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Optimum combination of heterogeneous environmental policy instruments and market for green transformation: Empirical evidence from China's metal sector

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ABSTRACT

Based on the new structural economics view that the combination of effective governments and efficient markets is the fundamental path to high-quality development, this study investigates how heterogeneous environmental policy instruments combine with marketization to improve the total factor energy-environmental efficiency (TFEEE) in China's metal sector. Utilizing the provincial panel data from 2006 to 2019, a super-efficiency slacks-based measure data envelopment analysis (SBM-DEA) integrated with the global Malmquist-Luenberger (GML) index is employed to estimate the energy-environmental efficiency and its dynamic changes. The evaluation results imply a significant increasing trend in the energy-environmental efficiency, but the overall level is rather low with disparities between sub-sectors and different regions. Using a dynamic panel threshold model, the "strong" version of the Porter Hypothesis is validated that command-and-control environmental policy (CEP), market-incentive environmental policy (MEP), and voluntary environmental policy (VEP) have an optimum stringency range to induce TFEEE growth, while the impact modes are drastically diverse. Further study verifies that higher marketization is conducive to triggering the facilitation effect of heterogeneous environmental policy instruments on the TFEEE but with completely different threshold values of marketization, which decrease sequentially corresponding to VEP, CEP, and MEP.

1. Introduction

As the risk of global climate change intensifies, it is relatively urgent for energy- and emission-intensive industrial sectors to propel green transformation. China's rapid economic development over the past 40 years has made the metal sector, a cornerstone of the economy that plays a critical role in industrialization and urbanization, to be a primary energy consumer and carbon emitter, making up roughly 14.3% and 16.34% of China's overall energy consumptions and carbon emissions, respectively (China Emission Accounts and Datasets, 2022). Moreover, with the mushroom deployment of metal-backed clean energy technologies such as photovoltaic, wind power, and new energy vehicles, the metal demand is anticipated to remain strong for a long time (Deetman et al., 2018; Li et al., 2020; Zeng et al., 2022). Therefore, the future energy consumption and carbon emissions from the metal sector will inevitably climb further, and high-efficiency energy utilization and low-carbon transformation are pivotal for China to thrive sustainably.

Confronted with the excessive material utilization and severe ecological deterioration, the Chinese government has formulated multiple environmental regulations to overcome market failures arising from the negative externalities of pollution. However, some policies were found to be ineffective since they have not prompted a significant improvement in energy and environmental performance (Greenstone and Hanna, 2014; Li et al., 2019; Wang et al., 2022b; Wen et al., 2022; Zhao and Sun, 2016), which is considered a government failure to some extent. It seems insufficient to achieve green transformation by relying solely on government interventions or market mechanisms. As the institutional and market system gradually consummates, the interactive relationship between the government and the market has evolved from market-oriented and government-oriented to coordinated engagement in macroeconomics (Huang and Song, 2021). In recent years, scholars find that environmental policies perform better in areas with higher

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marketization degrees, as a mature market serves to optimize resource allocation and foster market competition (Hu et al., 2020; Liu and Sun, 2021; Ren et al., 2022). However, it remains unclear how to combine policies with markets to achieve a win-win situation in terms of environmental and economic performances. These raise the following questions: Do environmental policy instruments improve the TFEEE? Is there variation in the effects of heterogeneous environmental policy instruments? Which kind of environmental policy instruments and what degree of marketization are the optimal combination to boost the TFEEE? In this connection, we employ a provincial panel dataset of China's metal sector to address the above research questions.

This study contributes to the existing literature in three ways. First, we construct an integrated analysis framework including the government, the market, and the industrial sector to examine how heterogeneous environmental policy instruments combine with marketization to improve the TFEEE of China's metal sector, which extends the application of new structural economic theory in the field of energy and environmental economics. Second, this study integrates the super-efficiency SBM-DEA with the global Malmquist-Luenberger index to analyze the energy-environmental efficiency and its dynamic changes from both static and dynamic perspectives; the dynamic panel threshold model, a threshold model incorporated with the generalized method of moments (GMM) capable of handling endogeneity issues, is employed to identify the optimal range of heterogenous policy instruments' stringency and marketization level for TFEEE growth. Third, proceeding from the national condition in China, we identify whether the policy and market in different regions have reached the optimal combination state, and provide suggestions on policy design, market reform, and instrument choice adapting to the local marketization.

We structure the remaining sections as follows. Literature review and theoretical mechanism analysis are conducted in Section 2. The methodology and data sources are introduced in Section 3. Section 4 presents and discusses the empirical results. Section 5 concludes the paper and provides policy implications.

2. Literature review and theoretical mechanism analysis

2.1. Literature review

Energy-environmental efficiency embodies energy input and undesirable environmental outputs besides ordinary economic inputs and outputs (Du et al., 2022a; Wang et al., 2021b; Zhang et al., 2022). DEA is the main technique for estimating energy- and environment-related efficiencies (Song et al., 2012). As traditional DEA models fail to consider the weak disposability of bad outputs and the SBM-DEA is unable to discriminate SBM-efficient DMUs (Lee et al., 2011), a super-efficiency SBM-DEA model was proposed by Tone (2002) to compensate for the shortcomings. It has been employed to estimate regional energy efficiency (Yu et al., 2019), provincial green economic efficiency (Shuai and Fan, 2020), industrial water-use efficiency (Liu et al., 2020b), etc. To explore the dynamic productivity changes, Oh (2010) established a GML index that could be resolved into efficiency change and technological change, and it overcomes the deficiency of the Malmquist index, which ignores undesirable outputs (Malmquist, 1953), and that of the Malmquist-Luenberger index, which is nontransitive and unable to produce feasible solutions in linear programming (Chung et al., 1997; Pastor and Lovell, 2005). The GML index has been extensively used to dissect the dynamic changes in national carbon efficiency (Feng et al., 2022), provincial green energy efficiency (Meng and Qu, 2022), environmental and emission abatement efficiency of the thermal power industry(Wang et al., 2018), etc.

Considerable research on the relationship between environmental policy and energy- and environment-related efficiency has been sparked but with no consensus yet, whose findings could be categorized into three kinds: negative relationship (Hille and Möbius, 2018; Jorgenson and Wilcoxen, 1990; Wagner, 2007); positive correlation (Liu et al., 2020a; Porter and Linde, 1995; Yuan and Xie, 2016); nonlinear relationship including "U" shape (Shuai and Fan, 2020; Wu et al., 2020) and inverted "U" shape (Liu et al., 2020c). Considering the variance in regulators, compliance costs, and application scopes among heterogeneous regulation tools, scholars distinguish environmental policy instruments into command-and-control environmental policy (CEP), market-incentive environmental policy (MEP), and voluntary environmental policy (VEP) (Du et al., 2022b; Zheng et al., 2022). Zhang et al. (2020) discovered that CEP, MEP, and VEP have inverted U-shaped relations with green innovation efficiency in the case of Xi'an city. Xie et al. (2017) constructed static threshold models for an examination of the effects of CEP, MEP, and VEP on province-level green productivity. The results indicated that all of them have threshold effects but with different threshold values and different numbers of inflection points.

A higher level of marketization indicates benign government-enterprise relations, the prosperity of the non-state-owned economy, sound market of factors and products, normal intermediary organizations, and legal environments (Fan et al., 2011; Ye and Liu, 2020; Zhang et al., 2018). Huang and Lei (2021) found that the marketization process plays a moderating role in strengthening the promotion effect of environmental regulation on corporate green investment, which was examined to improve environmental efficiency (Ren et al., 2022). Liu et al. (2023) confirmed that the pollution and carbon reduction effects of environmental regulations are more significant in the Yellow River Basin where there is a higher level of marketization. Particularly, the carbon emission trading scheme has been found to better enhance low-carbon technological innovation (Liu and Sun, 2021), energy saving and carbon emission reduction (Hu et al., 2020), and energy efficiency (Chen et al., 2021; Hong et al., 2022) in areas with a higher level of marketization. Wang et al. (2021a) employed a static threshold model and concluded that government intervention and market development are complementary, rather than a substitute for each other.

There are mainly three research gaps in the existing literature. First, the integration of super-efficiency SBM-DEA and GML index, effective in analyzing energy and environmental efficiency and its dynamic changes, has seldom been applied to evaluate the efficiency of metal sub-sectors. Second, despite substantial studies have examined the non-linear relationship between heterogeneous environmental regulation and energy- and environment-related efficiency, little research was done with the metal sub-sectors being the research object. Most crucially, there is a significant endogeneity constraint in the adopted models. Third, existing studies primarily explore the interaction relationship between marketization and general environmental regulation or market-incentive environmental policy, nevertheless, how heterogeneous environmental policies combine with market to induce green transformation is rarely investigated.

