TYPE Original Research
PUBLISHED 13 February 2023
DOI 10.3389/fenvs.2023.1120893

Check for updates

OPEN ACCESS

EDITED BY
Shigeyuki Hamori,
Kobe University, Japan

REVIEWED BY
Huwei Wen,
Nanchang University, China
Lin Zhang,
City University of Hong Kong, Hong Kong SAR, China
Xiaodong Yang,
Xinjiang University, China

*CORRESPONDENCE
Hong-Xing Wen,
hxwen2011@126.com

SPECIALTY SECTION
This article was submitted to Environmental Economics and Management, a section of the journal Frontiers in Environmental Science

RECEIVED 10 December 2022
ACCEPTED 31 January 2023
PUBLISHED 13 February 2023

CITATION
Liu X-Y, Wen H-X and Ding D-D (2023), The impact of new ambient air quality standards on green total factor energy efficiency: Evidence from an environmental information disclosure policy in China.
Front. Environ. Sci. 11:1120893.
doi: 10.3389/fenvs.2023.1120893

COPYRIGHT
© 2023 Liu, Wen and Ding. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

The impact of new ambient air quality standards on green total factor energy efficiency: Evidence from an environmental information disclosure policy in China

Xing-Yuan Liu[1], Hong-Xing Wen[2]* and Duo-Dong Ding[1]

[1]School of Economics and Management, Ningxia University, Yinchuan, China, [2]School of Economics, Institute of Guangdong High Quality Development, National Economics Research Center, Guangdong University of Finance & Economics (GDUFE), Guangzhou, China

The implementation of the new ambient air quality standards (NAAQS) in 2012 is a milestone in China's environmental information disclosure process. The fully automated collection and publication of pollution information provides a convenient way to measure the environmental protection process around the country. This paper investigates the association between NAAQS and green total factor energy efficiency (GTFEE) enhancement in Chinese resource-based cities, using the generalized multiperiod DID method and 2004–2019 panel data from 282 prefecture-level cities. We find that the implementation of this NAAQS significantly promotes GTFEE's improvement in China's resource-based cities. Furthermore, we discover that both the type of industrial base and the initial public monitoring motivation influence the improvement effect of the NAAQS on GTFEE. In further studies, NAAQS enhances GTFEE through industrial structure optimization, and the magnitude of the local NAAQS effect is influenced by the level of green innovation. Finally, we make recommendations including implementing targeted environmental regulations and enhancing environmental information regulation.

KEYWORDS

new ambient air quality standards, resource-based cities, green total factor energy efficiency (GTFEE), generalized multiperiod DID method, public monitoring

1 Introduction

As the world's fastest-growing economy, China has made amazing economic achievements in development since the reform and opening up. In the previous period, abundant natural resources fueled China's rapid economic development, and reliance on fossil energy and heavy industry was highly problematic in resource-endowed regions (i.e., the resource-based cities). The heavy dependence on fossil fuels, brought a large amount of environmental pollution, which has a series of negative impacts, such contributing to global warming, harming the health of the population, and jeopardizing national energy security (Bashir et al., 2020; Huang and Zou, 2020; Jiang et al., 2021). The sustainable development of Chinese society is being hampered by this predicament, and the resource-based cities are facing a particularly serious situation. China must adopt a more structural, quality-focused, and environmentally friendly development strategy that takes energy conservation into account while sustaining economic growth. Given the high cost of widespread usage of renewable energy sources, improving energy efficiency is a critical step that must be taken to assist energy conservation and emission reduction in order to address the existing challenges (Linares and Labandeira, 2010; Allcott and Greenstone, 2012; Yang et al., 2016; Boomhower and Davis, 2020; Zhang et al., 2020). According to the International Energy Agency's *Energy Efficiency 2020* report (IEA, 2020), improvements in energy efficiency may cut greenhouse gas emissions associated with energy usage by more than 40% worldwide.

Energy efficiency is generally classified as single factor energy efficiency and total factor energy efficiency. For the single factor energy efficiency, measurement bias results from having too few indicators, which implies that it ignores the complex production relations in reality. Regarding the traditional total factor energy efficiency, although it adds more production factor indicators at the input side, it ignores the pollution emissions from manufacturing operations, making energy efficiency overestimated. In contrast to the previous two types of energy efficiency, green total factor energy efficiency (GTFEE) considers both the complex production mix and the detrimental effects of pollution emissions during actual production (Li and Hu, 2012), allowing for a more accurate estimation of energy efficiency and assisting individuals in analyzing more precisely whether the usage of energy is efficient and reasonable. Therefore, the primary research object for this paper is GTFEE.

One of the key steps to increase energy efficiency is environmental regulation, and as a kind of informal environmental regulation, environmental information disclosure (EID) is playing an increasingly important role in environmental governance system. The Chinese Ministry of Environmental Protection issued the *Ambient Air Quality Standard GB3095-2012* (i.e., new ambient air quality standards, NAAQS) in 2012 and released batch-related implementation plans in 2012, 2013, and 2014. As an unconventional environmental regulation, environmental information disclosure (EID) differs from market-incentive-based environmental regulations and command-and-control environmental regulations in that it provides local environmental pollution information to all sectors through information transparency, thereby promoting economic agents' choices. The implementation of the NAAQS involves all-weather, automated, and real-time environmental information monitoring and distributes the data on authorized platforms by gradually establishing state-controlled air quality monitoring stations in cities. Prior to the implementation of automatic monitoring, the task of collecting pollution information in China's prefecture-level cities was executed by local governments, and it was difficult for the central government to verify the environmental information provided by localities, making it easier for local governments to manipulate real pollution data in pursuit of high economic growth rates. NAAQS have significantly increased the scope and accuracy of environmental information available to all sectors of society, and they have improved environmental supervision greatly, made it simpler for local governments and businesses to be penalized for inaction in environmental management. The process of environmental information disclosure will inevitably be sped up due to the growing concern for environmental information brought on by the increased awareness of environmental preservation. Consequently, some related activities, like increasing energy efficiency, may be impacted by the disclosure of environmental information. Local governments and enterprises will focus more on greening manufacturing operations as a result of increased environmental scrutiny, with increased energy efficiency being one of the key components.

Based on the context above, this study uses NAAQS as a quasi-natural experiment to examine the improvement effect on GTFEE at the city level, and the contributions of this paper are mainly as follows. Firstly, since there is a lack of research on the NAAQS as an EID policy in the literature examining the impact of environmental regulations on urban energy efficiency, and less attention paid to the resource-based city level, this paper provides a valuable addition to the field. Secondly, in addition to the overall effect, the mechanism of NAAQS and GTFEE was deeply explored from the perspective of industrial structure upgrading and green technology innovation, this further extends the depth of this study and optimizes the related mechanistic studies. Thirdly, by further differentiating the enhancement effects of NAAQS on GTFEE heterogeneously in terms of old industrial base and public monitoring enthusiasm, this paper fills the related gap in the existing literature on heterogeneity study.

The remainder of the paper is structured as follows: Part II is the literature review, Part III is the policy background and theoretical hypotheses, Part IV is the model construction and variable selection, Part V is the empirical analysis, Part VI is the moderating effect analysis, and Part VII is the main conclusions and policy recommendations.

2 Literature review

The literature related to this paper can mainly divided into the energy efficiency and environmental information disclosure. Energy efficiency is an expanded form of technical efficiency, which can be understood as the maximization of output for a given energy input or a reduction in energy consumption for a given output (Farrell, 1957; Lovell, 1993; Bosseboeuf et al., 1997). In the existing literature, energy efficiency is generally classified as single factor energy efficiency and total factor energy efficiency: single factor energy efficiency refers to the ratio between a certain amount of energy input and the GDP of the output (Patterson, 1996; Gillingham et al., 2009). But, single-factor energy efficiency cannot accurately measure the true efficiency of energy use in production and has limitations since economic production is often multi-input and complex. Total factor energy efficiency takes into account factors such as capital and labor in addition to energy inputs, and it is a more comprehensive measure (Hu and Wang, 2006). However, total factor energy efficiency considers only one output, GDP, and ignores undesirable outputs such as pollutant emissions, resulting in measurement bias and causing energy efficiency to be overestimated (Farrell, 1957; Yörük and Zaim, 2005; Lin and Tan, 2016). Some researchers include pollutant emissions as an undesirable output in the total factor energy efficiency framework and propose the concept of GTFEE, which solves the problem of overestimating energy efficiency when using total factor energy efficiency measurement and makes the measurement of energy efficiency more accurate (Li and Hu, 2012). Thus, this paper also uses GTFEE to evaluate the energy efficiency.

