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Original Research

Energy Eco-Efficiency in China's Oil and Gas Resource-Based Enterprises and Its Influencing Factors: a Data Envelopment Analysis from Static and Dynamic Perspectives

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Abstract

The oil and gas industry is an important basic energy industry in China, and its development is closely related to the improvement of comprehensive national power and quality of life. However, it is also a high energy consumption and high pollution industry, and the continuous input of various energy sources is often accompanied by damage to the surrounding environment. Therefore, it is important to evaluate the energy eco-efficiency of oil and gas enterprises for sustainable economic and social development. Based on both static and dynamic perspectives, this paper measures the energy eco-efficiency of 60 listed oil and gas resource-based companies from 2011-2019 using the SBM model and the Malmquist-Luenberger (ML) index model. The Tobit model is constructed to explore the influencing factors of energy eco-efficiency. The results show that the energy eco-efficiency of oil and gas resource-based enterprises shows a trend of rising and then falling, and there is much room for improvement. Among them, the energy eco-efficiency in the western region is basically consistent with the national average; technological progress has a greater impact on the energy eco-efficiency efficiency of oil and gas resource-based enterprises, while the role of technical efficiency is not significant; economic development, enterprise scale and technological innovation are positively and significantly related to energy eco-efficiency, however, energy consumption is negatively related to energy eco-efficiency.

Keywords: oil and gas resource-based enterprises, energy eco-efficiency, SBM model, Malmquist-Luenberger index, technological progress

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Introduction

Since the reform and opening up, China's industrial economy has developed rapidly, but at the same time, the gap between the speed of economic development and the demand for resources has become more and more significant, and the environmental problems have become more serious. Since 2000, China's annual average energy consumption has been growing rapidly at a rate of more than 10%. The latest data show that the total energy consumption in China reached 5.24 billion tons of standard coal in 2021, an increase of 408% compared with 1990. The imbalance of the ecosystem caused by factors such as climate change limits sustainable development, and may even affect the security of property and life (Suwarno et al., 2021; Ekwueme, 2022) [1, 2], so people are beginning to realize that the by-products produced during energy use are seriously damaging the ecological environment. Oil and natural gas are the basic energy and important chemical raw materials for the development of modern society and are directly related to the development of China's national economy. According to the National Bureau of Statistics, there are more than three thousand oil and gas resource-based enterprises among industrial enterprises above the scale of the industry. Oil and gas resource enterprises are an important part of China's enterprises, but they are also the industries with the most significant high energy consumption, pollution and emissions. Although the government has strengthened the regulation of resource conservation and environmental protection by raising the unit energy consumption and carbon emission standards, in the long run, the distribution of oil and gas resources and the structure of oil and gas production and consumption are seriously imbalanced, which seriously affects the energy eco-efficiency (Zhao and Dong, 2022) [3]. Since the 18th National Congress, China has attached great importance to the construction of ecological civilization, the improvement of energy eco-efficiency of oil and gas resource-based enterprises has played a decisive role in the improvement of the overall energy eco-efficiency of the country.

Energy plays a very important role in economic development, the impact of energy use is reflected in several systems such as economic, environmental and social. Energy eco-efficiency is a key indicator to measure the level of coordinated development of energy-economy-environment, which is to bring maximum economic output with minimum energy consumption and environmental impact (Cui et al., 2022) [4]. To measure the sustainable and coordinated development of an enterprise by energy eco-efficiency, it is necessary to consider the correlation and impact among various indicators such as production, energy consumption and environmental pollution. As an important part of the national economic system, oil and gas resource-based enterprises have a significant impact on economic development, but due to the traditional single development model of most oil and gas resource-based enterprises, this makes the low energy use efficiency and pollution pressure of enterprises gradually revealed (Wang and Li, 2021) [5]. The existing studies on energy eco-efficiency analysis mainly focus on national and region-specific levels or single industry level. For example, scholars have explored the energy eco-efficiency of logistics, manufacturing and mining industries (Li et al., 2019; Wang et al., 2020; Zhang et al., 2021) [6-8]. Zhou and Ai (2019) and Guan et al. (2022) evaluated the energy eco-efficiency of interprovincial and Yellow River basins in China, respectively [9, 10]. However, as a major "producer" of pollution and an important "consumer" of energy, few scholars have explored the energy eco-efficiency at the enterprise level. Cao et al. (2013) only analyzed the development paths of enterprises to reduce emissions and increase efficiency from a theoretical level, but lacked quantitative empirical exploration [11]. Oil and gas resource-based enterprises are important enterprises to ensure national energy security and stable economic development, how is the level of energy eco-efficiency of Chinese oil and gas resource-based companies? Are there regional differences? And what are the key factors influencing their energy eco-efficiency? Clarifying these questions will help accelerate oil and gas resource-based enterprises to improve energy use efficiency, relieve ecological and environmental pressure, and promote the realization of China's green and low-carbon development.

