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THE RELATIONSHIPS BETWEEN ENVIRONMENTAL REGULATION AND ECO-EFFICIENCY: EVIDENCE FROM CHINA

Abstract: This study explores the causal relationships between environmental regulation and eco-efficiency in China's industrial and power sectors using a vector autoregressive (VAR) model and Granger causality tests. By analysing data from 2006 to 2020, we find that energy structure plays a pivotal role in determining eco-efficiency within the industrial sector, while imperative environmental regulations are a significant Granger cause of eco-efficiency in the power sector. Industrial agglomeration also exerts notable effects in both sectors. These findings underscore the sector-specific differences in the effectiveness of environmental regulations and highlight the need for tailored policy approaches to improve eco-efficiency across industries.

Keywords: eco-efficiency, environmental regulation, causality, vector autoregressive model

Introduction

Environmental protection is a key pillar of China's modernisation, with the nation committed to controlling pollution emissions throughout its comprehensive economic and social development. This commitment aims to ensure the country's ecological security, reduce disaster risks, and preserve clear waters and green landscapes for future generations. However, the demands of environmental protection frequently clash with the needs of economic growth. Currently, China remains in a phase of extensive development, largely driven by significant resource investments to boost economic output. During this process, limited environmental awareness, coupled with challenges in law enforcement and an imperfect environmental protection system, often leaves environmental concerns in a weaker position compared to economic priorities. As a result, some polluting enterprises continue to operate, presenting significant challenges to addressing the root causes of environmental problems.

Amid the increasingly prominent conflict between environmental protection and economic development, the issues of environmental pollution and ecological imbalance have garnered significant attention from both the government and academic circles. Eco-efficiency has gradually emerged as an important concept and tool for measuring the coordinated development of regional economies and their environments. Since environmental regulation can partially alleviate corporate pollution, the relationship between environmental regulation and eco-efficiency has become a focus of scholarly research. However, existing studies, which vary in their sample selections and empirical

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methods, have yielded inconsistent conclusions, broadly categorised into three theories: the "Follow cost theory", the "Porter hypothesis", and the "Uncertainty theory".

Although the relationship between environmental regulation and eco-efficiency has been studied, most existing research focuses on listed companies across all industries, using panel regression methods to examine the link between environmental regulation and eco-efficiency. This paper recognises two key factors: (1) The industrial sector is a primary driver of China's economic growth but is also a major consumer of resources and a significant polluter. The power sector, on the other hand, ensures energy security for China's economy but generates considerable pollution, particularly when traditional energy sources dominate. Both sectors are thus highly relevant in discussions about the balance between economic growth and environmental protection. (2) Granger causality analysis can predict how past values of one variable influence current values of another, accounting for time-lag structures and offering a better understanding of dynamic relationships between variables. For this reason, this study employs vector autoregressive (VAR) modelling to explore the causal relationship between environmental regulation and eco-efficiency. Moreover, different types of environmental regulations may have varying empirical impacts on eco-efficiency. Therefore, this paper classifies environmental regulations into two categories - "incentive-based" and "imperative" - to further contribute to the sustainable development of the industrial and power sectors, ultimately promoting harmonious development of the economy, society, and environment.

Literature review

Theory of environmental regulation

Environmental regulation refers to the policies and measures implemented by governments to prevent and control environmental pollution and improve environmental quality. It also encompasses the binding influence of social organisations and the public on the pollutant discharge behaviour of polluting entities [1, 2]. Zhao et al. [3] argued that environmental regulation can be categorised into direct explicit regulation - such as command-and-control, market incentives, and voluntary measures - and indirect implicit regulation, which highlights the impact of informal social and cultural factors on environmental governance. Ren et al. [4] viewed environmental regulation as the combined impact of laws, industrial standards, and the binding influence of social organisations and the public, all aimed at curbing pollution and overcoming environmental externalities. Several scholars have also explored the impact of environmental regulation, laying a solid theoretical foundation for this research [5-12].

Eco-efficiency theory

In the face of resource depletion and environmental degradation, scholars worldwide have conducted extensive research on ecological efficiency across various fields [13]. The relationship between environmental regulation and eco-efficiency can generally be classified into three theories: the "Follow cost theory", the "Porter hypothesis", and the "Uncertainty theory".