How to improve energy efficiency, especially GTFEE at province, cities and firm level, is currently a hot topic of great interest to academia, and there are extensive works in the literature on what factors affect and how to influence GTFEE (Yang et al., 2022). Some literatures calculated and evaluated how heterogeneity policies and factors affect GTFEE from the micro-firm level (Haider et al., 2019; Bu et al., 2022), macro-province (Wu et al., 2021) and regional level (Tang and He, 2021). In relation to GTFEE of cities, many scholars in China and elsewhere have explored the factors influencing energy efficiency from various aspects. Among them, technological innovation (Wang and Wang, 2020; Wu et al., 2022), industrial structure upgrading (Yu, 2020), energy structure improvement (Tao et al., 2018), openness to the outside world (Wu et al., 2020; Gao et al., 2022a), and digitalization progress (Wu et al., 2021; Gao et al., 2022b; Zhao et al., 2022b; Hao et al., 2022), and infrastructure construction (Wen et al., 2022) all contribute to GTFEE improvement, while factor price distortion (Lin and Du, 2013; Lin and Chen, 2018), government corruption (Hao et al., 2020), market segmentation (Wei and Zheng, 2017; Guo and Liu, 2022) and other factors can reduce GTFEE.

As a policy tool, environmental regulation is widely used in emission reduction efforts and can also have a significant impact on energy efficiency (Chen et al., 2021; Feng et al., 2021; Hong et al., 2022). On one hand, some scholars agree that environmental regulation has a positive impact on improving energy efficiency (Mandal, 2010; Bi et al., 2014; Hancevic, 2016; Pan et al., 2019; Galeotti et al., 2020; Shi and Li, 2020); on the other hand, other scholars believe that there is a non-linear effect of environmental regulation on energy efficiency improvement (Tao et al., 2018).

Another series of literature explored the effect of environmental information disclosure, which is an important measure for the government, enterprises and the public to jointly promote environmental governance. In addition to government-oriented and market-based incentive environmental regulation, EID has received increasing attention as an unconventional means of environmental regulation. Some recent studies focus on the positively impact of environmental information disclosure on enterprise productivity, innovation and financial performance (Ahmad et al., 2019; Wang et al., 2020), and other studies showed that EID has negative or uncertain effect on firm (Lu and Zhang, 2022; Meng and Zhang, 2022). In the research towards the effect of EID at the urban level, we found that most of the existing studies focus on the policy effects of the industrial structure (Liu et al., 2021b), pollution-control (Tian et al., 2016; Feng and He, 2020), green technology innovation (Li et al., 2022). The similar studies to this paper focused on the effect of EID on environment and energy. EID can promote green innovation behavior and emission reduction by influencing corporate executives' motivation, improving the energy mix, increasing environmental regulatory pressure, and increasing social concern (Liu et al., 2010; Ahmad et al., 2019; Barwick et al., 2019; Tu et al., 2019; Shi et al., 2021; Wang and Wang, 2021; Zhang et al., 2022a). Furthermore, it is demonstrated that EID can enhance the energy efficiency of firms by improving the efficiency of investment utilization and the energy mix (Bu et al., 2022).

Current literature towards new ambient air quality standards (NAAQS), which is a typical EID policy, mainly focus on the standard formulation system, comparative analysis of the specific contents of different ambient air quality standards (Wang et al., 2023), and evaluation of the benefits of ambient air quality standards on pollution reduction (Wang et al., 2019; Liu et al., 2021a; Bai et al., 2021), public health (Zhang et al., 2022b) and businesses' desire for investing in environmental preservation (Zhang et al., 2019). The most related literature to this paper offers concrete evidence that NAAQS significantly alleviated the principal-agent problem between central and local governments in the environmental governance process, thereby reducing environmental information asymmetry (Greenstone et al., 2022).

Based on the literature above, we found that most of the existing studies focus on the policy effects of the industrial structure, resource allocation, and other factors as well as environmental regulation policies on GTFEE, and the research on the policy effects of EID and NAAQS mainly focuses on innovation, environment, industrial structure, etc., However, the existing literature still suffers from several deficiencies, and this study contributes to the literature on the following three grounds. First, we find that existing studies on the impact of energy efficiency mainly focus on the traditional method, using the energy consumption per unit of GDP to measure, the research on GTFEE are lacked (Hong et al., 2022). This study uses super-epsilon-based method including expected output and unexpected output with global Malmquist-Luenberger index to measure GTFEE, it is a useful addition to existing literature on energy efficiency. Second, the existing literature mainly focused on conventional market-incentive-based environmental regulations and command-and-control environmental regulations, with less attention to unconventional environmental regulations such as EID, especially the NAAQS in China, which is a key policy to improve the environment and quality of life (Wang et al., 2019). Therefore, it is still necessary to evaluate the effects of NAAQS policy on energy efficiency. Thirdly, there is less unified research framework for the impact of EID on energy efficiency, and the main influence channels and policy roles are unclear (Feng et al., 2021). Moreover, there are not many papers that consider the heterogeneous type of cities, especially in terms of resource and industrial base, the initial public monitoring motivation, this study fills the gap in the existing literature on channels, mechanism analysis, and heterogeneity.

3 Policy background and rationale theory hypothesis

3.1 Policy background

China's Ministry of Environmental Protection issued the Ambient Air Quality Standard (GB3095-2012) in 2012. It was implemented nationwide in 2016 and allowed to be implemented earlier in each region based on the situation. The NAAQS, which were implemented in 2013 and 2014, provide automated monitoring of pollutant emissions in each region by dividing air functional areas, setting pollutant limit values, and developing monitoring methods. The NAAQS are used to evaluate air quality and to gradually carry out air quality monitoring in three phases, 2013, 2014, and 2015, when automatic air quality monitoring points were built nationwide by each region. Through the three-stage implementation program, all regions across the country completed the installation of equipment at all air quality monitoring sites in 2016 and began automatic air quality monitoring in accordance with the NAAQS. Through the government websites of environmental protection authorities, the websites of environmental monitoring agencies and various social media, air quality information was released in real time for the whole society in all places, providing open and transparent access to environmental information for subjects from all walks of life.

3.2 Theoretical hypothesis

3.2.1 EID and energy efficiency improvement

Energy efficiency can be significantly impacted by environmental regulation, which is a common policy tool for reducing emissions and protecting the environment (Chen et al., 2021; Feng et al., 2021; Hong et al., 2022). Regarding traditional market-incentive-based and command-and-control environmental regulations, on the one hand, some scholars agree that environmental regulations have a positive impact on improving energy efficiency (Mandal, 2010; Hancevic, 2016; Pan et al., 2019); on the other hand, other scholars believe that there is a non-linear effect of environmental regulation on energy efficiency improvement (Tao et al., 2018). As an EID regulation, the NAAQS are different from conventional environmental regulation. Compared to using administrative orders and market mechanisms to achieve environmental goals, the NAAQS provide communities with judgment criteria by making environmental information transparent, which in turn influences individual behaviors. From the government perspective, EID offers criteria for evaluating environmental governance behaviors, making it simpler for higher-level governments to assess the environmental performance of lower-level governments. At the same time, the data monitored by state-controlled automatic monitoring equipment exclude the possibility of administrative intervention in air quality data by local governments, reducing the information asymmetry between the central and local levels (Greenstone et al., 2022). From the firms' perspective, environmental information disclosure makes them bear a heavier environmental responsibility, the community can utilize information about air quality to influence behavior, such as raising emission penalties and decreasing capital investment, to driving up the cost of emissions. As a result, environmental stakeholders, from regional governments to enterprises, need to control emissions in various ways to meet social expectations for environmental protection, and improving energy efficiency is one of the key aspects of promoting energy conservation and emission reduction. Thus, under the pressure exerted by the implementation of the NAAQS, local economic entities will put more effort into increasing energy efficiency.

Resource-based cities are cities whose main industries are the exploitation and processing of natural resources such as minerals and forests in the region. They have a superior natural resource endowment, but at the same time, the long-term exploitation, and processing of resources make resource-based cities face the situation of resource depletion. The depletion of natural resources, including fossil energy, will increase the cost of energy use in resource-based cities. In addition, the "resource curse" concept contends that because of long-term resource dependency, industrial modernization in resource-based cities is insufficient, and environmental degradation is worse in these places (Jiang and Li, 2013; Li and Zou, 2018). As a result, the pollution and energy problems of resource-based cities will be more clearly publicized under the implementation of the NAAQS nationwide. The need to increase energy efficiency to address the issues of resource depletion and excessive emissions will become more pressing in resource-based cities, as the task of energy conservation and emission reduction will become increasingly difficult and time consuming. Therefore, the hypothesis 1 (H1) is proposed as follows.

H1: After the implementation of the NAAQS, energy efficiency improvement is more prominent in resource-based cities than in non-resource-based cities.

3.2.2 Old industrial bases, public monitoring enthusiasm, and energy efficiency improvement

The promotion effect of NAAQS on GTFEE is influenced by local characteristics in different regions and shows heterogeneity. Firstly, Industrial structure characteristics have an impact on the ecological and environmental conditions of cities (Yin et al., 2020). Heavy industry is typically the main industry in old industrial bases, and these cities have qualities such as an enormous asset stock, a large industrial scale, and an important industrial status. However, they also have traits such as a low industrial modernization level and a high pollution intensity. Distinguished from resource-based cities, the heavy industry and government-led characteristics of old industrial bases are more significant. The primary problem is that state-owned enterprise reform is somewhat behind schedule due to a number of historical legacy issues and high reform costs, both of which severely limit industrial transformation and the development of old industrial bases. Correspondingly, the difficulty of structural changes makes it more challenging to increase energy efficiency. In contrast, the industrial structure in other cities is more reasonable, and industrial structure upgrading is easier, while the regional market mechanism is more complete. The government and businesses are therefore more likely to be pressured by societal oversight to take action on energy conservation and emission reduction.

