.155**	0.217*	0.148**	0.170*	0.150	0.214*	0.137**
	(0.039)	(0.069)	(0.033)	(0.060)	(0.057)	(0.094)	(0.032)	(0.056)
TEC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ER×TEC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
TEC <sup>2</sup>	No	Yes	No	Yes	No	Yes	No	Yes
ER×TEC <sup>2</sup>	No	Yes	No	Yes	No	Yes	No	Yes
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	107	107	151	151	97	97	159	159
Adjusted R <sup>2</sup>	0.920	0.915	0.940	0.942	0.974	0.976	0.934	0.939

Note: Standard errors clustered at county and sector level in parentheses, \*  $p < 10\%$ , \*\*  $p < 5\%$ , \*\*\*  $p < 1\%$ . Firm-level control variables include firm size, age, ownership type, gross value added, machine value, average education years of employees, the proportion of high-skilled employees, and government R&D subsidy.

**Table 5. The effect of the energy regulation on energy management practices**

	Energy management system		Energy management goal setting		Energy-related data analysis		Energy management team establishment	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ER	0.678**	0.884*	0.619***	0.527**	0.289***	0.313*	0.613***	0.512***
	(0.278)	(0.496)	(0.151)	(0.218)	(0.098)	(0.163)	(0.108)	(0.153)
TEC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ER×TEC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
TEC <sup>2</sup>	No	Yes	No	Yes	No	Yes	No	Yes
ER×TEC <sup>2</sup>	No	Yes	No	Yes	No	Yes	No	Yes
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	122	122	122	122	156	156	253	253
Adjusted R <sup>2</sup>	-0.106	-0.149	0.584	0.569	0.504	0.491	0.516	0.512

Note: Standard errors clustered at county and sector level in parentheses, \*  $p < 10\%$ , \*\*  $p < 5\%$ , \*\*\*  $p < 1\%$ . Firm-level control variables include firm size, age, ownership type, gross value added, machine value, average education years of employees, the proportion of high-skilled employees, and government R&D subsidy.

**Table 6. The effect of the energy regulation on technological innovation**

	R&D expenditure		Process innovation		Product innovation	
	(1)	(2)	(3)	(4)	(5)	(6)
ER	2.517** (0.965)	2.082 (1.714)	1.605*** (0.394)	1.935*** (0.637)	0.233 (0.163)	0.182 (0.248)
TEC	Yes	Yes	Yes	Yes	Yes	Yes
ER×TEC	Yes	Yes	Yes	Yes	Yes	Yes
TEC <sup>2</sup>	No	Yes	No	Yes	No	Yes
ER×TEC <sup>2</sup>	No	Yes	No	Yes	No	Yes
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Industry fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
City fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N	107	107	135	135	165	165
Adjusted R <sup>2</sup>	0.518	0.551	0.566	0.555	0.218	0.202

Note: Standard errors clustered at county and sector level in parentheses, \*  $p < 10\%$ , \*\*  $p < 5\%$ , \*\*\*  $p < 1\%$ . Firm-level control variables include firm size, age, ownership type, gross value added, machine value, average education years of employees, the proportion of high-skilled employees, and government R&D subsidy.

**Table 7. The effect of the energy regulation on energy efficiency across industries**

Dependent variable: Energy efficiency	High-energy-consumption industries		Other industries	
	(1)	(2)	(3)	(4)
ER	0.275*** (0.010)	0.286*** (0.013)	-0.010 (0.016)	-0.016 (0.021)
TEC	Y	Y	Y	Y
ER×TEC	Y	Y	Y	Y
TEC <sup>2</sup>	Y	Y	Y	Y
ER×TEC <sup>2</sup>	Y	Y	Y	Y
Control variables	Y	Y	Y	Y
Industry fixed effects	N	Y	N	N
City fixed effects	N	Y	N	N
N	102	102	46	46
Adjusted R <sup>2</sup>	0.981	0.990	0.973	0.971

Note: Standard errors clustered at county and sector level in parentheses, \*  $p < 10\%$ , \*\*  $p < 5\%$ , \*\*\*  $p < 1\%$ . Firm-level control variables include firm size, age, ownership type, gross value added, machinery value, average education years of employees, the proportion of high-skilled employees, and government R&D subsidy.

**Table 8. The effect of the energy regulation on energy efficiency across ownership structures**

Dependent variable: Energy efficiency	SOEs		Private enterprises		Foreign-invested enterprises	
	(1)	(2)	(3)	(4)	(5)	(6)
ER	0.381*** (0.082)	0.678** (0.231)	0.215*** (0.036)	0.282*** (0.051)	0.007 (0.079)	-0.043 (0.059)
TEC	Y	Y	Y	Y	Y	Y
ER×TEC	Y	Y	Y	Y	Y	Y
TEC <sup>2</sup>	N	Y	N	Y	Y	N
ER×TEC <sup>2</sup>	N	Y	N	Y	Y	N
Firm-level control	Y	Y	Y	Y	Y	Y
Industry fixed effects	N	Y	N	Y	Y	N
City fixed effects	N	Y	N	Y	Y	N
N	22	22	116	116	32	32
Adjusted R <sup>2</sup>	0.834	0.851	0.750	0.753	0.875	0.882

Note: Standard errors clustered at county and sector level in parentheses, \*  $p < 10\%$ , \*\*  $p < 5\%$ , \*\*\*  $p < 1\%$ . Firm-level control variables include firm size, age, ownership type, gross value added, machinery value, average education years of employees, the proportion of high-skilled employees, and government R&D subsidy.

**Table 9. The effect of the energy regulation on energy efficiency across firm ages**

Dependent variable: Energy efficiency	Older firms		New firms	
	(1)	(2)	(3)	(4)
ER	0.177*** (0.044)	0.181** (0.077)	0.300*** (0.034)	0.380*** (0.068)
TEC	Y	Y	Y	Y
ER×TEC	Y	Y	Y	Y
TEC <sup>2</sup>	N	Y	Y	Y
ER×TEC <sup>2</sup>	Y	Y	Y	Y
Firm-level control	Y	Y	Y	Y
Industry fixed effects	N	N	N	Y
City fixed effects	N	N	N	Y
N			31	31
Adjusted R <sup>2</sup>	0.752	0.723	0.941	0.944

Note: Standard errors clustered at county and sector level in parentheses, \*  $p < 10\%$ , \*\*  $p < 5\%$ , \*\*\*  $p < 1\%$ . Firm-level control variables include firm size, age, ownership type, gross value added, machinery value, average education years of employees, the proportion of high-skilled employees, and government R&D subsidy.