The "Follow cost theory" posits that environmental regulation increases production burdens for enterprises, complicates internal management processes, and to some extent, hampers the improvement of eco-efficiency [14]. Cui et al. [15] found that both compulsory environmental regulations and market-incentive environmental regulations (MER) hinder energy-related eco-efficiency, with the inhibitory effect being more pronounced in central and northeastern China. Konisky [16] identified that interactions between local governments on environmental regulation strategies can also limit improvements in eco-efficiency. Yuan et al. [17] observed that current environmental regulation levels suppress eco-efficiency improvements by raising costs and crowding out R and D investment.

The “Porter hypothesis” suggests that environmental regulation can increase vitality of production in enterprises, and can have a constructive and significant impact on ecological protection [18]. Qin et al. [19] found that policy measures related to pollution control and ecological protection significantly improve eco-efficiency. Korhonen et al. [20] pointed out that when the increment in production cost due to environmental protection can be overcompensated by net income, the environmental regulation tool is effective and efficient. Cox et al. [21] noted that due to the high costs brought about by environmental regulations, enterprises will accelerate the transition to renewable energy sources and consequently bring demand benefits for mined metals.

The “Uncertainty theory” believes that many factors create a nonlinear relationship between environmental regulation and eco-efficiency [22]. Yasmeen et al. [23] found that while environmental regulations have a positive correlation with eco-efficiency in central and eastern China, the opposite holds true for the western region. Luo et al. [24] found that the impact of environmental regulation on eco-efficiency follows an inverted U-shape, initially improving and then declining. Currently, the intensity of environmental regulations is insufficient to significantly improve eco-efficiency; only when regulation intensity surpasses a critical threshold does it positively impact eco-efficiency. Li and Sun [25] found that different regulatory tools affect energy efficiency in varied ways: environmental administrative penalties have a negative impact on China’s energy efficiency; market-based environmental incentives have a positive effect; and voluntary regulations are negatively correlated with energy efficiency, though not significantly.

Causality theory between eco-efficiency and environmental regulation

Causal analysis differs from general quantitative analysis by effectively explaining the order of interactions between variables, the duration of their impacts, and their future trends [26-29]. There are relatively few studies on the causal relationship between eco-efficiency and environmental regulation [30-32]. Omodero [33] employs ARDL or bound co-integration technique to test influence of financial instruments on pollutant reduction. And he finds financial instruments are not yet being directed toward reducing air pollution and environmental devastation in the country, which implies Nigeria needs more eco-friendly financial strategy to combat environmental hazards. This paper combines the factors of eco-efficiency, production characteristics of industrial and power enterprises, and environmental regulation, and employs an innovative approach using a vector autoregressive model and Granger causality tests.

Research methodology

Over the past three decades, China has experienced unprecedented growth in both its industrial and power sectors. However, the country now faces the pressing issues of resource depletion and environmental degradation. Achieving coordinated development between the industrial economy, the power sector, and the ecological environment - while enhancing eco-efficiency - will be critical for China's transformation from a big industrial nation to an industrial powerhouse, achieving a sustainable, modern economy [34]. Therefore, understanding the causal relationship between environmental regulation and eco-efficiency in these sectors is of great significance.

This paper employs the vector autoregressive (VAR) model, a method well-suited for studying causality, to examine the relationship between eco-efficiency and environmental regulation in the industrial and power sectors. The analysis follows nine main steps: (1) Variable selection: Relevant variables were selected based on the available literature and specific research objectives. (2) Data processing: Variables with multicollinearity were sequentially removed using variance inflation factor (VIF) values, retaining only those indicators that passed the collinearity test for model construction. (3) Stationarity test: The augmented dickey-fuller (ADF) test was conducted to determine the stationarity of the data. (4) Cointegration test: This step checks for any cointegration relationships between the variables. (5) Optimal lag order: The optimal lag order was selected based on information criteria. (6) VAR model construction: A VAR model of eco-efficiency and environmental regulation was developed based on the previous analyses. (7) Stability test of the VAR model: The stability of the VAR model was tested, as further analysis is only possible when the model is stationary. (8) Granger causality analysis: This test was used to assess whether causal relationships exist between the variables. (9) Impulse response function: Impulse response analysis was used to examine the interaction between endogenous variables by observing how a shock to one endogenous variable affects other variables within the model.