Secondly, the Coase theorem states that with sufficient information and zero transaction costs, negotiations between the parties to an externality will lead to efficient outcomes, and increased disclosure will reduce unnecessary losses to society (Coase, 1960; Acemoglu et al., 2012). As an EID regulation, the implementation of the NAAQS influences local environmental governance behavior by increasing information transparency and improving the public's right to know environmental information (Barwick et al., 2019; Wang and Wang, 2021). According to (Mastromonaco, 2015), the public's usage of information affects how effective EID is in reducing emissions, and the associated emission reduction effect occurs only when locals are aware of and make use of publicly available environmental information. In addition, air pollution itself can lead to a significant increase in migration (Qin and Zhu, 2018; Chen et al., 2022), which can also cause a decrease in surrounding housing prices (Currie et al., 2015). Furthermore, the dissemination of environmental information at the media level promotes the public's willingness to pay for improved environmental quality (Tu et al., 2020). In conclusion, the public monitoring situation will also have an impact on the enhancement effect of the NAAQS on GTFEE. For areas with low initial public monitoring motivation, the increased information disclosure after NAAQS implementation will cause a greater increase in local public monitoring motivation, and thus, the energy efficiency improvement effect of the policy will be more apparent. Based on the analysis above, the hypothesis 2 (H2) is proposed as follows.

H2: The enhancement effect of the NAAQS on GTFEE is higher in two types of resource-based cities: the city beyond old industrial bases, the city with lower initial public monitoring motivation.

3.2.3 Industrial structure optimization and energy efficiency improvement

The peculiarities of industrial structure influence energy consumption and pollution emissions to some extent. During the implementation of the NAAQS, the Chinese central government has instructed localities to increase industrial restructuring and accelerate the elimination of lagging production capacity, this order can support industrial structure optimization, which is crucial for raising GTFEE. In comparison to capital- and energy-intensive industries, the knowledge-intensive industries consume less energy and emits less pollution, which means this type of industries are more efficient in energy utilization (Cao et al., 2021). An increase in the proportion of energy-efficient individuals in a region can result in an improvement in local energy efficiency as a whole (Ma and Stern, 2008; Elliott et al., 2017; Dong et al., 2021). Modern service sectors are mostly knowledge-intensive industries, and the larger their share is, the stronger their role in promoting local GTFEE. Conversely, the traditional secondary industry, which mostly relies on energy-intensive production methods, will hinder the improvement of GTFEE. Therefore, the green and low-carbon qualities of local production activities will become more apparent from the standpoint of industrial structure optimization, when a region's industrial structure moves from a mostly secondary industry to a predominantly tertiary industry (Minihan and Wu, 2012). Hence, it can be assumed that the enhancement effect of the NAAQS on the GTFEE of resource-based cities will be effective through industrial structure optimization, and the hypothesis 3 (H3) is presented as follows.

H3: The NAAQS can improve GTFEE through industrial structure optimization.

3.2.4 Green innovation level and energy efficiency improvement

Green innovation has been an important tool for mitigating the conflict between high economic growth and severe environmental pollution (Tang et al., 2021). According to the Porter hypothesis, innovation can provide a competitive advantage by eliminating the constraints of reality (Porter and van der Linde, 1995). Under resource and environmental constraints, government regulations also tend to encourage green innovation more than traditional technological innovation to enhance energy efficiency while raising business productivity (Acemoglu et al., 2012; Li et al., 2020). To considerably increase energy efficiency, major green, low-carbon technological research and application must be bolstered, according to the Chinese government. For the enterprises themselves, innovation relies on long-term capacity accumulation and substantial upfront R&D investment, which is difficult to achieve overnight (Bu et al., 2022). Faced with the monitoring pressure brought about by sudden information disclosure, enterprises with a low level of innovation themselves are unlikely to immediately improve energy efficiency through innovation. Companies that engage in greater innovation frequently utilize advanced energy-saving technologies and improve their manufacturing techniques to raise GTFEE (Sun et al., 2019). Therefore, it can be assumed that in regions with a higher level of green innovation, firms are more likely to improve energy efficiency through technological innovation, which suggests that, in the face of pressure from NAAQS, they are better equipped to increase local energy efficiency, and the hypothesis 4 (H4) is proposed as follows.

H4: The level of green innovation impact he effectiveness of the NAAQS in improving the GTFEE in resource-based cities.

Consequently, the following graphic Supplementary Figure S1 can be used to show the channels and heterogeneity between NAAQS and GTFEE mentioned above.

4 Model construction and variable description

4.1 Identification strategy and model setting

To assess whether the NAAQS are effective in enhancing GTFEE, this study constructs a generalized multiperiod difference-in-differences (DID) model. The fundamental tenet of the DID method is to produce difference-in-differences statistics that indicate the impact of the policy by comparing the difference between the control group and the treatment group before and after the adoption of the policy (Yang et al., 2021). Since policies are often exogenous in relation to microeconomic entities, the problem of endogenous problems can be avoided to a significant extent (Zhao et al., 2022a; Yang et al., 2023). The traditional DID model presupposes that all individuals of the experimental group experience the effects of a policy at the same time (Abadie, 2005). However, when the policy implementation nodes are inconsistent, a generalized multiperiod DID model should be used (Beck et al., 2010; Wing and Marier, 2014). In this study, the NAAQS are considered a quasi-natural experiment, and 282 prefecture-level Chinese cities are chosen as the research's target due to the data's availability. Of these cities, 109 resource-based cities are set as the treatment group, and the remaining 173 cities are set as the control group. The DID method simultaneously controls the two differences and more exactly identifies the net effect of NAAQS policy on GTFEE. The baseline regression model is set as follows.

$$\boldsymbol{GTFEE}_{\text{it}} = \boldsymbol{\alpha} + \boldsymbol{\beta did}_{it} + \boldsymbol{\gamma Control}_{it} + \boldsymbol{\phi}_i + \boldsymbol{\mu}_t + \boldsymbol{\varepsilon}_{it} \tag{1}$$

In the equation, i, t represents the city and year, respectively. The dependent variable $GTFEE_{it}$ is the measure of GTFEE in city i in year t. did_{it}, which is the core independent variable, is a dummy variable for whether resource-based city i implemented the NAAQS in year t. φ_i and μ_t represent city and year fixed effects, respectively. $Control_{it}$ is a series of covariates. ε_{it} is an error term.

4.2 Dependent variable (GTFEE)

The core explanatory variable in this paper is green total factor energy efficiency (GTFEE), studies closely related to this paper using the Data envelopment analysis (DEA) method to estimate GTFEE, which can avoid the structural bias caused by traditional accounting methods and stochastic Frontier approach, and is mostly employed in efficiency evaluation (Shi and Li, 2020; Wu et al., 2021; Gao et al., 2022b). DEA, as a non-parametric technical efficiency analysis method based on a relative comparison among evaluated objects, is used to analyze the relative efficiency of observed individuals (i e., decision making units, DMUs) with multiple inputs and outputs, which is more accurate than previous efficiency assessment methods.

However, traditional DEA methods do not measure the efficiency losses caused by undesirable outputs such as pollution generated during the actual production process, to avoid this overestimation of efficiency, scholars proposed that the SBM model (Slacks-based measure), which includes undesirable outputs, and is widely used to measure eco-efficiency and energy efficiency in academia (Tone, 2001; Cao et al., 2021). Yet, the SBM model still has the issue of possible proportionality losses with the original inputs or outputs as the inputs are closely linked to the undesired outputs in a radial relationship, thus underestimating efficiency. Therefore, researchers further refined the SBM model to a non-oriented, non-desired output-based EBM model (epsilon-based measure model), which is compatible with radially and non-radially related input and output variables (Tone and Tsutsui, 2010). Whereas, the EBM still has a major drawback as the efficiency value of DMUs is at most 1, if multiple DMUs all have an efficiency value of 1, the model would not be able to effectively differentiate the efficiencies of DMUs, to address this issue, the Super EBM allows the efficiency value to exceed 1 (Andersen and Petersen, 1993).

Furthermore, while productivity and production technology level rely on long-term continuous production processes, both SBM and EBM models are just focus at a certain period. Therefore, on one hand, it is necessary to apply the directional distance function to the Malmquist index model, and obtain the Malmquist-Luenberger index (ML index), which can be used to measure the intertemporal changes of DMUs (Färe et al., 2001). On the other hand, to overcome the discontinuity in the ML index's measurement of technological advancement, scholars combine the ML index with the global directional distance function to construct the global Malmquist-Luenberger index (GML index) (Oh, 2010).