2.2. Theoretical mechanism analysis

The impact of heterogeneous environmental policy instruments on energy and environmental efficiency is thought to be driven by different theoretical mechanisms. CEP formulates compulsory restrictions on pollution discharges. When the CEP intensity is low, it is insufficient to motivate metal sectors to propel green technological upgrading and they select end-of-pipe treatment instead, because the compliance costs could be largely counteracted by government subsidies (Li et al., 2019). To be clear, metal sectors still have to bear an extra financial burden which would squeeze resources for production and operation activities, resulting in competitiveness impairment (Petroni et al., 2019). But if the regulatory intensity and compliance costs keep increasing, metal industries will be forced to optimize the production process and develop cleaner production technology (Zhu et al., 2021), consequently achieving economic benefits with less harmful emissions. MEP aims to encourage polluters to cut pollution emissions by internalizing environmental costs. Unlike CEP, MEP would bring about a cost surge directly. Metal producers and stakeholders, as profit seekers with loss

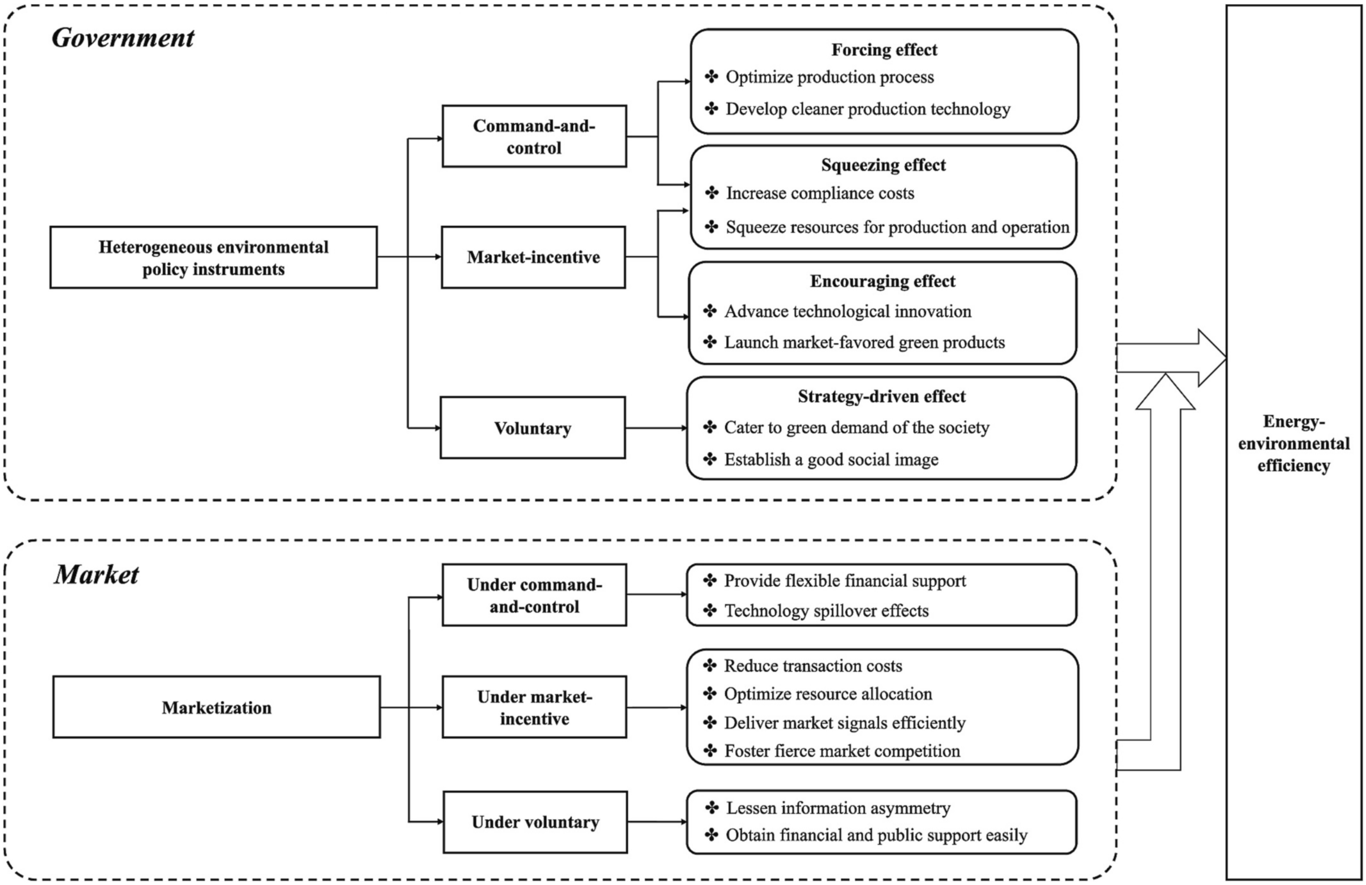

Fig. 1. The theoretical model of the effect of heterogeneous environmental policy instruments and marketization on the energy-environmental efficiency.

averse, are incentivized to advance technological innovation and launch differentiated green products, thereby gaining new market shares to compensate for environmental governance costs (Barney, 1991; Li and Xiao, 2020; Lv et al., 2023). However, excessive sewage charges would make it difficult for metal producers to invest in R&D activities, since they are typically located downstream of the global value chain with limited cost tolerance and low added value (Hu et al., 2021). VEP, consisting of citizen participation, voluntary agreements, and information devices (Ren et al., 2018), is a self-regulation instrument. As the social awareness of green development becomes increasingly tangible, metal production entities with strategic visions are enticed to adopt VEP to satisfy the green demand, thus establishing a good image and maintaining market competitiveness (Arora and Cason, 1995; Wang et al., 2022a; Zhu et al., 2021).

Lin (2017), a representative of new structural economics, pointed out that effective governments and efficient markets are both indispensable. Under the requirement of CEP, an efficient market mechanism makes it easier for metal sectors to obtain diversified financial support to relieve compliance cost burdens (Zhao et al., 2021). Moreover, a technology spillover effect would be reinforced (Fahad et al., 2022), laying the foundation for metal industries to introduce clean technologies with lower costs. When regulated by MEP, a mature market system lowers the transaction costs of emission rights (Shi and Li, 2020) and improves resource allocation efficiency (Yang et al., 2023), where the market signals reflecting the volatility of energy security, energy price, and metal price (Gong et al., 2022a; Gong et al., 2022b) could be more efficiently captured by MEP makers and reflected in the pollutant trading prices. Besides, fierce market competition further enhances the metal sectors' motivation for green innovation to gain competitive advantages (Shinkuma and Sugeta, 2016). In the context of VEP, higher marketization lessens the information asymmetry, which facilitates the access of investors and other stakeholders to information about producers' environmental performance (Ren et al., 2022), creating a favorable market environment for metal enterprises adopting VEP to obtain more financial and public support. Based on the literature review and critical analysis, a theoretical model shown in Fig. 1 is constructed.

3. Methodology and data sources

3.1. Econometric model

To confirm the potential nonlinear relationship between heterogeneous environmental policy instruments and the energy-environmental efficiency, the threshold model, where the regression coefficient can change in value based on the threshold variable, is a suitable methodological choice. Hansen (1999) originally developed a static threshold model with a strict assumption that both regressors and the threshold variable are exogenous, making it restrictive in many real applications. To ensure that this research fits within a realistic and general context, we employ a dynamic panel threshold model by introducing the first-order lag term of the dependent variable, which not only accounts for the dynamics of energy-environmental efficiency over time but also works as a proxy for possible omitted variables to address endogeneity (Bittencourt, 2011). Referring to Kremer et al. (2013), Diallo (2020), and Tenaw (2022), we figure out the threshold values and regression coefficients of heterogeneous environmental policy instruments using the following model.

$$lnTFEEE_{i,t} = \beta_0 + \beta_1 lnTFEEE_{i,t-1} + \beta_2 lnEPI_{i,t} \cdot I\left(q_{i,t} < c\right) + \beta_3 lnEPI_{i,t} \cdot I\left(q_{i,t} \geq c\right) + \beta_4 X + \alpha_i + \nu_t + \varepsilon_{i,t} \tag{1}$$

Table 1
The definitions of input and output indicators for the estimation of the energy-environmental efficiency.

Indicator		Definition
Input	Capital	The net value of fixed assets of the metal sub-sector in the province
	Labor	The average number of employees of the metal sub-sector in the province
	Energy	The energy consumption converted to standard coal of the metal sub-sector in the province
Expected Output	Industrial output	The industrial output value of the metal sub-sector in the province
Bad Output	CO_2	CO_2 emissions of the metal sub-sector in the province

Table 2
The definitions of indicators denoting the stringency of environmental policy instruments.

Variable	Abbreviation	Indicator	Definition
Command-and-control environmental policy	CEP	discharge intensity of SO_2	SO_2 emissions per unit of main business income of industrial enterprises above the designated size in the province
		discharge intensity of NO_x	NO_x emissions per unit of main business income of industrial enterprises above the designated size in the province
		discharge intensity of COD	COD discharges per unit of main business income of industrial enterprises above the designated size in the province
Market-incentive environmental policy	MEP	Sewage charge	The total amount of charges for the provincial pollutant discharges
Voluntary environmental policy	VEP	Education level	The average education level of employees in the province[a]

[a] The average education level of employees in the province is measured by $Edu_i = R_{i1}\times 6 + R_{i2}\times 9 + R_{i3}\times 12 + R_{i4}\times 16$, where R_{i1}, R_{i2}, R_{i3}, R_{i4} denote the ratio of employees in i^{th} province graduating respectively from primary school, junior high school, senior high school, and university or above. The weights correspond to the schooling year.

Where i and t respectively denote the observations and years; CEP, MEP, and VEP are simultaneously taken as the independent variable EPI and threshold variable q; I(•) indicate the indicator function; c are threshold values; X denotes the control variables; individual effects and time effects are captured by α_i and ν_t, and ε_{it} is the disturbance term.

To investigate the effects of heterogeneous environmental policy instruments on the energy-environmental efficiency in the context of different levels of marketization, the threshold variable q in eq. (1) will be replaced by the marketization index, and the rest of the variables and functions remain unchanged.

3.2. Variable description

(1) ***Total factor energy-environmental efficiency (TFEEE)*** is interpreted as the explained variable. The input indicators for energy-environmental efficiency estimation include Capital (K), Labor (L), and Energy (E). Industrial output (O) and CO_2 emissions (C) are the output indicators. Their definitions are shown in Table 1. As the calculated value of energy-environmental efficiency is extremely low, we refer to Feng et al. (2022) and take the following steps to generate TFEEE as the dependent variable. Under the assumption that the TFEEE in 2005 equals one, the TFEEE in 2006 is calculated by multiplying the GML index in 2006 by the TFEEE in 2005, and the TFEEE in 2007 is the GML index in 2007 times the TFEEE in 2006, then the TFEEE of the provincial metal sub-sectors from 2006 to 2019 could be acquired by analogy.