Variable selection and data processing

This empirical study incorporates the key variables that influence the causal relationship between environmental regulation and eco-efficiency in China's industrial sector. Specifically, we selected nine primary variables for the industrial sector: the explained variable is ecological efficiency (*IEE*), while the explanatory variables include imperative environmental regulation (*lncommand*), incentive environmental regulation (*ln_Fee*), energy structure (*energy_struc*), industrial agglomeration (*agglomeration*), technological innovation (*ln_innova*), foreign direct investment *(lnfori*), economic development level (*ln_rgdp*), and the level of openness to the outside world (*ln_open*). To ensure comparability, variables in the power sector were selected using the same rationale. In the power sector, we identified eight main variables, with ecological efficiency (*IEE*) as the explained variable and the explanatory variables including ecological environmental performance (*sthjjs*), economic performance (*jjjx*), effective invention logarithm (*yxfmds*), administrative penalty logarithm (*xzcfds*), sewage charge logarithm (*pwfds*), petition logarithm (*xfds*), tertiary industry/domestic (*dscy*), and import and export/GDP (*jck*).

All data utilised in this study are derived from the annual statistical yearbook provided by the China Economic and Social Big Data Research Platform (https://data.cnki.net/). It is essential to note that the industrial ecological efficiency (*IEE*) variable is a composite measure that integrates total energy consumption, industrial wastewater discharge, sulphur dioxide emissions, and carbon emissions, calculated using the commonly employed value-impact ratio method. The data spans from 2006 to 2020, encompassing a total of 15 years. Additionally, any missing data from the study period were supplemented using the moving average method.

To ensure that only indicators that passed the collinearity test are retained for the construction of the causal evidence model, we established the following: In the industrial sector, the explained variable for the index combination is ecological efficiency (*IEE*), while the explanatory variables include imperative environmental regulation (*lncommand*), incentive environmental regulation (*ln_Fee*), industrial agglomeration (*agglomeration*), and energy structure (*energy_struc*). In the power sector, the explained variable for the index combination is ecological efficiency (*ERE*), with the explanatory variables comprising power sector agglomeration (*agglomeration*), foreign direct investment (*lnfori*), command environmental regulation (*lncommand*), and incentive environmental regulation (*ln_Fee*).

Tests and optimal lag order

We applied the ADF test to analyse the data. In the industrial sector, all variables except for imperative and incentive environmental regulations exhibited non-stationarity; however, the other variables achieved stationarity at the 5 % significance level after differencing. In the power sector, the original sequence of incentive environmental regulation is stable, while the first-order of power aggregation and foreign direct investment are also stable. The second order of eco-efficiency is stable, indicating that all five variables meet the stationarity requirement at the 5 % significance level.

Based on the results of the trace test and the maximum eigenvalue test, we found no significant cointegration relationship between the variables. Consequently, we opted to use the VAR model for future causality testing.

After conducting the cointegration test, we proceeded to test the lag order of the dynamic system according to the information criterion to select the optimal lag order. Table 1 presents the results for determining the optimal lag order in the industrial sector. Given the characteristics of the data, the timeliness of environmental regulatory policies, and the applicability of akaike information criterion (AIC) and schwarz bayesian information criterion (SBIC) guidelines, we chose a lag order of 2 for the industrial sector. Similarly, we selected a lag order of 1 for the power sector.

Table 1

Optimal lag order

Lag	LL (Log - Likelihood) [-]	LR (Likelihood ratio test) [-]	df (Degrees of freedom) [-]	p_v (Probability value) [-]	FPE (Final prediction error) [-]	AIC [-]	HQIC (Hannan-Quinn information criterion) [-]	SBIC [-]
0	107.516				$8.6 \cdot 10^{-16}$	–20.5033	–20.6692	–20.352
1	.	.	25	0.000	$-4.3 \cdot 10^{-31*}$	.	.	.
2	1702.57		25	.	.	–330.513*	–332.173*	–329*
3	1657.43	–90.265	25	.	.	–321.487	–323.146	–319.974
4	1680.88	46.9*	25	0.005	.	–326.177	–327.837	–324.664

Note: * indicates that $p < 0.1$

VAR model

In the industrial sector, the VAR model comprises five variables: eco-efficiency, imperative environmental regulation, incentive environmental regulation, industrial agglomeration, and energy structure. Following the stationarity test, we found that, aside from imperative environmental regulation and incentive environmental regulation, which are stable, all other variables are first-order differenced non-stationary. Additionally, the unit root test confirmed that both imperative environmental regulation and incentive environmental regulation are non-differenced stable variables. The three variables eco-efficiency, industrial agglomeration, and energy structure are first-order differenced non-stationary. Based on these findings, this paper will construct a VAR model to analyse the factors influencing eco-efficiency.