Given this, to estimate GTFEE, the study incorporates measurements from the Super EBM model along with the GML index, based on considering undesirable outputs. The specific measurement indices of GTFEE are shown in Supplementary Table S1. We select labor, fixed asset investment, and energy consumption as inputs, choose regional gross domestic product (GDP) as the desirable output, consider industrial SO2, industrial wastewater, industrial soot and dust, and carbon dioxide emissions to be undesirable outputs (Tao et al., 2018; Shi and Li, 2020). Among the energy consumption calculations, a linear model without intercepts is adopted to decompose the provincial energy data into prefecture-level cities by nighttime-light data (Shi and Li, 2020; Engstrom et al., 2021). Since the Malmquist method cannot calculate GTFEE for the base period, the main econometric analysis in this paper is measured using data from 2005 to 2019.

4.3 Independent variables

$did_{it} = treated_i{}^* post_{it}$ is the dummy variable for the NAAQS, representing the implementation status of resource-based city i in year t. The dummy variable $treated_i$ takes the value of one if the city is a resource-based city and the NAAQS were implemented and 0 otherwise. Based on the phasing scheme of the NAAQS, 2013, 2014, and 2015 are set as the phased implementation points, and $post_{it}$ takes the value of one in the current and subsequent years of the corresponding implementation cities in these 3 years and 0 otherwise.

4.4 Covariates and other variables

For reference, the following covariates at the prefecture city level are selected in this paper: 1) the regional population (pop), measured using the year-end household population; 2) education expenditure (edu), measured using the education expenditure in the general public budget expenditure of local governments; 3) science and technology expenditure (tec), measured using the science and technology expenditure in the general public budget expenditure of local governments; 4) the degree of digitalization (internet), measured in this paper using the number of households with internet broadband access; 5) the level of economic development (lnpgdp), measured using real GDP *per capita* (Feng et al., 2021); 6) the level of financial development (lnfinance), measured using the year-end financial institution deposit and loan balances as a share of GDP (Dong et al., 2022); 7) the level of government intervention (fiscal), measured in this paper using the ratio of local general public budget revenue to local general public budget expenditure (Gao et al., 2022b); 8) the level of foreign openness (fdi), measured using the actual utilization of foreign capital in the current year. Supplementary Table S2 shows the descriptive statistics (observations, means, standard deviations, and minimum and maximum values) for the main variables used in this paper.

4.5 Data sources

This paper selects a total of 282 cities in China from 2004 to 2019. Raw data for the statistical variables were obtained from the China Statistical Yearbook (National Bureau of Statistics of China, 2022), China City Statistical Yearbook, and China Environmental Statistical Yearbook (CNKI, 2022). Provincial energy data were obtained from the China Energy Statistical Yearbook (CNKI, 2022). Nighttime-light data were obtained from the raster data provided by the National Tibetan Plateau Data Center (CAS) (Zhang et al., 2021). The data on the green innovation of listed enterprises were obtained from the China National Intellectual Property Agency (CNIPA), and the few missing values were filled in by interpolation.

5 Empirical analysis

5.1 The GTFEE enhancement effect of the NAAQS

Supplementary Table S3 reports the results of the baseline regression using the DID method. The result in Column 1) shows that the estimation coefficient of the DID term is significantly positive at the 5% level when no covariates are included. This result verifies the correlation between the implementation of the NAAQS and the GTFEE in resource-based cities. Columns 2), 3), and 4) add covariates based on Column 1), and the estimation coefficients remain significantly positive at the 5% level when adding city fixed effects and omitting covariates. Column 5) adds year fixed effects, city fixed effects and covariates at the same time, making the regression results more plausible, and the estimated result is significantly positive at the 1% level, which means that the NAAQS significantly contribute to improving the GTFEE in resource-based cities. These results are consistent with existing studies, H1 is verified, and the remaining covariates are basically consistent with expectations.

5.2 Parallel trend test

An important prerequisite for assessing policy effects using the DID approach is that the explanatory variables need to satisfy the parallel trend assumption between the treatment and control groups, i e., in the absence of a policy shock, the trends in the dependent variables should be the same for both groups. The test uses the year prior to NAAQS implementation as a baseline. We construct cross-multiplication terms between the year dummy variables and the corresponding policy dummy variables for a 12-year window, spanning from 6 years before implementation until 6 years after implementation (Beck et al., 2010; McGavock, 2021). The specific model is set as follows.

$$\boldsymbol{GTFEE_{it}} = \boldsymbol{\alpha} + \sum_{s=2}^{6} \boldsymbol{\beta_{pre\_s} D_{pre\_s}} + \boldsymbol{\beta_{current} D_{current}} + \sum_{s=1}^{6} \boldsymbol{\beta_{post\_s} D_{post\_s}} + \boldsymbol{\gamma Control_{it}} + \boldsymbol{\phi_i} + \boldsymbol{\mu_t} + \boldsymbol{\varepsilon_{it}} \quad (2)$$

$D_{pre\_s}, D_{current}, D_{post\_s}$ represent the cross-multiplication terms of the year dummy variables and the corresponding policy dummy variables before, in the year of, and after the start of the NAAQS implementation program, respectively, and $\beta_{pre\_s}, \beta_{current}, \beta_{post\_s}$ are the corresponding coefficient. The results are shown in Supplementary Figure S2. The time-varying trend of GTFEE before NAAQS implementation is not significantly different and non-significant, satisfying the parallel trend hypothesis. In addition, the subsequent regressions of the dynamic test show that the NAAQS significantly improve the GTFEE of pilot cities from the year after the implementation of the policy.

5.3 Robustness tests

5.3.1 Placebo test

This paper conducts unduplicated random sampling for all pilot cities and policy times (Cao et al., 2021). Each time, 109 cities are selected as the virtual treatment group, the corresponding policy implementation time is randomly selected, and the remaining cities are used as the virtual control group. This process is repeated 1,000 times, and 1,000 virtual DID regression estimations are obtained. The test results are shown in Supplementary Figure S3. The dark line is the probability density distribution of DID coefficients corresponding to the placebo test, and the light line is the normal density distribution. The vertical solid line on the right side indicates the DID estimation coefficients in Column 5) of the baseline regression, which are located in the low tail of the coefficient distribution in the placebo test. Thus, the baseline regression results of this paper pass the placebo test.

5.3.2 PSM-DID

The DID approach used for policy effect assessment always experiences self-selection bias since real-life policies are essentially non-randomized experiments. The propensity score matching (PSM) method can be used to approximate randomization in the quasi-natural experiment by matching samples from each treatment group to a specific control group. In order to avoid the self-selection bias, making the treatment group and the control group have the similar individual characteristics, the cross-sectional PSM method was conducted for the whole sample. Through Supplementary Figure S4, the vast majority of samples in the treatment and control groups were within the common range of values, while the propensity score values for samples outside the common range of values were more extreme, which indicates that most of the treatment groups and control groups have been successfully matched.

The balance test is used to test whether there are significant differences among values of the covariates taken after matching between two groups, and it is more reasonable to employ a matched sample for DID regression if the differences are not statistically significant, which indicates that the matching effect of PSM is adequate. From Supplementary Figure S5, it can be seen that the vast majority of covariates had %bias values less than 10%, and the absolute value of %bias decreased significantly from the pre-matching, that means individual disparities have decreased between the treatment group and control group after matching. Furthermore, as shown in Supplementary Figure S6, Supplementary Figure S7, by comparing the kernel density estimates of the propensity scores before and after matching, the mean distance of the kernel density curves between the treatment and control groups was shortened after matching, and the overlap of the propensity scores of the two groups was significantly increased, which is consistent with the results of balance test, indicating that the matching was effective.

Subsequently, DID regressions were conducted using the samples with non-null weights (indicates that the sample is involved in matching) and the samples satisfying the common support hypothesis (indicates that the sample is in the range of common values) after PSM. The results are shown in Supplementary Table S4, Columns 1) and 2), and the baseline regression results remain robust when the selection bias problem is taken into account, indicating that the NAAQS has a considerable beneficial impact on resource-based cities' GTFEE. In addition, considering that the NAAQS underwent their first phase of implementation in 2013 and the policy effect has emerged, the policy may change regionally relevant economic variables. Thus, the study proceeds to match year-to-year propensity scores only for the sample before the policy impact (i e., from 2005 to 2012). In this section, the regression uses samples within the range of common values. As shown in Column 3) of Supplementary Table S4, the results indicate that the DID coefficients remain positive and significant at the 1% level.

5.3.3 Adding other control variables

When researching environment-related issues, researchers frequently use weather variables as covariates as climate has a significant impact on such factors. Weather conditions like rainfall and wind speed can alter pollutant concentrations, affect regional pollution, and ultimately have an influence on decisions relating to the environment, such as energy efficiency (Filippini and Zhang, 2016; Zhang, 2017). Therefore, to test the accuracy of the baseline regression results, we repeat the DID regression by adding average rainfall (AR), average air pressure (AP), average wind speed (AW) and average air temperature (AT) to the control variables of the model based on the baseline regression. The result is shown in Supplementary Table S5, the did coefficient remains significantly positive at the 1% level when the weather factor is taken into account, which means resource-based cities receive a 10.07% increment in GTFEE when the NAAQS is implemented, as it is consistent with the baseline regression results, the latter's authenticity has been established.