(2) ***Heterogeneous environmental policy instruments*** are treated as explanatory variables. ***① Command-and-control environmental policy (CEP)***. From a viewpoint of mandatory enforcement effect, the provincial discharge intensity of industrial pollutants could represent the stringency of CEP. Referring to Ouyang et al. (2020), we select three indicators, namely the discharge intensity of SO_2, NO_x and COD, for CEP estimation. The smaller the index, the stricter the CEP is. ***② Market-incentive environmental policy (MEP)***. The sewage charge is utilized to demonstrate the intensity of MEP (Li et al., 2019). The larger the indicator, the more rigorous the MEP is. ***③Voluntary environmental policy (VEP)***. Education is a crucial determinant of the intensity of informal regulation, as illustrated by Goldar and Banerjee (2004). We refer to Xie et al. (2017) and employ the education level as an indicator for estimating VEP stringency. The larger the metrics, the more stringent the VEP is. Based on the selected indicators of CEP, MEP, and VEP, we further apply an entropy method to construct a comprehensive and dimensionless index for the policy intensity, which is conducive to validly comparing the regulatory effects among heterogeneous policies. Indicators denoting the stringency of environmental policy instruments are described in Table 2.

(3) ***Marketization (MAR)*** is regarded as the threshold variable. Following Fan et al. (2011), we take the marketization index issued by National Economic Research Institute to denote MAR.

(4) ***Control variables.*** ①Technological innovation (TI). It is a crucial factor for the improvement of green total factor productivity, and the number of patent authorizations by the province is used to measure the technological innovation level (Li and Xiao, 2020). ②Foreign direct investment (FDI). Some scholars deem that FDI brings advanced technologies to host countries (Xie et al., 2017). Others hold the opposite opinion that FDI may destroy the environment as a result of the pollution haven effect (Hu et al., 2020). The registered investment of foreign-funded enterprises divided by the provincial GDP is taken to denote FDI. ③ Industrial Profit (IP). High-profit industries may have comparative advantages in attracting more market investments and increasing R&D investment. It is expressed by the total amount of profit achieved by metal sub-sectors in the province. ④ Industrial scale (IS). The industrial scale seems to be positively associated with industrial energy consumption and pollution discharges (Pang et al., 2019), which is denoted by the number of industrial firms in the province. ⑤ Economic policy uncertainty (EPU). Previous research has shown that the uncertainty of economic policy intensifies information asymmetry in the capital market, resulting in an increase in capital cost through risk premium (Zhou et al., 2022), which restricts enterprises from obtaining finance for environmental investments. China's economic policy uncertainty index is used to express it.

3.3. Data sources and processing

The samples are comprised of 5 metal sub-sectors of 30 provinces in China, excluding Tibet, Hong Kong, Macao, and Taiwan, from 2006 to

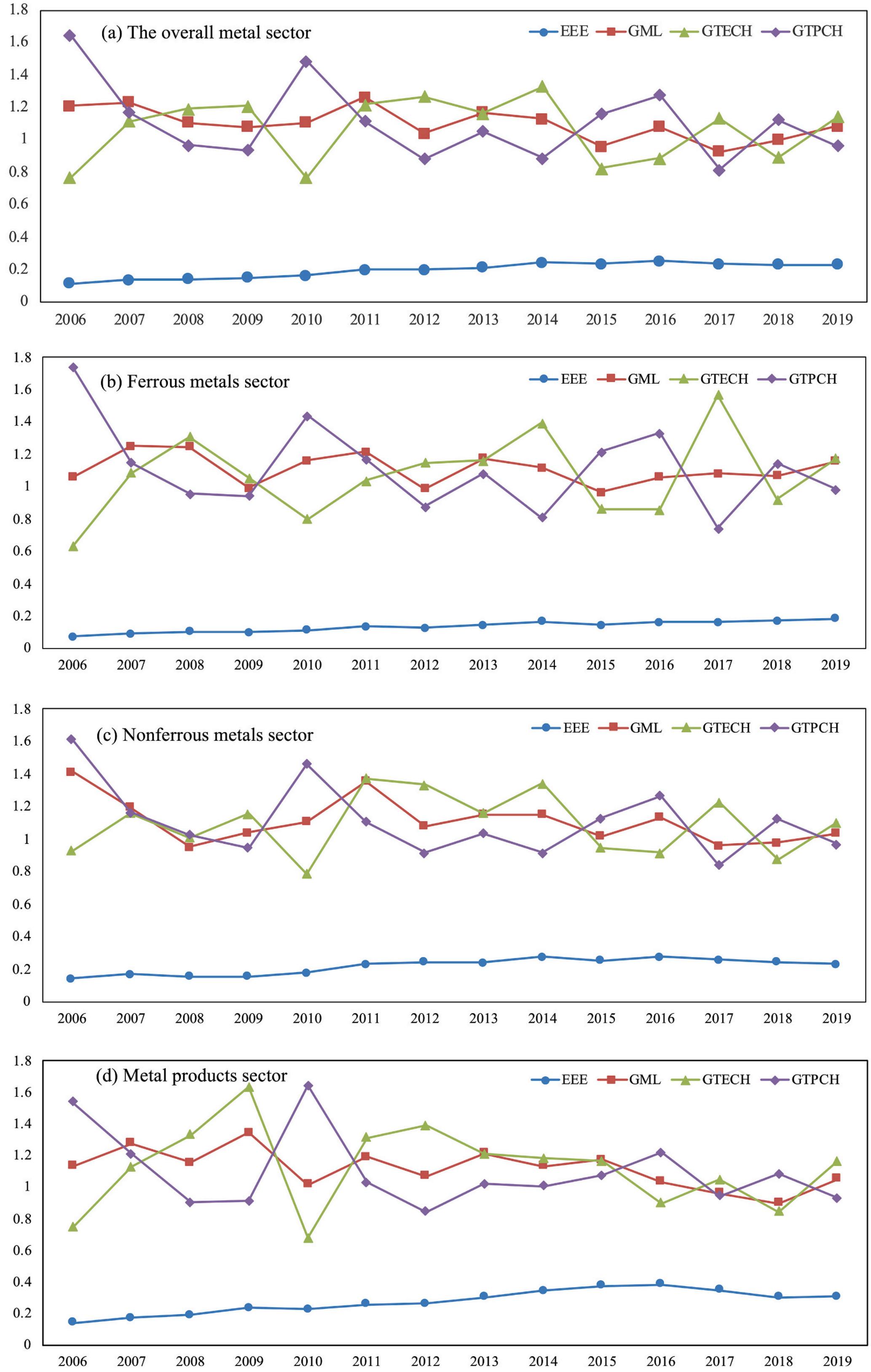

Fig. 2. The temporal evolution diagram of the energy-environmental efficiency, global Malmquist-Luenberger index, and its decomposition of the overall metal sector and its sub-sectors.

Note: EEE denotes the energy-environmental efficiency.

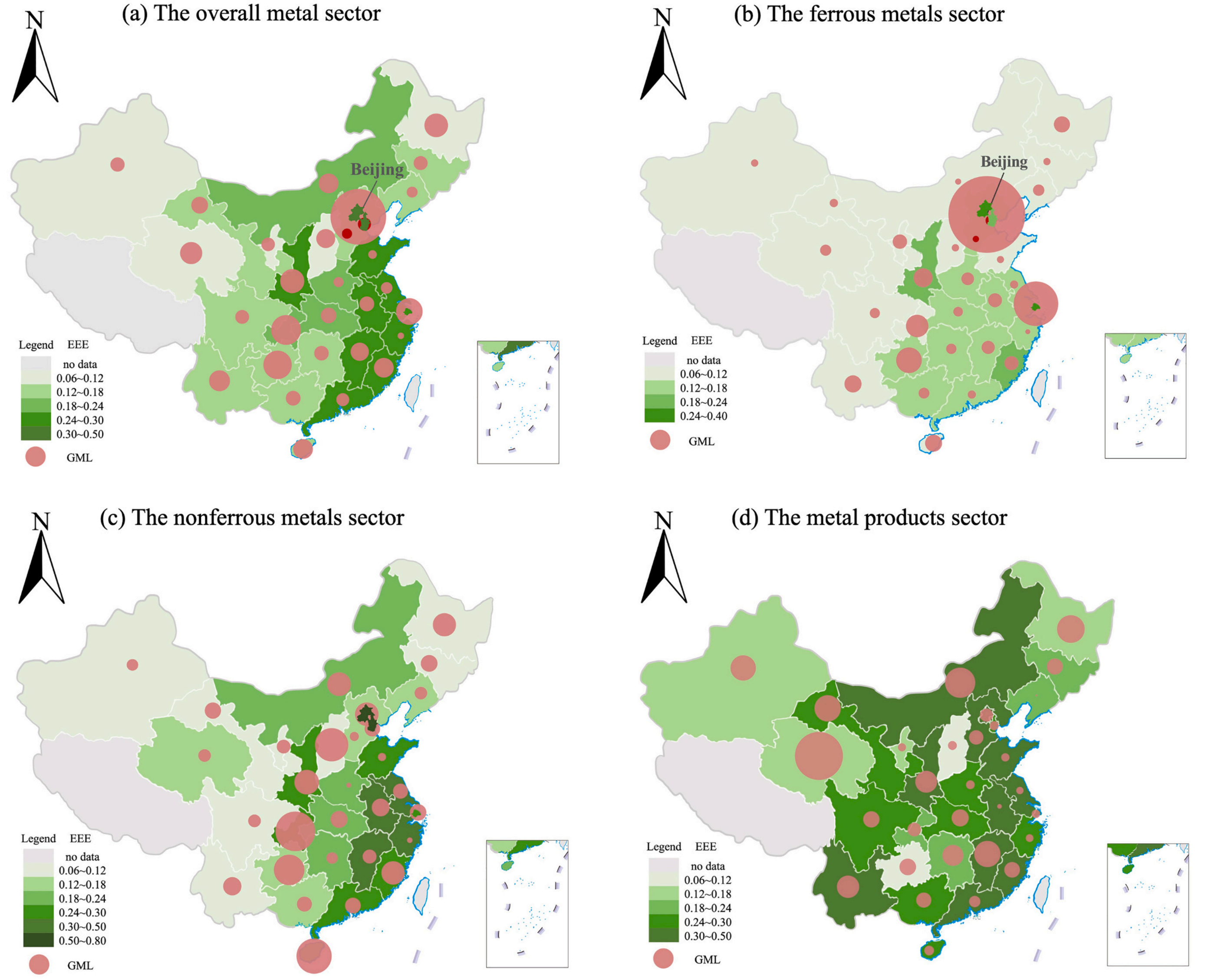

Fig. 3. The spatial distribution pattern for the energy-environmental efficiency and global Malmquist-Luenberger index of the overall metal sector and its sub-sectors.
Note: EEE denotes the energy-environmental efficiency.