The specific VAR equation is as follows:

$$\begin{aligned}\Delta IEE_t = \alpha_0 &+ \sum_{i=1}^{k} \alpha_{1i}\, \Delta IEE_{t-i} + \sum_{i=1}^{k} \alpha_{2i}\, lncommand_{t-i} + \sum_{i=1}^{k} \alpha_{3i}\, ln\_Fee_{t-i} \\ &+ \sum_{i=1}^{k} \alpha_{5i}\, \Delta agglomeration_{t-i} + \sum_{i=1}^{k} \alpha_{6i}\, \Delta energy\_struc_{t-i} + \mu_{1t}\end{aligned} \tag{1}$$

$$\begin{aligned}lncommand_t = \beta_0 &+ \sum_{i=1}^{k} \beta_{1i}\, \Delta IEE_{t-i} + \sum_{i=1}^{k} \beta_{2i}\, lncommand_{t-i} + \sum_{i=1}^{k} \beta_{3i}\, ln\_Fee_{t-i} \\ &+ \sum_{i=1}^{k} \beta_{5i}\, \Delta agglomeration_{t-i} + \sum_{i=1}^{k} \beta_{6i}\, \Delta energy\_struc_{t-i} + \mu_{2t}\end{aligned} \tag{2}$$

$$\begin{aligned}ln\_Fee_t = \gamma_0 &+ \sum_{i=1}^{k} \gamma_{1i}\, \Delta IEE_{t-i} + \sum_{i=1}^{k} \gamma_{2i}\, lncommand_{t-i} + \sum_{i=1}^{k} \gamma_{3i}\, ln\_Fee_{t-i} \\ &+ \sum_{i=1}^{k} \gamma_{5i}\, \Delta agglomeration_{t-i} + \sum_{i=1}^{k} \gamma_{6i}\, \Delta energy\_struc_{t-i} + \mu_{3t}\end{aligned} \tag{3}$$

$$\begin{aligned}\Delta agglomeration_t = \delta_0 &+ \sum_{i=1}^{k} \delta_{1i}\, \Delta IEE_{t-i} + \sum_{i=1}^{k} \delta_{2i}\, lncommand_{t-i} \\ &+ \sum_{i=1}^{k} \delta_{3i}\, ln\_Fee_{t-i} + \sum_{i=1}^{k} \delta_{5i}\, \Delta agglomeration_{t-i} \\ &+ \sum_{i=1}^{k} \delta_{6i}\, \Delta energy\_struc_{t-i} + \mu_{4t}\end{aligned} \tag{4}$$

$$\begin{aligned}\Delta energy\_struc_t = \varepsilon_0 &+ \sum_{i=1}^{k} \varepsilon_{1i}\, \Delta IEE_{t-i} + \sum_{i=1}^{k} \varepsilon_{2i}\, lncommand_{t-i} \\ &+ \sum_{i=1}^{k} \varepsilon_{3i}\, ln\_Fee_{t-i} + \sum_{i=1}^{k} \varepsilon_{5i}\, \Delta agglomeration_{t-i} \\ &+ \sum_{i=1}^{k} \varepsilon_{6i}\, \Delta energy\_struc_{t-i} + \mu_{5t}\end{aligned} \tag{5}$$

where Δ denotes the first-order difference, k is the optimal lag order, and t is the period. In the four formulas $\alpha_0, \beta_0, \gamma_0, \delta_0, \varepsilon_0$ are constant terms, and $\mu_{1t}, \mu_{2t}, \mu_{3t}, \mu_{4t}, \mu_{5t}$ are unrelated error terms with zero mean.

In the power sector, the VAR model consists of five variables: eco-efficiency, imperative environmental regulation, incentive environmental regulation, electricity agglomeration, and foreign direct investment. Following the stationarity test, we found that, except for the incentive environmental regulation, which is stable, all other variables are first-order differenced non-stationary. Furthermore, eco-efficiency, imperative environmental regulation, agglomeration, and foreign direct investment are also identified as unstable variables. Based on these findings, this paper will construct a VAR model to analyse the factors influencing eco-efficiency. Due to space constraints, the VAR equation for the power sector is omitted.