5.4 Endogeneity processing

This paper further adopts the instrumental variable method to overcome the influence of endogenous factors as much as possible. To satisfy the correlation and exogeneity conditions of instrumental variables, this study refers to the approach of (Hering and Poncet, 2014; Cai et al., 2016), choosing the air ventilation coefficient (*vebticoe*) as an instrumental variable for whether to select a city for NAAQS implementation. First, the air ventilation coefficient affects the pollutant concentration, which further influences local environmental regulation behavior, i e., places with higher pollutant concentrations have stricter environmental regulations and greater environmental protection efforts and are more likely to be selected as cities to carry out NAAQS monitoring layout work earlier than other areas. Therefore, as an instrumental variable, the air ventilation coefficient meets the relevance condition. Second, the air ventilation coefficient is determined by natural geographical conditions, which is consistent with the exogeneity premise.

Regression uses two-stage least squares (2SLS) for the instrumental variable. The results are presented in Supplementary Table S6. In the first-stage regression, the coefficients of the interaction terms of the instrumental variables and the time variables are all significant, indicating that the instrumental variables satisfy the correlation condition. The DID term is still significant in the second-stage regression, and the direction of the effect on the explanatory variables is the same as in the baseline regression, showing that the NAAQS can still significantly improve GTFEE even after the endogeneity issue in the city selection of the experimental group has been resolved and that the bias in sample selection is not the cause of the regression results of the DID model.

5.5 Heterogeneity analysis

5.5.1 Industrial base types

In 2013, China's National Development and Reform Commission released the National Plan for the Adjustment and Transformation of Old Industrial Bases (2013–2022). This plan lists 120 old industrial bases, including prefecture-level cities and the municipal districts of provincial capital cities. The high energy consumption problem of old industrial base cities, which are an important national industrial base and energy base, is more serious. A series of historical legacy problems make it difficult for old industrial base cities to transform and reduce emissions, imposing constraints on improving their energy efficiency. Studying whether the implementation of the NAAQS can promote an improvement in the GTFEE of old industrial base cities can provide a reference for future environmental policy formulation.

In this study, among resource-based cities, the old industrial base cities located in NAAQS implementation sites are used as the experimental group, and the remaining old industrial base cities are used as the control group. The same control grouping was carried out for the rest of resource-based cities to compare the effects of NAAQS implementation on the GTFEE of the two types of resource-based cities.

The results in Supplementary Table S7 show that the NAAQS have a more significant effect on the GTFEE improvement of resource-based cities out of the old industrial bases. This result is positive and significant at the 1% level, and as shown by the DID coefficient, the improvement in cities out of old industrial bases is stronger than the integral level. In contrast, the energy efficiency improvement effect on resource-based cities in old industrial bases is not significant, and the coefficient is negative, which means that the NAAQS do not improve the GTFEE of these areas. The possible reasons are that old industrial bases have a high energy consumption intensity, high pollution characteristics, heavy industry and government-led characteristics. Green transformation is difficult because of the many historical problems and the high cost of internal reform. Therefore, it is more difficult to promote technological change and industrial upgrading to improve energy efficiency by means of external monitoring, such as EID. In contrast, younger industrial bases are more market-oriented and have weaker heavy-duty features of the industrial structure. The modernization and upgrading of industries in younger industrial bases are significantly easier because there are not as many hindrances due to historical legacy issues, and a higher degree of marketization will enable EID to better direct capital flows, thereby promoting green upgrading and energy efficiency in local industries (Bu et al., 2022).

5.5.2 Public monitoring

In this study, the Baidu indices of 25 environment-related terms are summed to obtain the public monitoring motivation index. Additionally, the dummy variable *eword* is further set, using the total mean values of 2011 and 2012 as the basis for classification, with *eword* taking the value of one when the index is greater than the mean value and 0 otherwise. On this basis, we distinguish the initial situation into high public monitoring motivation and low public monitoring motivation to explore the difference in the effectiveness of the NAAQS in improving the GTFEE in resource-based cities under different levels of initial public monitoring motivation.

As shown by the test results in Supplementary Table S8, the effect of the NAAQS on GTFEE enhancement in resource-based cities is more significant with low initial public monitoring motivation. This result is positive and significant at the 1% level. Comparatively, the effect in cities with high initial public monitoring motivation is significant at only the 10% level. One possible reason is that cities with low initial public monitoring motivation have a lower level of EID, fewer channels for the public to obtain environmental information, and poor promotion of environmental protection concepts, which results in low public attention to local environmental information. The NAAQS have made it easier and more effective for the public to access environmental information. Local governments will be forced to focus more on promoting environmental protection as a result of the assessment pressure brought by EID from higher levels of government, which will increase public support for environmental conservation. Increased local public scrutiny will prompt companies and governments to increase their GTFEE to maintain their public image (Wang and Wang, 2021). In contrast, cities with a high level of initial public monitoring motivation pay more attention to environmental protection, and the level of EID is higher. Because local public monitoring already has a greater impact on GTFEE improvement from the start, the impact of the NAAQS on GTFEE improvement is limited.

H2 was verified according to the empirical evidence above.

6 Further analysis

6.1 Mediating effect

The results of the baseline regression and robustness tests demonstrate that the NAAQS can significantly promote GTFEE improvement in resource-based cities, and the influence channel needs to be further investigated. This study assumes that the enhancement effect of NAAQS works through the industrial structure optimization. Therefore, we construct the model as the equation below, regressing the mediating variable on the policy dummy variable did_{it}.

$$\boldsymbol{Mediator}_{it} = \alpha + \beta \boldsymbol{did}_{it} + \gamma \boldsymbol{Control}_{it} + \phi_i + \mu_t + \varepsilon_{it} \tag{3}$$

$Mediator_{it}$ is the mediating variable, representing the share of value added of the secondary sector in GDP (Ind2), and the level of industrial structure optimization is greater when the indicator is lower. The rest of the variables are the same as in Formula (1). The regression results are shown in Supplementary Table S9, it can be seen that NAAQS has successfully improved industrial structure optimization which can promote GTFEE of resource-based cities, since the share of secondary sector is negatively affected by the policy at a 5% significant level, H3 was verified. Not only do local governments need to accelerate the elimination of high-polluting industries in response to the central government's call, but firms themselves need to seek environmentally friendly and energy-efficient transformation paths in the face of increasing social pressure. Under the policy requirements and stimulation, the high-emission industrial sector is gradually withdrawing from the stage to make room for the development of modern service industries and other energy-efficient industries. Consequently, NAAQS has promoted the regional GTFEE improvement from the industrial distribution.

6.2 Moderating effect

The results of the baseline regression and robustness tests demonstrate that the NAAQS can significantly promote GTFEE improvement in resource-based cities, and the influence mechanism needs to be further investigated. This study assumes that both the level of the industrial structure and green innovation may affect the enhancement effect of the NAAQS on the GTFEE in resource-based cities. Therefore, drawing on previous research, the mechanism is tested by introducing moderating variables (Beck et al., 2010), and the formula is expressed as follows.

$$\begin{aligned}\boldsymbol{GTFEE}_{it} = \alpha + \beta_1 \boldsymbol{did}_{it} + \beta_2 \boldsymbol{did}_{it} {}^* \boldsymbol{Moderator}_{it} + \beta_3 \boldsymbol{Moderator}_{it} \\ + \gamma \boldsymbol{Control}_{it} + \phi_i + \mu_t + \varepsilon_{it}\end{aligned} \tag{4}$$

$Moderator_{it}$ is the moderating variable, representing the number of green invention patents granted to Chinese A-share listed companies from 2005 to 2019. The rest of the variables are the same as in Formula (1). In the mechanism test analysis, we focus on the coefficients of the interaction term between the moderating variables and the core independent variables, i e., the coefficients of $did_{it} \times Moderator_{it}$. Then, the influencing mechanisms are analyzed as follows.

The regression results are shown in Supplementary Table S10. The results indicate that the level of green innovation significantly enhances the improvement effect of the NAAQS on GTFEE, H4 was verified. The transition to green technologies is considered one of the key solutions for addressing climate change and energy intensity (Acemoglu et al., 2012), and it is also a key determinant in improving energy efficiency (Wurlod and Noailly, 2018). However, although green innovation can leads to GTFEE closer to the cutting edge, and strengthen the beneficial effects of NAAQS on it, this positive impact is limited by the existing level of local green innovation. The NAAQS present chance for cities to increase GTFEE through innovation, but regions with weaker green innovation capacity are less likely to take advantage of this opportunity. What's more, local companies seeking alternatives to reduce pollution emissions by seeking cleaner energy will further crowd out R&D investment (Bu et al., 2022).