Table 3
The threshold values of the stringency for heterogeneous environmental policy instruments and the confidence intervals.

Threshold variable	Dynamic panel threshold model	Threshold value	SupWStar statistic	P-value	BS	90% confidence interval	
						Lower	Upper
CEP	SYS-GMM	0.483	4.240***	0.000	1000	0.472	0.541
MEP	SYS-GMM	0.800	4.760***	0.000	1000	0.761	0.994
VEP	SYS-GMM	0.420	4.880***	0.000	1000	0.412	0.424

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; the SupWStar statistic is used as a post-estimation to determine whether the threshold effect is significant; BS denotes the number of replications for the bootstrap procedure.

2019.[1] After merging the data and eliminating the missing values, 2002 observations are obtained. The input and output indicators' data for energy-environmental efficiency calculation are collected from the China Industrial Statistical Yearbook, except that the data on energy consumption and carbon emission is obtained from the China Emission Accounts and Datasets (CEADs). Concerning CEP, MEP, and VEP, their data are derived from the China Environmental Statistical Yearbook and China Statistical Yearbook. The data on marketization is obtained from the Marketization Index Report of China's Provinces. The data of control variables come chiefly from the China Statistical Yearbook on Science and Technology, China Industrial Statistical Yearbook, and provincial statistical yearbooks. Additionally, we deflate the industrial output,

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[1] The sample period is determined by data availability that the latest available data on carbon emissions and energy consumption of provincial metal subsectors is only compiled up to 2019, and the data on the provincial discharge of NOx is unavailable before 2006.

Table 4
The nonlinear relationship between the stringency for heterogeneous environmental policy instruments and the total factor energy-environmental efficiency.

	(1)	(2)	(3)
Variables	lnTFEEE	lnTFEEE	lnTFEEE
L.lnTFEEE	0.836***	0.856***	0.698***
	(12.39)	(11.85)	(7.29)
lnCEP (CEP≥0.483)	−0.243		
	(−1.42)		
lnCEP (CEP<0.483)	0.874**		
	(1.99)		
lnMEP (MEP≤0.800)		1.129***	
		(2.81)	
lnMEP (MEP>0.800)		−0.003	
		(−0.01)	
lnVEP (VEP≤0.420)			1.658**
			(2.02)
lnVEP (VEP>0.420)			1.085**
			(2.03)
lnTI	−0.035	−0.068	−0.110*
	(−1.29)	(−0.53)	(−1.71)
lnFDI	0.413***	0.176***	−0.159
	(3.00)	(2.59)	(−0.55)
lnIP	4.139***	2.751	3.128**
	(3.81)	(0.88)	(2.56)
lnIS	0.043	−0.140	0.040
	(0.35)	(−0.30)	(0.16)
lnEPU	0.001	0.062	0.033
	(0.03)	(1.01)	(0.79)
AR (2)	0.589	0.497	0.648
	[0.556]	[0.619]	[0.517]
Sargan test	62.842	4.635	19.932
	[0.277]	[0.327]	[0.462]
Observations	1859	1859	1859

Notes: The prefix "ln" before variables denotes the logarithm of the variable adding one; lnCEP is the opposite number of the logarithm of CEP adding one; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, correspondingly. Figures in () are the z-values of the coefficients, and those in [] are the *p*-values of the statistics of relevant tests.

capital, and other economic variables to 2006 constant prices using the producer price index, fixed asset investment price Index, and GDP deflator, respectively. To eliminate the bias caused by extreme values, we winsorize all the variables at 5% and 95% quantiles and then take the logarithm of them for estimation. Table A1 in Appendix A presents the results of descriptive statistics.

4. Empirical results and discussions

4.1. Energy-environmental efficiency of China's metal sector

4.1.1. Temporal evolution diagram of energy-environmental efficiency

The energy-environmental efficiency and its dynamic changes are calculated by MATLAB 2021. As shown in Fig. 2 (a), although the energy-environmental efficiency of the metal sector in China increased significantly from 2006 to 2019, the general level remained incredibly low with an average value of 0.1969. The average GML index was 1.1011, demonstrating an increase of 10.11% annually, for which technical efficiency improvement (GTECH) contributed 6.69%, and technological progress (GTPCH) contributed 10.83%. Simultaneously, the changing trend of energy-environmental efficiency presented prominent stage characteristics, as the GML, GTECH, and GTPCH all presented an apparent fluctuation from 2006 to 2019.

As depicted in Figs. 2 (b), 2 (c), and 2 (d), the average levels of energy-environmental efficiency in the ferrous metals sector, nonferrous metals sector,[2] and metal products sector were 0.1354, 0.2177, and 0.2755, and the annual growth rates were 11.07%, 11.20%, and 11.77%, respectively. According to the average GTECH and GTPCH of sub-sectors, the growth of energy-environmental efficiency in the ferrous and nonferrous metals sectors was influenced by technological progress more than technical efficiency improvement, while the main factor inducing green transformation in the metal products sector was technical efficiency enhancement. Moreover, the GML of sub-sectors fluctuated at the same pace consistent with the overall changing trend except that only the ferrous metals sector kept an increasingly rising trend during the "13th Five-Year Plan", since it was the principal regulation target during the high-quality development period due to its massive energy input, substantial emissions, and overcapacity. The average values of energy-environmental efficiency, GML, and its decompositions for the overall metal sector and its sub-sectors in each year are listed in Appendix A(see Table A2).

4.1.2. Spatial distribution pattern of energy-environmental efficiency

As portrayed in Fig. 3 (a), the average energy-environmental efficiency of China's metal industry was distributed as a gradient, with the central region having a higher level than the western region and the highest level found in the eastern region. Exceptionally, the metal sector in Shanxi (a central province) had the lowest value among all provinces since it was the most coal-rich province with a laggard energy structure; the overall level of Heilongjiang, located in the old industrial base of the northeast, is also relatively low due to the "resource curse" dilemma; Shaanxi, a western province, had the level within the highest range mainly because it took the metal sector as one of the dominant industries. Regarding the GML index and its decompositions, the average values for all provinces were higher than 1 with relatively close values of GTECH and GTPCH for each province. Nevertheless, the GML index and its decompositions of the central and western regions were significantly higher than that of the eastern region attributed to the second-mover advantage in institutions and technology, excluding the province with a first-mover advantage far ahead of others, such as Beijing. Whatever the sub-sector was, as depicted in Fig. 3 (b)-(d), the spatial distribution pattern of the energy-environmental efficiency and GML was generally consistent with that of the overall metal sector. The average values of the energy-environmental efficiency, GML, and its decompositions for China's overall metal sector and its sub-sectors in each province are presented in Appendix A (see Table A3).

4.2. Threshold effect of heterogeneous environmental policy instruments on TFEEE

4.2.1. Results of threshold effect tests

The following empirical results are obtained by Stata 16. As can be seen in Table 3, the *P*-values of the SupWStar statistic for three single-threshold models are 0.000, which indicates that the nonlinear relationship with one threshold between heterogeneous environmental policy instruments and TFEEE is highly significant at the 1% level. The threshold values for CEP, MEP, and VEP are 0.483, 0.800, and 0.420, correspondingly.

4.2.2. Estimation results of the dynamic panel threshold model

We apply SYS-GMM to estimate eq. (1) and solve potential endogeneity issues. As shown in Table 4, the P-values of the AR(2) are >0.1, which confirms that there is no second-order autocorrelation for the random error term. Likewise, the Sargan test results indicate that the

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[2] The ferrous metals sector consists of the two sub-sectors of ferrous metals mining & dressing and ferrous metals smelting & pressing. The nonferrous metals sector is comprised of the sub-sectors of nonferrous metals mining & dressing and nonferrous metals smelting & pressing.