To verify the stationarity of the vector autoregressive model established in this study, we examined the distribution of the reciprocal features of the model by establishing the reciprocal distribution of the eigenroots. The results show that all eigenvalues of the VAR model are located within the unit circle, indicating that the VAR system is stable and meets the conditions necessary for impulse response analysis.

Granger causal analysis

The Granger causality test is a method used to examine the relationship between two variables, *X* and *Y*. When the chi^2 statistic is large and the corresponding p-value is less than 0.05, this indicates that we can reject the null hypothesis that "*X* is not a Granger cause of *Y*" at the 5 % significance level, thus establishing the existence of a Granger causal relationship between the two variables. At this significance level, the following Granger causality relationships can be derived from Tables 2 and 3:

(1) Imperative environmental regulation is a "Granger cause" of incentive-based environmental regulation in both the industrial and power sectors. As environmental awareness increases and economic efficiency is considered, incentive environmental regulations have emerged, reducing the burden on enterprises while promoting a win-win scenario for environmental protection and economic development. This has led to the optimisation and diversification of regulatory methods.

(2) Energy structure is identified as a "Granger cause" of industrial eco-efficiency, imperative environmental regulation, and industrial agglomeration. The rationale is that an increased proportion of clean energy necessitates policy support and standardised management to ensure healthy development. Such support fosters industrial agglomeration. Concurrently, the traditional energy sector faces environmental pressures and must reduce pollution while enhancing ecological efficiency through regulations.

(3) Eco-efficiency serves as a "Granger cause" for incentivised environmental regulation in the industrial sector. The improvement in eco-efficiency underscores the need for resource conservation and environmental protection. Incentive-based administrative regulations further enhance eco-efficiency through measures such as sewage charges, encouraging enterprises and individuals to adopt more environmentally friendly production and consumption practices. This synergistic relationship supports the achievement of Sustainable Development Goals.

Table 2

Results of the Granger causality test of industrial sector

Equation [-]	**Excluded [-]**	**chi^2 (chi - squared statistic) [-]**	**df [-]**	**Prob (probability) >chi^2 [-]**
D_iee	*lncommand*	3.676	1	0.055*
D_iee	*ln_Fee*	0.406	1	0.524
D_iee	*D.energy_struc*	6.279	1	0.012**
D_iee	*D.agglomeration*	0.005	1	0.945
D_iee	*ALL*	11.285	4	0.024**
lncommand	*D.iee*	1.119	1	0.290
lncommand	*ln_Fee*	1.386	1	0.239
lncommand	*D.energy_struc*	8.205	1	0.004***
lncommand	*D.agglomeration*	0.002	1	0.962
lncommand	*ALL*	13.880	4	0.008***
ln_Fee	*D.iee*	8.626	1	0.003***
ln_Fee	*lncommand*	8.908	1	0.003***
ln_Fee	*D.energy_struc*	1.371	1	0.242
ln_Fee	*D.agglomeration*	0.529	1	0.467
ln_Fee	*ALL*	13.317	4	0.010**
D_energy_struc	*D.iee*	0.166	1	0.684
D_energy_struc	*lncommand*	1.238	1	0.266
D_energy_struc	*ln_Fee*	2.412	1	0.120
D_energy_struc	*D.agglomeration*	2.611	1	0.106
D_energy_struc	*ALL*	6.623	4	0.157
D_agglomeration	*D.iee*	1.822	1	0.177
D_agglomeration	*lncommand*	7.776	1	0.005***
D_agglomeration	*ln_Fee*	4.346	1	0.037**
D_agglomeration	*D.energy_struc*	10.925	1	0.001***
D_agglomeration	*ALL*	26.435	4	0.000***

Note: * indicates that $p < 0.1$, ** indicates that $p < 0.05$, *** indicates that $p < 0.01$. Similarly hereinafter for other relevant statistical results

(4) Both imperative and incentive environmental regulations act as “Granger causes” of industrial agglomeration. These regulations encourage companies to self-regulate their pollutant emissions and resource use by establishing strict environmental standards. To comply with these regulations, companies may choose to cluster in specific areas, sharing environmental facilities, technology, and management expertise, thereby reducing compliance costs and improving efficiency. Additionally, agglomeration can yield economies of scale, promote specialised labour division, strengthen industrial chain coordination, and further support sustainable industry development.