7 Conclusions and policy recommendations

7.1 Key findings

This paper constructs city-level green total factor energy efficiency (GTFEE) indicators using the DEA method, and using panel data for

282 cities in China from 2004–2019, and regards the New Ambient Air Quality Standards (NAAQS) as a quasi-natural experiment, which has significantly reduced the asymmetry of pollution information between China's central and local governments as well as between the government and the public. The impact of the policy on GTFEE and its mechanism are assessed using a generalized multi-period DID method. The results of the benchmark regression indicate that the implementation of the NAAQS can significantly improve the GTFEE of resource-based cities, it remains reliable after a series of robustness tests instrumental variables method to solve endogeneity problems. Additionally, the heterogeneity analysis shows that the promotion effect of NAAQS is more significant in relatively non-old industrial base and cities with lower initial public monitoring motivation cities. Further, the industrial structure optimization and level of green innovation are vital for helping the NAAQS improve GTFEE, as shown by the mediating and moderating effects. In conclusion, this study adds to the existing empirical studies on the causal relationship between environmental information disclosure policy and energy efficiency, and it proposes several unique ideas for heterogeneity, mediating and moderating effect.

7.2 Policy implications

Based on the findings above, this paper makes the following recommendations. Firstly, since NAAQS can better enhance GTFEE in resource-based cities, targeted environmental regulations should be implemented. For resource-based cities and non-resource-based cities, the government should consider using different policy mixes to promote energy conservation, emission reduction and energy efficiency improvement. Secondly, the structural solidification and historical legacy problems of old industrial bases need further attention due to the fact that these problems provide serious obstacles to the promotion of local GTFEE. On the one hand, the energy efficiency of traditional industries can be improved through their internal transformation. On the other hand, the ability of traditional industries to improve energy efficiency can be increased through the externalities of the economic activities of local high-tech industries and green industries, such as technology spillovers. Therefore, the government should pay attention to the role of industrial structure adjustment on GTFEE, accelerate structural transformation and upgrading, and fully stimulate the innovation ability of firms. Thirdly, public supervision plays a positive role in promoting the impact of NAAQS on GTFEE, therefore, the government should improve environmental information regulation and the environmental quality assessment system, and the promotion of environmental protection concepts should be strengthened.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: The data used in this paper can be obtained from the corresponding sources provided in the paper. Requests to access these datasets should be directed to X-YL, liuxy_eco@163.com

Author contributions

X-YL is a major contributor in writing the manuscript. H-XW is in charge of editing this manuscript. D-DD is in charge of visualization and data collection. All authors read and approved the final manuscript.

Funding

This work is financially supported by the National Natural Science Foundation of China (No. 72003044), the Natural Science Foundation of Guangdong Province (No. 2022A1515011903).

Conflict of interest

The 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.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1120893/full#supplementary-material

References

Abadie, A. (2005). Semiparametric difference-in-differences estimators. *Rev. Econ. Stud.* 72, 1–19. doi:10.1111/0034-6527.00321

Acemoglu, D., Aghion, P., Bursztyn, L., and Hemous, D. (2012). The environment and directed technical change. *Am. Econ. Rev.* 102, 131–166. doi:10.1257/aer.102.1.131

Ahmad, N., Li, H.-Z., and Tian, X.-L. (2019). Increased firm profitability under a nationwide environmental information disclosure program? Evidence from China. *J. Clean. Prod.* 230, 1176–1187. doi:10.1016/j.jclepro.2019.05.161

Allcott, H., and Greenstone, M. (2012). Is there an energy efficiency gap? *J. Econ. Perspect.* 26, 3–28. doi:10.1257/jep.26.1.3

Andersen, P., and Petersen, N. C. (1993). A procedure for ranking efficient units in data envelopment analysis. *Manag. Sci.* 39, 1261–1264. doi:10.1287/mnsc.39.10.1261

Bai, Y., Ni, Y., and Zeng, Q. (2021). Impact of ambient air quality standards revision on the exposure-response of air pollution in tianjin, China. *Environ. Res.* 198, 111269. doi:10.1016/j.envres.2021.111269

Barwick, P. J., Li, S., Lin, L., and Zou, E. (2019). *From fog to smog: The value of pollution information*. Cambridge: National Bureau of Economic Research.

Bashir, M. A., Sheng, B., Doğan, B., Sarwar, S., and Shahzad, U. (2020). Export product diversification and energy efficiency: Empirical evidence from OECD countries. *Struct. Change Econ. Dyn.* 55, 232–243. doi:10.1016/j.strueco.2020.09.002

Beck, T., Levine, R., and Levkov, A. (2010). Big bad banks? The winners and losers from bank deregulation in the United States. *J. Finance* 65, 1637–1667. doi:10.1111/j.1540-6261.2010.01589.x

Bi, G., Song, W., Zhou, P., and Liang, L. (2014). Does environmental regulation affect energy efficiency in China's thermal power generation? Empirical evidence from a slacks-based DEA model. *Energy Policy* 66, 537–546. doi:10.1016/j.enpol.2013.10.056

Boomhower, J., and Davis, L. (2020). Do energy efficiency investments deliver at the right time? *Am. Econ. J. Appl. Econ.* 12, 115–139. doi:10.1257/app.20170505

Bosseboeuf, D., Chateau, B., and Lapillonne, B. (1997). Cross-country comparison on energy efficiency indicators: The on-going European effort towards a common methodology. *Energy Policy* 25, 673–682. doi:10.1016/s0301-4215(97)00059-1

Bu, C., Zhang, K., Shi, D., and Wang, S. (2022). Does environmental information disclosure improve energy efficiency? *Energy Policy* 164, 112919. doi:10.1016/j.enpol.2022.112919

Cai, X., Lu, Y., Wu, M., and Yu, L. (2016). Does environmental regulation drive away inbound foreign direct investment? Evidence from a quasi-natural experiment in China. *J. Dev. Econ.* 123, 73–85. doi:10.1016/j.jdeveco.2016.08.003

Cao, X., Deng, M., and Li, H. (2021). How does e-commerce city pilot improve green total factor productivity? Evidence from 230 cities in China. *J. Environ. Manag.* 289, 112520. doi:10.1016/j.jenvman.2021.112520

CAS National Tibetan Plateau Data center [online]. Available at: https://data.tpdc.ac.cn/home (Accessed June 20, 2022).

Chen, S., Oliva, P., and Zhang, P. (2022). The effect of air pollution on migration: Evidence from China. *J. Dev. Econ.* 156, 102833. doi:10.1016/j.jdeveco.2022.102833

Chen, Z., Song, P., and Wang, B. (2021). Carbon emissions trading scheme, energy efficiency and rebound effect – evidence from China's provincial data. *Energy Policy* 157, 112507. doi:10.1016/j.enpol.2021.112507

CNIPA Patent publication announcement. Available at: http://epub.cnipa.gov.cn/.

CNKI (2022). National knowledge infrastructure. Available at: https://www.cnki.net (Accessed June 20, 2022).

Coase, R. H. (1960). The problem of social cost. *J. Law Econ.* 3, 1–44. doi:10.1086/466560

Currie, J., Davis, L., Greenstone, M., and Walker, R. (2015). Environmental health risks and housing values: Evidence from 1,600 toxic plant openings and closings. *Am. Econ. Rev.* 105, 678–709. doi:10.1257/aer.20121656

Dong, F., Li, Y., Li, K., Zhu, J., and Zheng, L. (2022). Can smart city construction improve urban ecological total factor energy efficiency in China? Fresh evidence from generalized synthetic control method. *Energy* 241, 122909. doi:10.1016/j.energy.2021.122909

Dong, F., Li, Y., Zhang, X., Zhu, J., and Zheng, L. (2021). How does industrial convergence affect the energy efficiency of manufacturing in newly industrialized countries? Fresh evidence from China. *J. Clean. Prod.* 316, 128316. doi:10.1016/j.jclepro.2021.128316

Elliott, R. J. R., Sun, P., and Zhu, T. (2017). The direct and indirect effect of urbanization on energy intensity: A province-level study for China. *Energy* 123, 677–692. doi:10.1016/j.energy.2017.01.143

Engstrom, R., Hersh, J., and Newhouse, D. (2021). Poverty from space: Using high resolution satellite imagery for estimating economic well-being. *World Bank Econ. Rev.* 36, 382–412. doi:10.1093/wber/lhab015

FäRE, R., Grosskopf, S., Pasurka, J., and Carl, A. (2001). Accounting for air pollution emissions in measures of state manufacturing productivity growth. *J. Regional Sci.* 41, 381–409. doi:10.1111/0022-4146.00223

Farrell, M. J. (1957). The measurement of productive efficiency. *J. R. Stat. Soc. Ser. A General.* 120, 253–281. doi:10.2307/2343100

Feng, Y., and He, F. (2020). The effect of environmental information disclosure on environmental quality: Evidence from Chinese cities. *J. Clean. Prod.* 276, 124027. doi:10.1016/j.jclepro.2020.124027

Feng, Y., Wang, X., Liang, Z., Hu, S., Xie, Y., and Wu, G. (2021). Effects of emission trading system on green total factor productivity in China: Empirical evidence from a quasi-natural experiment. *J. Clean. Prod.* 294, 126262. doi:10.1016/j.jclepro.2021.126262

Filippini, M., and Zhang, L. (2016). Estimation of the energy efficiency in Chinese provinces. *Energy Effic.* 9, 1315–1328. doi:10.1007/s12053-016-9425-z

Galeotti, M., Salini, S., and Verdolini, E. (2020). Measuring environmental policy stringency: Approaches, validity, and impact on environmental innovation and energy efficiency. *Energy Policy* 136, 111052. doi:10.1016/j.enpol.2019.111052