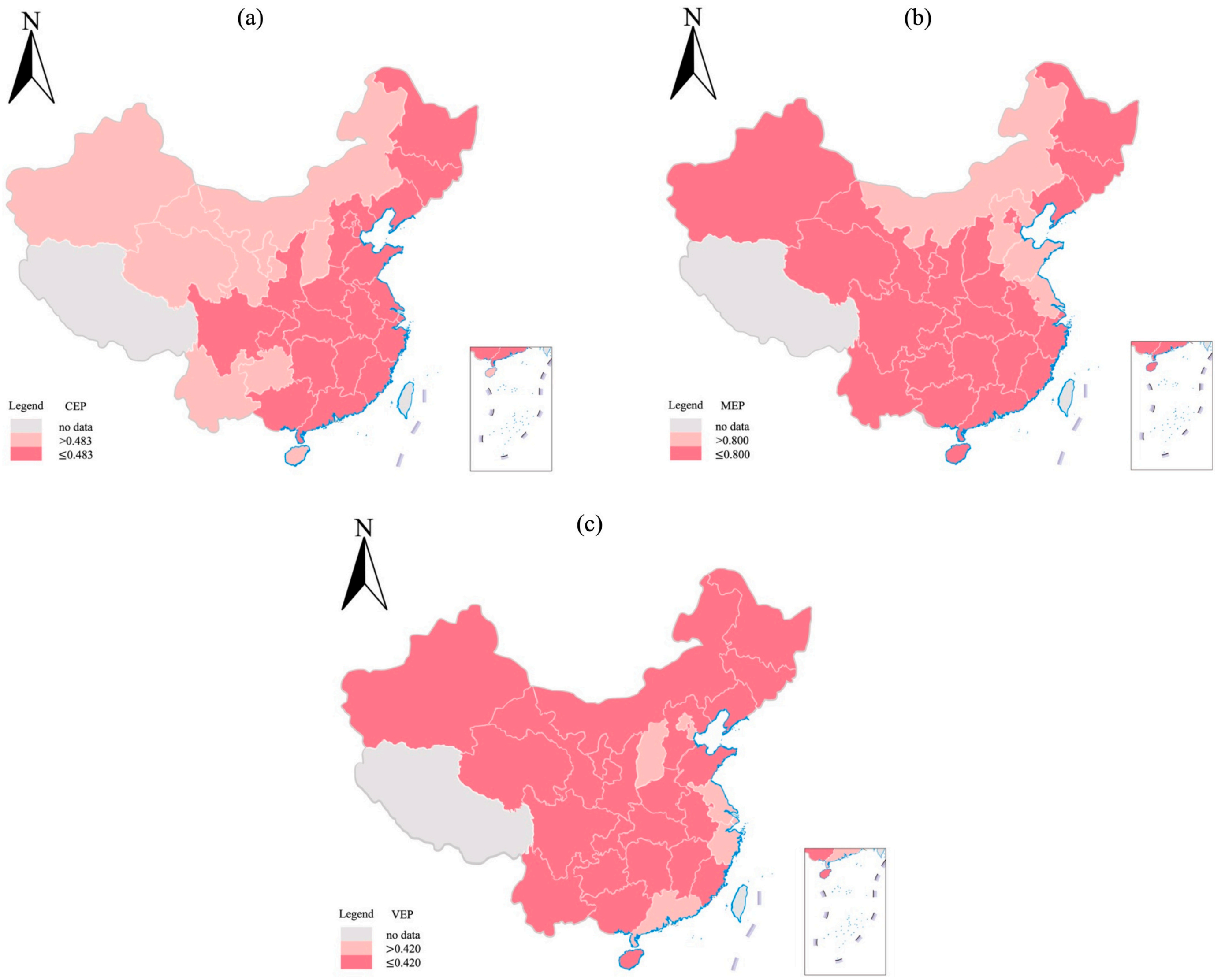

Fig. 4. The spatial distribution of the current stringency for (a)command-and-control environmental policy, (b)market-incentive environmental policy, and (c) voluntary environmental policy.

Note: The provinces with the darker color represent that the stringency for the environmental policy instrument falls into the optimal range for the growth of the total factor energy-environmental efficiency.

Table 5

The threshold value of marketization and its confidence interval under the regulation of heterogeneous environmental policy.

Threshold variable	Dynamic panel threshold model	Threshold value	SupWStar statistic	P-value	BS	90% confidence interval	
						Lower	Upper
MAR (under CEP)	SYS-GMM	6.590	5.330***	0.000	1000	6.480	6.590
MAR (under MEP)	SYS-GMM	4.823	3.680***	0.000	1000	4.814	4.960
MAR (under VEP)	SYS-GMM	6.980	3.640***	0.000	1000	6.918	7.169

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; the SupWStar statistic is used as a post-estimation to determine whether the threshold effect is significant; BS denotes the number of replications for the bootstrap procedure.

null hypothesis of valid overidentifying restrictions cannot be rejected. Furthermore, the coefficients of the first-order lag term of lnTFEEE are found to be positive at the 1% significance level, indicating that the TFEEE has been accumulating continuously and it is reasonable to construct the dynamic model.

As indicated in Table 4, a significant nonlinear relationship between three kinds of environmental policy instruments and TFEEE with one turning point has been proved. Since CEP is an inverse variable, the larger the value, the smaller the CEP intensity. We take lnCEP, the opposite number of the logarithm of CEP adding 1, for regression. As shown in column (1), when CEP exceeds 0.483, the coefficient of lnCEP is not significant, while lnCEP's coefficient equals 0.874 at the significance level of 5% if CEP remains within 0.483. We can see from Fig. 4 (a) that the current (in 2019) CEP intensity of 9 provinces located in the central and western regions hasn't reached the optimum level where TFEEE growth is inhibited by CEP. The results listed in column (2) indicate that if MEP ≤ 0.800, the coefficient of lnMEP equals 1.129 and is highly significant at the 1% level. When MEP>0.800, the coefficient

Table 6
The threshold effects of marketization on the relationship between heterogeneous environmental policy instruments and the total factor energy-environmental efficiency.

	(1)	(2)	(3)
VARIABLES	lnTFEEE	lnTFEEE	lnTFEEE
L.lnTFEEE	0.821***	0.826***	0.624***
	(14.88)	(11.27)	(4.33)
lnCEP (MAR$\leq$6.590)	−0.284*		
	(−1.70)		
lnCEP MAR>6.590)	1.014**		
	(2.00)		
lnMEP (MAR$\leq$4.823)		1.266	
		(1.51)	
lnMEP (MAR>4.823)		1.227**	
		(2.15)	
lnVEP (MAR$\leq$6.980)			1.506**
			(2.50)
lnVEP (MAR>6.980)			1.712**
			(2.53)
lnTI	0.055	0.232*	−0.034
	(1.59)	(1.69)	(−0.30)
lnFDI	0.491***	0.223	−0.151
	(3.69)	(1.53)	(−0.60)
lnIP	4.602***	3.150*	1.672*
	(4.25)	(1.70)	(1.86)
lnIS	−0.205**	−0.880**	−0.097
	(−2.43)	(−2.23)	(−0.50)
lnEPU	−0.011	−0.012	0.036
	(−0.44)	(−0.20)	(1.04)
AR (2)	0.331	0.844	0.068
	[0.741]	[0.399]	[0.946]
Sargan test	81.625	37.438	13.648
	[0.162]	[0.110]	[0.253]
Observations	1859	1859	1859

Notes: The prefix "ln" before variables denotes the logarithm of the variable adding one; lnCEP is the opposite number of the logarithm of CEP adding one; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, correspondingly. Figures in () are the z-values of the coefficients, and those in [] are the *p*-values of the statistics of relevant tests.

turns out to be insignificant. The current MEP stringency of most regions (26 provinces) belongs to the optimal range (See Fig. 4 (b)). As shown in column (3), the coefficient of lnVEP equals 1.658 when VEP is lower than 0.420 and equals 1.085 if VEP exceeds 0.420 at the significance level of 5%. According to Fig. 4 (c), although the current stringency of VEP in 27 provinces is classified into the optimum range, it is also within the low regime, indicating a large room to enhance VEP intensity.

The findings suggest that in the context of China's metal sector, the "strong" version of the PH would be supported only if the stringency of environmental policy instruments falls into a certain range. The magnitude of TFEEE growth motivated by VEP is significantly greater than that driven by MEP, whereas that facilitated by CEP is the smallest. It is because CEP stipulates mandatory requirements with less flexibility, which drives heavy polluters to give priority to taking expedient measures such as end-of-pipe treatment and other short-term behaviors. Alternatively, MEP is more effective in internalizing external costs, and polluters are thus encouraged to seek solutions from the roots, such as R&D investment. In contrast, VEP with minimal governmental intervention induces the metal sector to spontaneously restrain pollutant emissions to reap a preeminent social reputation convertible to economic benefits, which makes it the most effective instrument to promote TFEEE growth. These findings imply that we are required to not only ensure the optimal policy stringency but also pay attention to the choice of appropriate instruments.

4.3. *Threshold effects of marketization on the relationship between heterogeneous environmental policy instruments and TFEEE*

4.3.1. *Results of threshold effect tests*

In accordance with the coefficient of SupWStar and its P-values provided in Table 5, single-threshold characteristics are found in three dynamic panel threshold models at the 1% significance level, suggesting that the impact of each kind of environmental policy instruments on the TFEEE is nonlinear due to marketization. The threshold value of MAR under the regulation of CEP, MEP, and VEP are 6.590, 4.823, and 6.980, respectively.

4.3.2. *Estimation results of the dynamic panel threshold model*

Table 6 reports the regression results of the threshold effect of marketization on the relationship between environmental policy instruments and TFEEE estimated by two-step SYS-GMM. There is no second-order sequence correlation for the random error term, and selected instrument variables are valid, according to the results of AR (2) and the Sargan test.

As can be observed from column (1), when MAR is lower than 6.590, the coefficient of lnCEP significantly equals −0.284, and it rises to 1.014 at the 5% significance level if the marketization level is higher than 6.590. Until 2019, only a minority of provinces located in the western region have fallen into the optimal range of marketization (see Fig. 5 (a)). The results presented in column (2) reveal that lnMEP's coefficient is not significant if the marketization degree remains within 4.823, but it significantly equals 1.227 at the 5% level if the marketization level exceeds 4.823. As depicted in Fig. 5 (b), the eastern and central provinces have completely crossed the threshold value of marketization in 2019. From column (3), we can see that the coefficients of lnVEP in the context of lower and higher marketization are1.506 and 1.712 at the 5% significance level, respectively, but about half of the provinces haven't stepped over the marketization threshold (see Fig. 5 (c)).