(5) Imperative environmental regulation is a “Granger cause” of eco-efficiency in the power sector. This regulation manifests through investments in environmental pollution control that often lead to the adoption of cleaner and more efficient production technologies. Implementing these technologies can reduce pollutant emissions and enhance resource efficiency, thereby improving the eco-efficiency of electricity production. Furthermore, investment in environmental pollution control may include measures that improve energy efficiency and reduce waste generation. By minimising resource waste and energy consumption, the power sector can enhance its production processes’ eco-efficiency. The government typically regulates the power sector’s environmental behaviour through laws and regulations, requiring companies to invest in pollution control. To comply, companies may increase their investments in environmental pollution control, leading to improved ecological efficiency.

(6) Agglomeration in the power sector is a “Granger cause” of eco-efficiency in that sector. This phenomenon allows enterprises in the power sector to share resources, including infrastructure and technical equipment. Such resource sharing can reduce production costs and enhance resource utilisation efficiency. Additionally, companies can collaborate on technology research, development, and innovation activities, promoting advancements in industry technology and thus improving ecological efficiency.
(7) Eco-efficiency, along with imperative and incentivised environmental regulations and industrial agglomeration, are “Granger causes” of foreign direct investment in the power sector. This relationship suggests that eco-efficiency, environmental regulations, and industrial agglomeration all reflect corporate social responsibility. Companies with strong social responsibility performance are better positioned to attract foreign direct investment.

Table 3

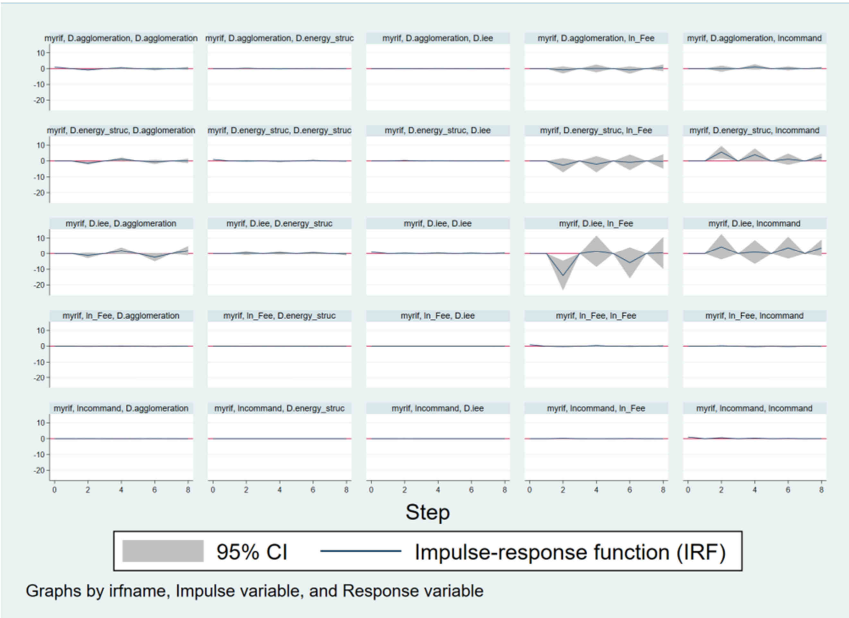
Results of the Granger causality test of power sector

Equation [-]	**Excluded [-]**	**chi^2 [-]**	**df [-]**	**Prob>chi^2 [-]**
D2_iee	*D2.lncommand*	9.6671	1	0.002***
D2_iee	*ln_Fee*	1.3128	1	0.252
D2_iee	*D_agglomeration*	5.3682	1	0.021**
D2_iee	*D.lnfori*	0.87915	1	0.348
D2_iee	*ALL*	15.493	4	0.004***
D2.lncommand	*D2_iee*	3.2185	1	0.073*
D2.lncommand	*ln_Fee*	0.25996	1	0.610
D2.lncommand	*D_agglomeration*	0.00139	1	0.970
D2.lncommand	*D.lnfori*	3.7076	1	0.054*
D2.lncommand	*ALL*	6.0992	4	0.192
ln_Fee	*D2_iee*	0.71848	1	0.397
ln_Fee	*D2.lncommand*	7.4844	1	0.006***
ln_Fee	*D_agglomeration*	2.9728	1	0.970
ln_Fee	*D.lnfori*	3.8579	1	0.054*
ln_Fee	*ALL*	14.914	4	0.192
D_agglomeration	*D2_iee*	0.3823	1	0.845
D_agglomeration	*D2.lncommand*	0.79335	1	0.373
D_agglomeration	*ln_Fee*	0.50974	1	0.475
D_agglomeration	*D.lnfori*	2.6387	1	0.104
D_agglomeration	*ALL*	4.2606	4	0.372
D.lnfori	*D2_iee*	8.4082	1	0.004***
D.lnfori	*D2.lncommand*	3.9268	1	0.048**
D.lnfori	*ln_Fee*	11.355	1	0.001***
D.lnfori	*D_agglomeration*	5.1045	1	0.024**
D.lnfori	*ALL*	16.577	4	0.002***