Gao, D., Li, G., Li, Y., and Gao, K. (2022a). Does FDI improve green total factor energy efficiency under heterogeneous environmental regulation? Evidence from China. *Environ. Sci. Pollut. Res.* 29, 25665–25678. doi:10.1007/s11356-021-17771-1

Gao, D., Li, G., and Yu, J. (2022b). Does digitization improve green total factor energy efficiency? Evidence from Chinese 213 cities. *Energy* 247, 123395. doi:10.1016/j.energy.2022.123395

Gillingham, K., Newell, R. G., and Palmer, K. (2009). Energy efficiency economics and policy. *Annu. Rev. Resour. Econ.* 1, 597–620. doi:10.1146/annurev.resource.102308.124234

Greenstone, M., He, G., Jia, R., and Liu, T. (2022). Can technology solve the principal-agent problem? Evidence from China's war on air pollution. *Am. Econ. Rev. Insights* 4, 54–70. doi:10.1257/aeri.20200373

Guo, W., and Liu, X. (2022). Market fragmentation of energy resource prices and green total factor energy efficiency in China. *Resour. Policy* 76, 102580. doi:10.1016/j.resourpol.2022.102580

Haider, S., Danish, M. S., and Sharma, R. (2019). Assessing energy efficiency of Indian paper industry and influencing factors: A slack-based firm-level analysis. *Energy Econ.* 81, 454–464. doi:10.1016/j.eneco.2019.04.027

Hancevic, P. I. (2016). Environmental regulation and productivity: The case of electricity generation under the CAAA-1990. *Energy Econ.* 60, 131–143. doi:10.1016/j.eneco.2016.09.022

Hao, Y., Gai, Z., and Wu, H. (2020). How do resource misallocation and government corruption affect green total factor energy efficiency? Evidence from China. *Energy Policy* 143, 111562. doi:10.1016/j.enpol.2020.111562

Hao, Y., Guo, Y., and Wu, H. (2022). The role of information and communication technology on green total factor energy efficiency: Does environmental regulation work? *Bus. Strategy Environ.* 31, 403–424. doi:10.1002/bse.2901

Hering, L., and Poncet, S. (2014). Environmental policy and exports: Evidence from Chinese cities. *J. Environ. Econ. Manag.* 68, 296–318. doi:10.1016/j.jeem.2014.06.005

Hong, Q., Cui, L., and Hong, P. (2022). The impact of carbon emissions trading on energy efficiency: Evidence from quasi-experiment in China's carbon emissions trading pilot. *Energy Econ.* 110, 106025. doi:10.1016/j.eneco.2022.106025

Hu, J.-L., and Wang, S.-C. (2006). Total-factor energy efficiency of regions in China. *Energy Policy* 34, 3206–3217. doi:10.1016/j.enpol.2005.06.015

Huang, L., and Zou, Y. (2020). How to promote energy transition in China: From the perspectives of interregional relocation and environmental regulation. *Energy Econ.* 92, 104996. doi:10.1016/j.eneco.2020.104996

IEA (2020). Energy efficiency 2020. Available at: https://www.iea.org/reports/energy-efficiency-2020 (Accessed June 20, 2022).

Jiang, B., and Li, J. (2013). Government Scale,Labor-resource intensive industries and development lags of producer services: Mechanism and empirical research. *China Ind. Econ.*, 64–76. doi:10.19581/j.cnki.ciejournal.2013.01.006

Jiang, L., Zhou, H., and He, S. (2021). Does energy efficiency increase at the expense of output performance: Evidence from manufacturing firms in Jiangsu province, China. *Energy* 220, 119704. doi:10.1016/j.energy.2020.119704

Li, G., Xue, Q., and Qin, J. (2022). Environmental information disclosure and green technology innovation: Empirical evidence from China. *Technol. Forecast. Soc. Change* 176, 121453. doi:10.1016/j.techfore.2021.121453

Li, H., and Zou, Q. (2018). Environmental regulations, resource endowments and urban industry transformation: Comparative analysis of resource-based and non-resource-based cities. *Econ. Res. J.* 53, 182–198.

Li, J., Zhang, X., Ali, S., and Khan, Z. (2020). Eco-innovation and energy productivity: New determinants of renewable energy consumption. *J. Environ. Manag.* 271, 111028. doi:10.1016/j.jenvman.2020.111028

Li, L.-B., and Hu, J.-L. (2012). Ecological total-factor energy efficiency of regions in China. *Energy Policy* 46, 216–224. doi:10.1016/j.enpol.2012.03.053

Lin, B., and Chen, Z. (2018). Does factor market distortion inhibit the green total factor productivity in China? *J. Clean. Prod.* 197, 25–33. doi:10.1016/j.jclepro.2018.06.094

Lin, B., and Du, K. (2013). The energy effect of factor market distortion in China. *Econ. Res. J.* 9, 125–136.

Lin, B., and Tan, R. (2016). Ecological total-factor energy efficiency of China's energy intensive industries. *Ecol. Indic.* 70, 480–497. doi:10.1016/j.ecolind.2016.06.026

Linares, P., and Labandeira, X. (2010). Energy efficiency: Economics and policy. *J. Econ. Surv.* 24, 573–592. doi:10.1111/j.1467-6419.2009.00609.x

Liu, G., Dong, X., Kong, Z., and Dong, K. (2021a). Does national air quality monitoring reduce local air pollution? The case of PM2.5 for China. *J. Environ. Manag.* 296, 113232. doi:10.1016/j.jenvman.2021.113232

Liu, S., Liu, C., and Yang, M. (2021b). The effects of national environmental information disclosure program on the upgradation of regional industrial structure: Evidence from 286 prefecture-level cities in China. *Struct. Change Econ. Dyn.* 58, 552–561. doi:10.1016/j.strueco.2021.07.006

Liu, X., Yu, Q., Fujitsuka, T., Liu, B., Bi, J., and Shishime, T. (2010). Functional mechanisms of mandatory corporate environmental disclosure: An empirical study in China. *J. Clean. Prod.* 18, 823–832. doi:10.1016/j.jclepro.2009.12.022

Lovell, C. K. (1993). Production frontiers and productive efficiency. *Meas. Prod. Effic. Tech. Appl.* 3, 67.

Lu, Y., and Zhang, L. (2022). Environmental information disclosure and firm production: Evidence from the estimated efficiency of publicly listed firms in China. *J. Prod. Analysis* 59, 99–119. doi:10.1007/s11123-022-00655-y

Ma, C., and Stern, D. I. (2008). China's changing energy intensity trend: A decomposition analysis. *Energy Econ.* 30, 1037–1053. doi:10.1016/j.eneco.2007.05.005

Mandal, S. K. (2010). Do undesirable output and environmental regulation matter in energy efficiency analysis? Evidence from Indian cement industry. *Energy Policy* 38, 6076–6083. doi:10.1016/j.enpol.2010.05.063

Mastromonaco, R. (2015). Do environmental right-to-know laws affect markets? Capitalization of information in the toxic release inventory. *J. Environ. Econ. Manag.* 71, 54–70. doi:10.1016/j.jeem.2015.02.004

Mcgavock, T. (2021). Here waits the bride? The effect of Ethiopia's child marriage law. *J. Dev. Econ.* 149, 102580. doi:10.1016/j.jdeveco.2020.102580

Meng, J., and Zhang, Z. (2022). Corporate environmental information disclosure and investor response: Evidence from China's capital market. *Energy Econ.* 108, 105886. doi:10.1016/j.eneco.2022.105886

Minihan, E. S., and Wu, Z. (2012). Economic structure and strategies for greenhouse gas mitigation. *Energy Econ.* 34, 350–357. doi:10.1016/j.eneco.2011.05.011

National Bureau of Statistics of China (2022). China statistical Yearbook. Available at: www.stats.gov.cn (Accessed June 20, 2022).