It can be drawn from the above findings that higher marketization is conducive to triggering and reinforcing the facilitation effect of environmental policy instruments on the TFEEE in China's metal sector. However, differentiation occurs in the threshold values of marketization under heterogeneous instruments, which decrease sequentially corresponding to VEP, CEP, and MEP. Since VEP is a kind of self-regulation, a small magnitude variation in the degree of marketization cannot be immediately transformed into a shock on the relationship between VEP and TFEEE. Compared with VEP, CEP directly brings about cost burdens, which can be largely alleviated by market operation mechanisms, so it's less hard to capture the motivative effect of marketization on TFEEE growth spurred by CEP. Critically, MEP works efficiently based on fundamental market transactions, whose compliance costs are the easiest to offset through marketization.

4.4. *Robustness tests*

To examine whether the above findings are robust, we conduct robustness tests by substituting the explained variable, TFEEE, with the energy-environmental efficiency. The detailed estimation results are shown in Appendix A (see Tables A4–A7). It can be found that the threshold effects pass the significance tests at the 1% level and the threshold values as well as the estimated coefficients appear to be almost the same as those in Section 4.2 and Section 4.3. The results confirm that the empirical evidence for the optimum stringency of heterogeneous environmental policy instruments and the optimum combination of them with marketization is credible.

5. Conclusion and policy implications

By integrating a super-efficiency SBM-DEA model with the GML index, we evaluate the energy-environmental efficiency and its dynamic changes of China's metal industry from 2006 to 2019. Temporal

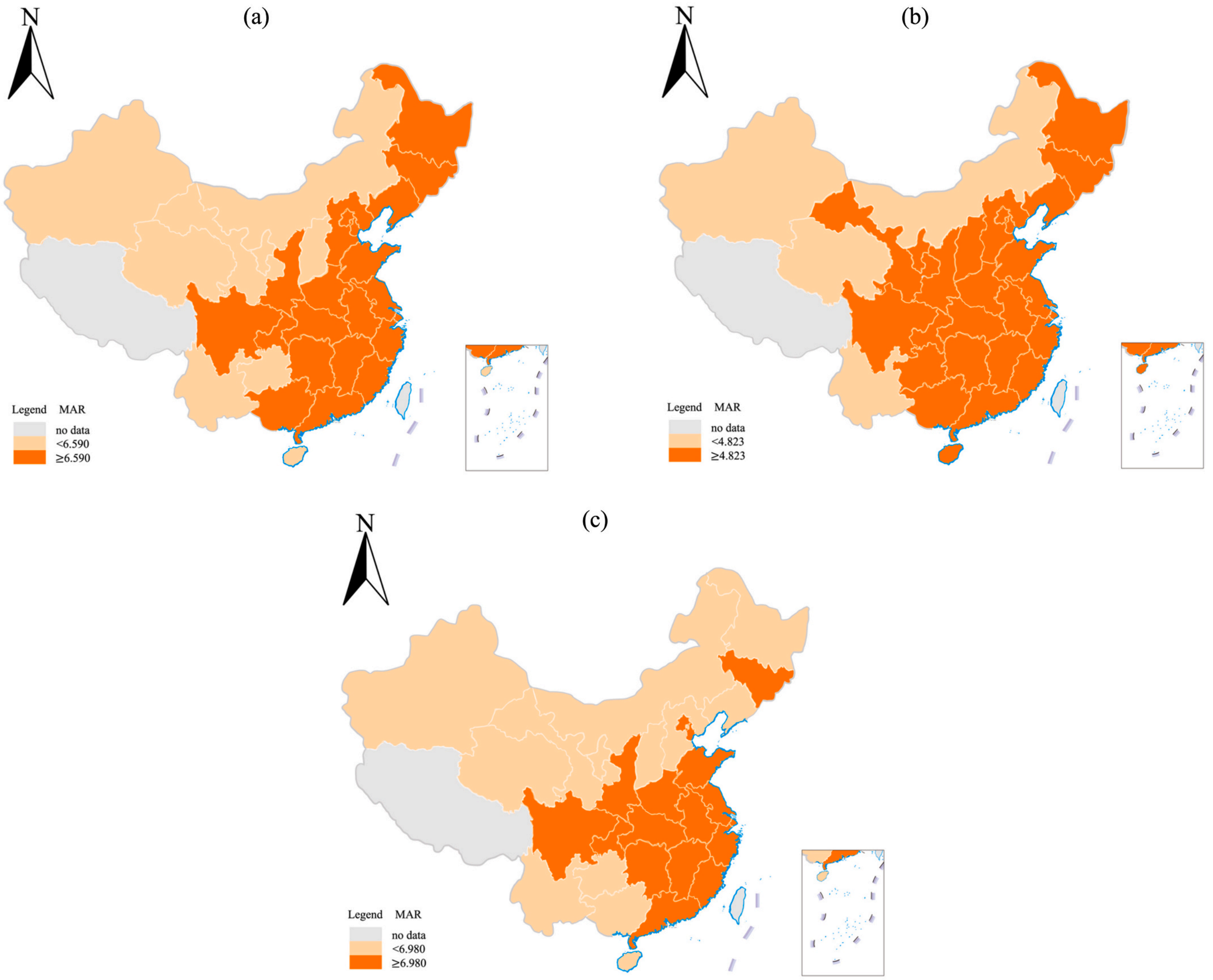

Fig. 5. The spatial distribution of marketization under the regulation of (a)command-and-control environmental policy, (b)market-incentive environmental policy, and (c)voluntary environmental policy.
Note: The provinces with the darker color represent that the stringency for the environmental policy instrument falls into the optimal range for the growth of the total factor energy-environmental efficiency.

evolution results indicate a significant growth in the energy-environmental efficiency which could be jointly explained by technical efficiency improvement and technological progress, but the overall level is rather low. Moreover, the average levels of energy-environmental efficiency for the metal products sector, nonferrous metals sector, and ferrous metals sector decrease in order with each of them showing a dynamic rising trend. From a spatial perspective, the energy-environmental efficiency of the eastern provinces is considerably higher than that of the central and western provinces, diametrically opposite to the distribution pattern of its dynamic growth rate, and this spatial distribution characteristic also holds for sub-sectors. The regression results based on dynamic panel threshold models show that the "strong" version of the Porter Hypothesis is supported by the evidence that each kind of environmental policy instrument induces TFEEE growth with different constraints on its stringency, and the stimulation effect driven by VEP is much stronger than that motivated by MEP, which is more efficient than that caused by CEP. In addition, higher marketization is found to be conducive to triggering and reinforcing the facilitation effect of heterogeneous environmental policy instruments on the TFEEE but with different threshold values of marketization, which decrease sequentially corresponding to VEP, CEP, and MEP, reflecting their sensitivity to market changes.

This study correspondingly derives several policy implications from the above findings. First, it's essential for the Chinese government to consider the differences among metal sub-sectors and regions when formulating policies. As each metal sub-sector has special characteristics, in-depth and long-term investigations on the operational and environmental circumstances at the sector and firm level are required. Regarding the metal sector located in the eastern region, the government should emphasize how to give full play to the location advantages. While the utilization of second-mover advantage will be the biggest breach for the green transformation of the metal sector located in the central and western regions. Meanwhile, to prevent a pollution paradise effect, the excessive pollution transfer from the eastern region should be strictly constrained.

Second, policymakers are required to consider not only the policy stringency but also the instrument design. Concerning the policy intensity, the eastern provinces could generally maintain the existing stringencies, which in the central and western provinces should be rationally strengthened based on the corresponding threshold values of heterogeneous instruments. The policy structure should be adjusted by weakening the dominance of CEP and attaching more importance to MEP and VEP. For instance, the legislation and pilot of the carbon tax could be expedited by drawing on foreign experiences as well as China's unique conditions, and it is also necessary to consummate the supporting system for environmental information disclosure. Additionally, a mix of instruments requiring sophisticated top-level design is another way to break through the dilemma of low energy-environmental efficiency.

Third, China should speed up market reform and adopt policy instruments compatible with local marketization. To avoid a Matthew effect, it is crucial for the western region to shape its new development momentum through cooperation with the eastern region, in which the western region cultivates characteristic industries based on its resource endowment while the eastern region provides financial and technological support. Given the geographical differences in marketization processes and the successively decreasing threshold values corresponding to VEP, CEP, and MEP, the central and western regions could mainly implement CEP and MEP, and greater focus should be placed on the development of VEP in the eastern region so that the combination of policy and the market could perform optimally.

CRediT authorship contribution statement

Shuangmei Li: Conceptualization, Methodology, Data curation, Software, Validation, Visualization, Writing – original draft. **Xuehong Zhu:** Supervision, Validation, Writing – review & editing. **Tao Zhang:** Conceptualization, Supervision, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no competing interests.

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Appendix A. Appendix

A.1. Super-efficiency SBM-DEA

Referring to Tone (2002), we suppose there're n decision-making units (DMUs), DMU_j ($j=1, 2, \cdots$, n) and m inputs for each DMU, x_i ($i=1, 2, \cdots$,m). y_k^g (k $=1, 2, \cdots, q_1$) denotes the expected outputs, and the undesired outputs are represented by y_l^b (l $=1, 2, \cdots, q_2$). We construct the model as follows.

$$\begin{aligned}
\rho = min&\frac{1+\dfrac{1}{m}\sum\limits_{i=1}^{m}\dfrac{s_i^-}{x_{io}}}{1-\dfrac{1}{q_1+q_2}\left(\sum\limits_{k=1}^{q_1}\dfrac{s_k^g}{y_{ko}^g}+\sum\limits_{l=1}^{q_2}\dfrac{s_l^b}{y_{lo}^b}\right)}\\
&s.t.x_{io} \geq \sum_{j=1,\neq o}^{n}\lambda_j x_{ij}-s_i^-, \forall i;\\
&y_{ko}^g \leq \sum_{j=1,\neq o}^{n}\lambda_j y_{kj}^g+s_k^g, \forall k;\\
&y_{lo}^b \geq \sum_{j=1,\neq o}^{n}\lambda_j y_{lj}^b-s_l^b, \forall l;\\
&1-\frac{1}{q_1+q_2}\left(\sum_{k=1}^{q_1}\frac{s_k^g}{y_{ko}^g}+\sum_{l=1}^{q_2}\frac{s_l^b}{y_{lo}^b}\right)>0;\\
&s_i^- \geq 0, s_k^g \geq 0, s_l^b \geq 0, \lambda_j \geq 0, \forall i, k, l, j
\end{aligned} \tag{2}$$

Energy-environmental efficiency is demonstrated by ρ in formula (2); s_k^g, s_i^-, and s_l^b are the lack of good outputs, the surplus in inputs and bad outputs, respectively; the λ indicates the weight of the input and output; the subscript o represents the DMU being estimation. If $\rho \geq 1$, the energy-environmental efficiency in the given year is in an ideal situation.