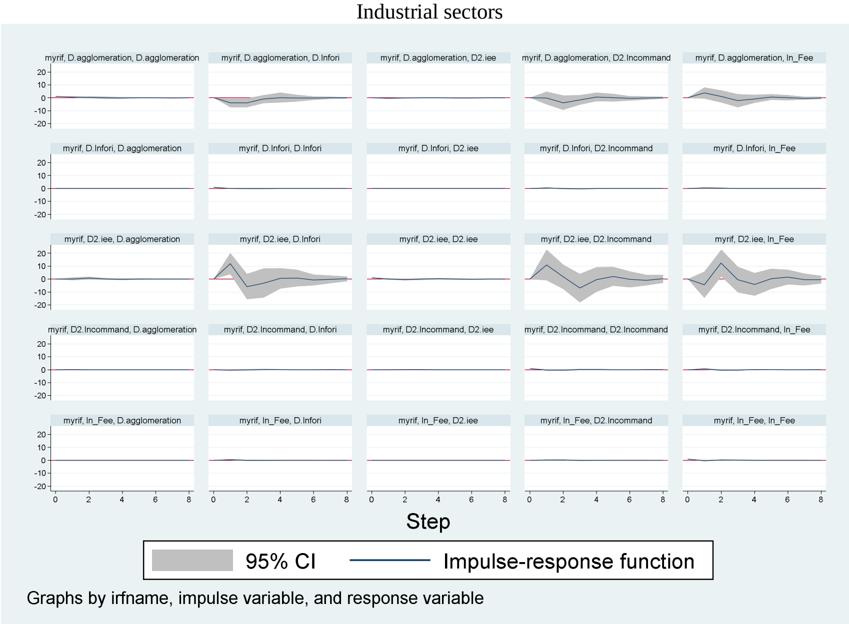
Impulse response function

In this paper, we will utilise the impulse response function analysis method to further quantify and examine the interactions between eco-efficiency variables and their influencing factors. Specifically, we will apply a standard deviation of positive impact to the model of the eco-efficiency variable and each of the influencing variables in the current period, systematically displaying the response results of these variables to the impact.

In this analysis, the horizontal axis of the impulse response function represents the lag period, while the vertical axis indicates the fluctuation level of the target variable in response to a unit shock. The solid line depicts the impulse response function. Since the impulse response results converge, this indicates that the model functions effectively. The impulse response analysis is illustrated in Figure 1.



Industrial sectors



Power sectors

Fig. 1. Impulse response analysis diagram

Taking each variable as the response variable in turn, and testing the impulse response of the other variables to the response variable, it can be found that:

In the industrial sector, (1) the impact of most variables on the response variable is relatively limited, and fails to produce significant response results. (2) When *ln_Fee* is a response variable, *energy_struc* and *IEE* will have a significant impact on it. However, *energy_struc* shock is expressed as "0-negative peak-0", and *IEE* shock is expressed as "0-negative peak-0-positive peak-0". (3) When *lncommand* is the response variable, the *energy_struc* and *IEE* will have an obvious positive impact effect on it. Among them *energy_struc* the impact is "0-positive peak-0", and *IEE* impact is "0-positive peak-0-positive peak-0".

In the power sector, (1) the impact of most variables on the response variables is relatively limited, and fails to produce significant response results. (2) When *ln_Fee* is a response variable, *agglomeration* and *ERE* will have a significant impact on it. However, the *agglomeration* shock is characterised by "0-positive peak-0", and the *ERE* shock is characterised by "0-negative peak-0-positive peak-0". (3) When *lncommand* is the response variable, *agglomeration* and *ERE* will have obvious positive impact effects on it, and both of them are "0-positive peak-0". (4) When *lnfori* is the response variable, *agglomeration* and *ERE* will have a significant impact on it. However, the *agglomeration* shock is characterised by "0-negative peak-0-positive peak-0", and the *ERE* shock is "0-positive peak-0".