Oh, D.-H. (2010). A global Malmquist-Luenberger productivity index. *J. Prod. analysis* 34, 183–197. doi:10.1007/s11123-010-0178-y

Pan, X., Ai, B., Li, C., Pan, X., and Yan, Y. (2019). Dynamic relationship among environmental regulation, technological innovation and energy efficiency based on large scale provincial panel data in China. *Technol. Forecast. Soc. Change* 144, 428–435. doi:10.1016/j.techfore.2017.12.012

Patterson, M. G. (1996). What is energy efficiency?: Concepts, indicators and methodological issues. *Energy Policy* 24, 377–390. doi:10.1016/0301-4215(96)00017-1

Porter, M. E., and Van Der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *J. Econ. Perspect.* 9, 97–118. doi:10.1257/jep.9.4.97

Qin, Y., and Zhu, H. (2018). Run away? Air pollution and emigration interests in China. *J. Popul. Econ.* 31, 235–266. doi:10.1007/s00148-017-0653-0

Shi, D., Bu, C., and Xue, H. (2021). Deterrence effects of disclosure: The impact of environmental information disclosure on emission reduction of firms. *Energy Econ.* 104, 105680. doi:10.1016/j.eneco.2021.105680

Shi, D., and Li, S. (2020). Emissions trading system and energy use efficiency—Measurements and empirical evidence for cities at and above the prefecture level. *China Ind. Econ.* 9, 5–23. doi:10.19581/j.cnki.ciejournal.2020.09.001

Sun, H., Edziah, B. K., Sun, C., and Kporsu, A. K. (2019). Institutional quality, green innovation and energy efficiency. *Energy Policy* 135, 111002. doi:10.1016/j.enpol.2019.111002

Tang, L., and He, G. (2021). How to improve total factor energy efficiency? An empirical analysis of the yangtze river economic belt of China. *Energy* 235, 121375. doi:10.1016/j.energy.2021.121375

Tang, M., Leonardus, W. W. M., Muhammad, H., Syed, A. R. K., and Jermsittiparsert, K. (2021). The dynamics effect of green technology innovation on economic growth and CO2 emission in Singapore: New evidence from bootstrap ARDL approach. *Environ. Sci. Pollut. Res.* 28, 4184–4194. doi:10.1007/s11356-020-10760-w

Tao, C., Li, C., and Wang, X. (2018). Suitability of environmental regulation effect on total-factor energy efficiency and relation to energy consumption structure evolution. *China Popul. Resour. Environ.* 28, 98–108. doi:10.12062/cpre.20171005

Tian, X. L., Guo, Q. G., Han, C., and Ahmad, N. (2016). Different extent of environmental information disclosure across Chinese cities: Contributing factors and correlation with local pollution. *Glob. Environ. Change* 39, 244–257. doi:10.1016/j.gloenvcha.2016.05.014

Tone, K. (2001). A slacks-based measure of efficiency in data envelopment analysis. *Eur. J. operational Res.* 130, 498–509. doi:10.1016/s0377-2217(99)00407-5

Tone, K., and Tsutsui, M. (2010). An epsilon-based measure of efficiency in DEA–a third pole of technical efficiency. *Eur. J. Operational Res.* 207, 1554–1563. doi:10.1016/j.ejor.2010.07.014

Tu, M., Zhang, B., Xu, J., and Lu, F. (2020). Mass media, information and demand for environmental quality: Evidence from the "Under the Dome". *J. Dev. Econ.* 143, 102402. doi:10.1016/j.jdeveco.2019.102402

Tu, Z., Hu, T., and Shen, R. (2019). Evaluating public participation impact on environmental protection and ecological efficiency in China: Evidence from PITI disclosure. *China Econ. Rev.* 55, 111–123. doi:10.1016/j.chieco.2019.03.010

Wang, H., and Wang, M. (2020). Effects of technological innovation on energy efficiency in China: Evidence from dynamic panel of 284 cities. *Sci. Total Environ.* 709, 136172. doi:10.1016/j.scitotenv.2019.136172

Wang, K., Yin, H., and Chen, Y. (2019). The effect of environmental regulation on air quality: A study of new ambient air quality standards in China. *J. Clean. Prod.* 215, 268–279. doi:10.1016/j.jclepro.2019.01.061

Wang, S., Wang, H., Wang, J., and Yang, F. (2020). Does environmental information disclosure contribute to improve firm financial performance? An examination of the underlying mechanism. *Sci. Total Environ.* 714, 136855. doi:10.1016/j.scitotenv.2020.136855

Wang, X., and Wang, Y. (2021). The impact of environmental governance policy on green innovation: Evidence from China's quasi-natural experiment. *J. Financial Res.* 496, 134–152.

Wang, Z., Tan, Y., Guo, M., Cheng, M., Gu, Y., Chen, S., et al. (2023). Prospect of China's ambient air quality standards. *J. Environ. Sci.* 123, 255–269. doi:10.1016/j.jes.2022.03.036

Wei, C., and Zheng, X. (2017). A new perspective on energy efficiency enhancement: A test based on market segmentation. *Soc. Sci. China* 10, 90–111. doi:10.1080/02529203.2020.1719736

Wen, H., Liang, W., and Lee, C. C. (2022). Urban broadband infrastructure and green total-factor energy efficiency in China. *Util. Policy* 79, 101414. doi:10.1016/j.jup.2022.101414

Wing, C., and Marier, A. (2014). Effects of occupational regulations on the cost of dental services: Evidence from dental insurance claims. *J. Health Econ.* 34, 131–143. doi:10.1016/j.jhealeco.2013.12.001

Wu, H., Hao, Y., Ren, S., Yang, X., and Xie, G. (2021). Does internet development improve green total factor energy efficiency? Evidence from China. *Energy Policy* 153, 112247. doi:10.1016/j.enpol.2021.112247

Wu, H., Ren, S., Yan, G., and Hao, Y. (2020). Does China's outward direct investment improve green total factor productivity in the "belt and road" countries? Evidence from dynamic threshold panel model analysis. *J. Environ. Manag.* 275, 111295. doi:10.1016/j.jenvman.2020.111295

Wu, J., Xia, Q., and Li, Z. (2022). Green innovation and enterprise green total factor productivity at a micro level: A perspective of technical distance. *J. Clean. Prod.* 344, 131070. doi:10.1016/j.jclepro.2022.131070

Wurlod, J. D., and Noailly, J. (2018). The impact of green innovation on energy intensity: An empirical analysis for 14 industrial sectors in OECD countries. *Energy Econ.* 71, 47–61. doi:10.1016/j.eneco.2017.12.012

Yang, M., Hu, Z., and Yuan, J. (2016). The recent history and successes of China's energy efficiency policy. *WIREs Energy Environ.* 5, 715–730. doi:10.1002/wene.213

Yang, S., Ding, D., and Sun, C. (2022). Does innovative city policy improve green total factor energy efficiency? Evidence from China. *Sustainability* 14, 12723. doi:10.3390/su141912723

Yang, X., Wang, W., Wu, H., Wang, J., Ran, Q., and Ren, S. (2023). The impact of the new energy demonstration city policy on the green total factor productivity of resource-based cities: Empirical evidence from a quasi-natural experiment in China. *J. Environ. Plan. Manag.* 66, 293–326. doi:10.1080/09640568.2021.1988529

Yang, X., Zhang, J., Ren, S., and Ran, Q. (2021). Can the new energy demonstration city policy reduce environmental pollution? Evidence from a quasi-natural experiment in China. *J. Clean. Prod.* 287, 125015. doi:10.1016/j.jclepro.2020.125015

Yin, H., Zhang, L., and Ye, X. (2020). The time-varying effects of the industrial structure adjustment on the total factor productivity in China. *J. World Econ.* 43, 122–142. doi:10.19985/j.cnki.cassjwe.2020.01.008

YöRüK, B. K., and Zaim, O. (2005). Productivity growth in oecd countries: A comparison with malmquist indices. *J. Comp. Econ.* 33, 401–420. doi:10.1016/j.jce.2005.03.011

Yu, B. (2020). Industrial structure, technological innovation, and total-factor energy efficiency in China. *Environ. Sci. Pollut. Res.* 27, 8371–8385. doi:10.1007/s11356-019-07363-5

Zhang, H., Xu, T., and Feng, C. (2022a). Does public participation promote environmental efficiency? Evidence from a quasi-natural experiment of environmental information disclosure in China. *Energy Econ.* 108, 105871. doi:10.1016/j.eneco.2022.105871

Zhang, L. (2017). Correcting the uneven burden sharing of emission reduction across provinces in China. *Energy Econ.* 64, 335–345. doi:10.1016/j.eneco.2017.04.005

Zhang, L., Ren, Z., Chen, B., Gong, P., Fu, H., and Xu, B. (2021). A prolonged artificial nighttime-light dataset of China (1984-2020). *Natl. Tibet. Plateau Data Cent.* 101, 1. doi:10.11888/Socioeco.tpdc.271202

Zhang, Q., Zheng, Y., and Kong, D. (2019). Local environmental governance pressure, executive's working experience and enterprise investment in environmental protection: A quasi-natural experiment based on China's "ambient air quality standards 2012". *Econ. Res. J.* 54, 183–198.

Zhang, X., Wang, Y., Zhang, Z., and Long, H. (2022b). How does environmental information disclosure affect public health? Evidence from the new ambient air quality standards. *Int. J. Environ. Res. Public Health* 19, 15141. doi:10.3390/ijerph192215141

Zhang, Y., Xiong, Y., Li, F., Cheng, J., and Yue, X. (2020). Environmental regulation, capital output and energy efficiency in China: An empirical research based on integrated energy prices. *Energy Policy* 146, 111826. doi:10.1016/j.enpol.2020.111826

Zhao, J., Yan, J., Ran, Q., Yang, X., Su, X., and Shen, J. (2022a). Does the opening of high-speed railways improve urban livability? Evidence from a quasi-natural experiment in China. *Socio-Economic Plan. Sci.* 82, 101275. doi:10.1016/j.seps.2022.101275

Zhao, S., Peng, D., Wen, H., and Wu, Y. (2022b). Nonlinear and spatial spillover effects of the digital economy on green total factor energy efficiency: Evidence from 281 cities in China. *Environ. Sci. Pollut. Res.*, 1–21. doi:10.1007/s11356-022-22694-6