A.2. GML index

Following Oh (2010), the global direction distance function $D^G(x, y, b)$ and the global production possibility P^G are utilized to construct the GML index, which could be described as follows:

$$P^G = P^1 \cup P^2 \cup \cdots \cup P^T \tag{3}$$

$$\overrightarrow{D^G}\left(x, y^g, y^b; g_y, g_b\right) = max\left\{\beta \middle| \left(y^g+\beta g_y, y^b-\beta g_b\right) \in P^G(x)\right\} \tag{4}$$

$P^t(t=1, \cdots, \text{T})$ is a production possibility set at a specific time t. g $=(g_y, -g_b)$ is a direction vector indicating the direction of expected output and bad output, and β denotes a ratio that could be maximized by boosting expected outputs while reducing bad outputs. On this basis, the GML index along with its decompositions from period t to t + 1 is defined as eq. (5).

$$
\begin{aligned}
GML_0^{t,t+1} &= \frac{1+\overrightarrow{D^G}\left(x_0^t, y_0^{gt}, y_0^{bt}; g_0^t\right)}{1+\overrightarrow{D^G}\left(x_0^{t+1}, y_0^{g(t+1)}, y_0^{b(t+1)}; g_0^{t+1}\right)} \\
&= \frac{1+\overrightarrow{D}\left(x_0^t, y_0^{gt}, y_0^{bt}; g_0^t\right)}{1+\overrightarrow{D}\left(x_0^{t+1}, y_0^{g(t+1)}, y_0^{b(t+1)}; g_0^{t+1}\right)} \times \left[\frac{1+\overrightarrow{D^G}\left(x_0^t, y_0^{gt}, y_0^{bt}; g_0^t\right)}{1+\overrightarrow{D}\left(x_0^t, y_0^{gt}, y_0^{bt}; g_0^t\right)} \Bigg/ \frac{1+\overrightarrow{D^G}\left(x_0^{t+1}, y_0^{g(t+1)}, y_0^{b(t+1)}; g_0^{t+1}\right)}{1+\overrightarrow{D}\left(x_0^{t+1}, y_0^{g(t+1)}, y_0^{b(t+1)}; g_0^{t+1}\right)}\right] \\
&= \mathrm{GTECH} \times \mathrm{GTPCH}
\end{aligned}
\tag{5}
$$

GTECH and GTPCH correspond to the technological efficiency changes and technological progress changes. The energy-environmental efficiency is rising, steady, or declining between two periods if the GML index is higher than, equal to, or lower than 1.

Table A1
Description of variables.

Variable	N	Unit	Mean	Std. Dev.	Min	Max
lnTFEEE	2002	–	1.071	0.318	0.601	1.781
lnCEP	2002	–	−0.252	0.298	−0.997	−0.004
lnMEP	2002	–	0.302	0.368	0.000	1.247
lnVEP	2002	–	0.278	0.140	0.017	0.633
lnMAR	2002	–	1.952	0.241	1.497	2.373
lnTI	2002	10^4 pieces	1.083	0.839	0.093	2.988
lnFDI	2002	–	0.276	0.199	0.074	0.783
lnIP	2002	10^{11} yuan	0.030	0.041	−0.001	0.147
lnIS	2002	10^4 individuals	0.675	0.491	0.054	1.717
lnEPU	2002	–	1.105	0.457	0.550	2.153

Table A2
The energy-environmental efficiency, global Malmquist-Luenberger index, and its decomposition of the overall metal sector and its sub-sectors every year.

Year	The overall metal sector				The ferrous metals sector			
	EEE	GML	GTECH	GTPCH	EEE	GML	GTECH	GTPCH
2006	0.1157	1.2131	0.7690	1.6505	0.0739	1.0613	0.6308	1.7414
2007	0.1388	1.2347	1.1192	1.1703	0.0906	1.2506	1.0881	1.1508
2008	0.1432	1.1093	1.1946	0.9703	0.1059	1.2477	1.3102	0.9576
2009	0.1507	1.0809	1.2099	0.9392	0.1006	0.9915	1.0576	0.9420
2010	0.1631	1.1104	0.7680	1.4905	0.1154	1.1631	0.8002	1.4404
2011	0.1999	1.2654	1.2220	1.1190	0.1384	1.2151	1.0365	1.1705
2012	0.2018	1.0396	1.2682	0.8844	0.1296	0.9903	1.1504	0.8756
2013	0.2139	1.1711	1.1651	1.0533	0.1443	1.1762	1.1609	1.0836
2014	0.2452	1.1289	1.3327	0.8882	0.1669	1.1177	1.3928	0.8086
2015	0.2353	0.9599	0.8265	1.1615	0.1474	0.9673	0.8628	1.2173
2016	0.2522	1.0827	0.8909	1.2778	0.1611	1.0611	0.8613	1.3325
2017	0.2347	0.9306	1.1354	0.8196	0.1652	1.0837	1.5701	0.7421
2018	0.2301	1.0024	0.8932	1.1248	0.1708	1.0668	0.9234	1.1456
2019	0.2315	1.0859	1.1424	0.9665	0.1848	1.1568	1.1758	0.9854
average	0.1969	1.1011	1.0669	1.1083	0.1354	1.1107	1.0729	1.1138

Year	The nonferrous metals sector				The metal products sector			
	EEE	GML	GTECH	GTPCH	EEE	GML	GTECH	GTPCH
2006	0.1430	1.4119	0.9269	1.6125	0.1421	1.1343	0.7468	1.5378
2007	0.1684	1.1973	1.1590	1.1654	0.1731	1.2756	1.1282	1.2087
2008	0.1555	0.9501	1.0101	1.0263	0.1895	1.1570	1.3324	0.9019
2009	0.1569	1.0398	1.1532	0.9479	0.2344	1.3426	1.6320	0.9137
2010	0.1770	1.1085	0.7848	1.4619	0.2268	1.0156	0.6775	1.6427
2011	0.2297	1.3563	1.3717	1.1070	0.2587	1.1925	1.3107	1.0305
2012	0.2443	1.0804	1.3338	0.9158	0.2621	1.0699	1.3880	0.8430
2013	0.2389	1.1519	1.1588	1.0375	0.3017	1.2147	1.2100	1.0206
2014	0.2744	1.1490	1.3408	0.9176	0.3449	1.1312	1.1803	1.0070
2015	0.2515	1.0187	0.9480	1.1302	0.3758	1.1717	1.1626	1.0738
2016	0.2750	1.1346	0.9153	1.2658	0.3865	1.0319	0.8987	1.2163
2017	0.2566	0.9586	1.2273	0.8377	0.3471	0.9609	1.0453	0.9418
2018	0.2444	0.9769	0.8767	1.1247	0.3052	0.8972	0.8434	1.0823
2019	0.2316	1.0344	1.1023	0.9673	0.3086	1.0526	1.1635	0.9276
average	0.2177	1.1120	1.0935	1.1084	0.2755	1.1177	1.1228	1.0962

Note: EEE denotes the energy-environmental efficiency.

Table A3
The energy-environmental efficiency, global Malmquist-Luenberger index of the overall metal sector and its sub-sectors for every province.