Results and discussion

This paper explores the relationship between environmental regulation and eco-efficiency using VAR analysis in both the industrial and power sectors. The findings indicate that the impact of the two types of environmental regulations on eco-efficiency in the industrial sector is not significant, whereas imperative environmental regulation has a notable effect on eco-efficiency in the power sector. This discrepancy may be explained by the "Follow cost theory", the "Porter hypothesis", and the "Uncertainty theory", which highlight differing conclusions regarding these relationships. It is essential for scholars to analyse the interplay between environmental regulations and eco-efficiency by considering the specific samples and categories of environmental regulations.

Based on the in-depth analysis of the research results and the reasons for the results, it can be concluded that: (1) In the industrial sector, the impact of environmental regulation on eco-efficiency is not particularly pronounced. This may be attributed to the diversity of production processes within the industrial sector, where the implementation and effectiveness of environmental regulations are influenced by various factors. Specifically, production activities span a wide range of areas - including manufacturing, mining, and construction - each with its own unique processes and environmental impacts. This diversity complicates the implementation of environmental regulations, as different sub-sectors encounter distinct environmental challenges and require tailored solutions. Additionally, variations in the scale of industrial enterprises, technological capabilities, and the ability to adapt to environmental regulations affect the realisation of regulatory impacts. Consequently, while environmental regulations aim to enhance eco-efficiency, their effects in the industrial sector may not be direct or immediate. (2) In the power sector, the impact of imperative environmental regulation on eco-efficiency is more direct and significant. This may stem from the relatively centralised nature of production processes in the power industry, making it easier to implement and monitor environmental regulations. Compared to the industrial sector, power production involves a more concentrated process that primarily encompasses the generation, transmission, and distribution of energy. This concentration allows regulators to develop and enforce policies more effectively across a limited number of energy production and distribution nodes. Moreover, technological advancements in the power sector - such as the development of clean energy and the adoption of efficient power generation technologies - provide strong support for improving ecological efficiency. Therefore, the causal relationship between environmental regulation and eco-efficiency is more evident in the power industry. (3) Imperative environmental regulation significantly impacts incentive environmental regulation in both the industrial and power sectors. With increasing awareness of environmental protection and the need for economic efficiency, incentive environmental regulations have emerged that not only alleviate the burden on enterprises but also foster a win-win situation for both environmental protection and economic development, leading to the optimisation and diversification of regulatory methods.

Based on the findings of this paper, the following policy recommendations are proposed: (1) To enhance the positive role of environmental regulation on eco-efficiency, the government should consider factors such as industry scale and production processes. In the power sector, strengthening environmental regulations could further promote eco-efficiency. (2) The government should implement more imperative environmental regulations compared to incentive-based regulations to maximise their positive effects on eco-efficiency. Simultaneously, efforts should be made to improve the effectiveness of incentive-based environmental regulations to ensure they also contribute positively to enhancing eco-efficiency.

Conclusion

This study examined the causal relationships between environmental regulation and eco-efficiency in China's industrial and power sectors using VAR modelling and Granger causality tests. Our findings reveal sector-specific differences in these relationships. In the industrial sector, the energy structure plays a crucial role in determining eco-efficiency, while environmental regulations have a limited direct impact. In contrast, in the power sector, imperative environmental regulations are significant Granger causes of eco-efficiency. Additionally, industrial agglomeration emerged as an important factor in both sectors. These results underscore the need for tailored environmental policies that consider sector-specific characteristics. Future research should delve into the mechanisms underlying these sectoral differences and investigate the long-term impacts of environmental regulations on eco-efficiency across various industries.

In this study, the vector autoregressive model was employed to explore the interaction between environmental regulation and eco-efficiency in the industrial and power sectors, providing supplementary insights to existing research. However, certain limitations must be acknowledged. First, the Granger causality test indicates only a predictive causal relationship, which does not necessarily reflect a true, economically significant causal relationship. Second, the Granger causality test has strict data requirements. Although some data processing has been done in this paper through cointegration test, lag order and other operations, the potential influence of data characteristics on the accuracy of the results cannot be completely ruled out. If the assumptions of stationarity and cointegration are not fully met, the reliability of the Granger causality test results may be significantly compromised. Therefore, to enhance the accuracy of future research conclusions, it is advisable to explore a combination of other methods to analyse the causal relationships between variables more comprehensively and accurately.

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