Province	The overall metal sector				The ferrous metals sector			
	EEE	GML	GTECH	GTPCH	EEE	GML	GTECH	GTPCH
Anhui	0.2868	1.0930	1.0484	1.1068	0.1268	1.1045	1.0435	1.0985
Beijing	0.4406	1.3488	1.2970	1.1676	0.3598	1.5742	1.5741	1.2397
Fujian	0.2580	1.1235	1.1127	1.0919	0.1889	1.1042	1.0569	1.1047
Gansu	0.1337	1.1057	1.0663	1.1186	0.0833	1.0623	1.0293	1.1618
Guangdong	0.2425	1.0811	1.0323	1.0888	0.1698	1.0619	1.0054	1.0989
Guangxi	0.1629	1.0929	1.0431	1.0877	0.1447	1.0813	1.0383	1.0887
Guizhou	0.1343	1.1784	1.1373	1.0904	0.1415	1.1919	1.1523	1.0920
Hainan	0.1774	1.1236	1.1560	1.1626	0.0946	1.1265	1.0732	1.1004
Hebei	0.1746	1.0635	1.0130	1.0968	0.1266	1.0471	1.0003	1.0962
Henan	0.1916	1.0634	1.0132	1.0965	0.1378	1.0954	1.0491	1.0971
Heilongjiang	0.0997	1.1484	1.1138	1.0893	0.0963	1.1204	1.1048	1.0888
Hubei	0.1908	1.0972	1.0468	1.0904	0.1430	1.0724	1.0333	1.0894
Hunan	0.1688	1.0914	1.0435	1.0891	0.1283	1.0773	1.0292	1.0866
Jilin	0.1231	1.0879	1.0254	1.0896	0.0990	1.0542	1.0079	1.0940
Jiangsu	0.2997	1.0728	1.0599	1.1404	0.1533	1.0608	1.0096	1.1841
Jiangxi	0.2818	1.1140	1.0874	1.0956	0.1318	1.0985	1.0598	1.0943
Liaoning	0.1343	1.0684	1.0448	1.0902	0.1073	1.0854	1.0550	1.0932
Inner Mongolia	0.1881	1.1233	1.1456	1.1076	0.1077	1.0455	1.0104	1.0974
Ningxia	0.1117	1.0850	1.0429	1.0924	0.0823	1.1073	1.0770	1.0830
Qinghai	0.1063	1.1388	1.1941	1.1098	0.0651	1.0838	1.0354	1.0888
Shandong	0.2467	1.0539	1.0386	1.1206	0.1146	1.0533	1.0013	1.0951
Shanxi	0.0779	1.1186	1.0708	1.0853	0.0817	1.0549	1.0038	1.0881
Shaanxi	0.2622	1.1511	1.2161	1.1253	0.2025	1.1412	1.1153	1.1003
Shanghai	0.2744	1.1669	1.2596	1.2785	0.3274	1.3337	1.4989	1.6589
Sichuan	0.1379	1.0869	1.0430	1.0913	0.0932	1.0762	1.0418	1.0873
Tianjin	0.4156	1.0823	1.0392	1.1027	0.1893	1.0801	1.0372	1.1073
Xinjiang	0.0931	1.0897	1.0727	1.1037	0.0806	1.0547	1.0101	1.0965
Yunnan	0.1396	1.1311	1.0934	1.0913	0.0853	1.1282	1.0959	1.0998
Zhejiang	0.2947	1.0404	0.9891	1.0975	0.1615	1.0375	0.9772	1.0921
Chongqing	0.1905	1.1869	1.2353	1.1216	0.0856	1.1677	1.1296	1.0859

Province	The nonferrous metals sector				The metal products sector			
	EEE	GML	GTECH	GTPCH	EEE	GML	GTECH	GTPCH
Anhui	0.3836	1.1103	1.0381	1.1059	0.4133	1.0354	1.0785	1.1250
Beijing	0.6874	1.1466	1.0036	1.1201	0.3552	1.1002	1.0364	1.0709
Fujian	0.2418	1.1450	1.1579	1.0848	0.4288	1.1192	1.1342	1.0805
Gansu	0.1170	1.1013	1.0467	1.0930	0.2679	1.2013	1.1794	1.0834
Guangdong	0.2721	1.0974	1.0522	1.0814	0.3286	1.0868	1.0465	1.0834
Guangxi	0.1305	1.0933	1.0343	1.0920	0.2640	1.1151	1.0703	1.0771
Guizhou	0.1464	1.1903	1.1443	1.0964	0.0959	1.1276	1.0932	1.0750
Hainan	0.2089	1.2192	1.3747	1.2477	0.2798	0.9266	0.8842	1.1170
Hebei	0.1521	1.0569	1.0044	1.0930	0.3154	1.1097	1.0558	1.1055
Henan	0.2208	1.0298	0.9797	1.0959	0.2408	1.0664	1.0086	1.0965
Heilongjiang	0.0721	1.1444	1.0888	1.0921	0.1617	1.2124	1.1817	1.0846
Hubei	0.1852	1.1055	1.0457	1.0929	0.2978	1.1302	1.0760	1.0874
Hunan	0.1832	1.0711	1.0168	1.0897	0.2209	1.1601	1.1253	1.0930
Jilin	0.0967	1.1043	1.0210	1.0889	0.2238	1.1227	1.0691	1.0821
Jiangsu	0.4106	1.0933	1.1356	1.1291	0.3709	1.0557	1.0092	1.0752
Jiangxi	0.3533	1.0863	1.0491	1.1030	0.4388	1.2006	1.2191	1.0836
Liaoning	0.1260	1.0785	1.0551	1.0899	0.2050	1.0142	1.0037	1.0850
Inner Mongolia	0.1858	1.1471	1.1826	1.1177	0.3534	1.2313	1.3420	1.1080
Ningxia	0.0780	1.0854	1.0255	1.1020	0.1748	1.0623	1.0263	1.0920
Qinghai	0.1244	1.0790	1.0108	1.1052	0.1525	1.3682	1.8781	1.1610
Shandong	0.2893	1.0497	1.0694	1.1564	0.4257	1.0631	1.0513	1.1001
Shanxi	0.0640	1.2076	1.1442	1.0877	0.0982	1.0680	1.0580	1.0747
Shaanxi	0.2769	1.1528	1.2677	1.1259	0.3523	1.1671	1.3147	1.1742
Shanghai	0.2403	1.1028	1.2613	1.0721	0.2554	1.0642	1.0185	1.1046
Sichuan	0.1152	1.0791	1.0229	1.0913	0.2724	1.1238	1.0853	1.0994
Tianjin	0.7629	1.0969	1.0335	1.0881	0.2946	1.0699	1.0470	1.1125
Xinjiang	0.0791	1.0723	1.0002	1.1006	0.1463	1.1945	1.3429	1.1241
Yunnan	0.1118	1.1140	1.0479	1.0986	0.3037	1.1708	1.1792	1.0595
Zhejiang	0.4267	1.0341	0.9856	1.1107	0.2972	1.0586	1.0201	1.0820
Chongqing	0.2764	1.2474	1.4336	1.1730	0.2286	1.1043	1.0500	1.0900

Note: EEE denotes the energy-environmental efficiency.

Table A4
The robustness test for the threshold values and the confidence intervals of the stringency for heterogeneous environmental policy instruments by substituting the explained variable with the energy-environmental efficiency.

Threshold variable	Dynamic panel threshold model	Threshold value	SupWStar statistic	P-value	BS	90% confidence interval	
						Lower	Upper
CEP	SYS-GMM	0.523	2.870***	0.004	1000	0.472	0.548
MEP	SYS-GMM	0.806	3.670***	0.000	1000	0.800	0.994
VEP	SYS-GMM	0.416	4.930***	0.000	1000	0.409	0.424

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; the SupWStar statistic is used as a post-estimation to determine whether the threshold effect is significant; BS denotes the number of replications for the bootstrap procedure.

Table A5
The robustness test for the nonlinear relationship between the stringency for heterogeneous environmental policy instruments and the total factor energy-environmental efficiency by substituting the explained variable with the energy-environmental efficiency.

	(1)	(2)	(3)
Variables	lnEEE	lnEEE	lnEEE
L.lnEEE	0.881***	0.875***	0.802***
	(13.66)	(11.35)	(12.22)
lnCEP (CEP≥0.523)	−0.042		
	(−0.18)		
lnCEP (CEP<0.523)	0.855**		
	(2.03)		
lnMEP (MEP≤0.806)		1.188**	
		(2.58)	
lnMEP (MEP>0.806)		0.130	
		(0.31)	
lnVEP (VEP≤0.416)			1.758***
			(3.36)
lnVEP (VEP>0.416)			1.050***
			(2.91)
Control variables	Y	Y	Y
AR(2)	−0.262	0.118	0.093
	[0.794]	[0.906]	[0.926]
Sargan test	71.742	9.181	81.721
	[0.106]	[0.164]	[0.203]
Observations	1859	1859	1859

Notes: The prefix "ln" before variables denotes the logarithm of the variable adding one; EEE denotes the energy-environmental efficiency; lnCEP is the opposite number of the logarithm of CEP adding one; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, correspondingly. Figures in () are the z-values of the coefficients, and those in [] are the p-values of the statistics of relevant tests.

Table A6
The robustness test for the threshold values and the confidence intervals of marketization by substituting the explained variable with the energy-environmental efficiency.

Threshold variable	Dynamic panel threshold model	Threshold value	SupWStar statistic	P-value	BS	90% confidence interval	
						Lower	Upper
MAR(under CEP)	SYS-GMM	6.590	3.860***	0.000	1000	6.480	6.590
MAR(under MEP)	SYS-GMM	4.814	3.300***	0.001	1000	4.814	4.950
MAR(under VEP)	SYS-GMM	7.160	3.020***	0.003	1000	6.918	7.237

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively; the SupWStar statistic is used as a post-estimation to determine whether the threshold effect is significant; BS denotes the number of replications for the bootstrap procedure.

Table A7
The robustness test for the threshold effects of marketization on the relationship between heterogeneous environmental policy instruments and the total factor energy-environmental efficiency by substituting the explained variable with the energy-environmental efficiency.

	(1)	(2)	(3)
Variables	lnEEE	lnEEE	lnEEE
L.lnEEE	0.856***	0.720***	0.676***
	(9.90)	(7.75)	(6.42)
lnCEP(MAR≤6.590)	−0.022		
	(−0.13)		

(*continued on next page*)

Table A7 (*continued*)

Variables	(1) lnEEE	(2) lnEEE	(3) lnEEE
lnCEP MAR>6.590)	1.040** (2.13)		
lnMEP(MAR≤4.814)		1.118 (1.39)	
lnMEP(MAR>4.814)		1.240** (2.00)	
lnVEP(MAR≤7.160)			0.861** (1.98)
lnVEP(MAR>7.160)			1.646*** (2.60)
Control variables	Y	Y	Y
AR(2)	−0.051 [0.960]	0.163 [0.871]	0.063 [0.950]
Sargan test	62.063 [0.185]	29.636 [0.331]	33.401 [0.151]
Observations	1859	1859	1859

Notes: The prefix “ln” before variables denotes the logarithm of the variable adding one; EEE denotes the energy-environmental efficiency; lnCEP is the opposite number of the logarithm of CEP adding one; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, correspondingly. Figures in () are the z-values of the coefficients, and those in [] are the p-values of the statistics of relevant tests.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2023.106735.

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