The paper has the following main contributions. First, energy eco-efficiency is a comprehensive measure of energy use from the economic, environmental and social system levels, and it has more theoretical and practical values. Moreover, considering the important development status of oil and gas resource-based enterprises, this paper takes Chinese 60 listed oil and gas resource-based enterprises as research objects and constructs a suitable evaluation index system from a micro perspective to evaluate the static and dynamic development levels of energy eco-efficiency, which further expands the research dimension of energy eco-efficiency. Second, in terms of energy eco-efficiency impact factor analysis, differing from the selection of impact factors at the national or city group level, this paper combines the development characteristics of Chinese oil and gas resource-based enterprises to analyze the impact factors of energy eco-efficiency from four dimensions, including economic development, enterprise size, technological Innovation and energy consumption. This helps to optimize the production and operation of oil and gas resource-based enterprises more flexibly and improve the level of energy eco-efficiency.

Energy eco-efficiency is the ratio of energy input to effective economic industry considering ecological factors, which takes into account the economic and ecological benefits in production activities and requires the maximum economic output with the minimum energy input and environmental input. Energy eco-efficiency is the unification of energy efficiency and eco-efficiency, which can express the total factor production efficiency more effectively and scientifically. The current research on energy eco-efficiency focuses on two aspects, which are evaluation methods and influencing factors.

The measurement methods of energy eco-efficiency mainly include single-factor energy eco-efficiency and full-factor energy eco-efficiency. The single-factor approach only considers the relationship between individual outputs and energy inputs of an economy. The full-factor approach considers the relationship between multiple outputs (including environmental pollution) and all factor inputs, which can measure energy efficiency more comprehensively and has been widely recognized and used. The data envelope approach (DEA), which allows flexible adjustment of input-output indicators, is a typical current method for measuring total factor energy efficiency. For example, Wu and Li (2016) combined the common frontier theory and DEA method to measure the total factor energy efficiency of the middle reaches of Yangtze River urban agglomeration and analyze and compare regional differences [12]; Liu (2019) applied the DEA method to measure and evaluate the total factor energy efficiency at the G20 country level in China. To overcome the problem of inaccurate results due to radiality and perspective [13], Tone (2004a) proposed the SBM model that considers slack variables and deals with non-expected outputs [14]. Li et al. (2019) used the SBM model to study energy eco-efficiency in various industries [6]; Tian (2020) et al. used the common frontier dynamic SBM model with non-expected outputs and Tobit regression analysis to comprehensively analyze the energy efficiency and its changes in the three major urban agglomerations [15]. The Malmquist index is commonly used to measure dynamic efficiency, but it cannot handle "bad" output. To solve the above problem, Chung et al. (1995a) proposed the Malmquist-Luenberger (ML) productivity index based on DDF, which has been widely used [16]. Lu et al. (2019) used the ML index to measure the green productivity of tourism in the Yangtze River Economic Zone and found that technological progress contributed to the increase in green productivity [17]; Tachega (2021) et al. used the DEA-SMB method to assess energy efficiency and the Malmquist productivity index method to estimate energy productivity [18].

About the study on the factors influencing energy eco-efficiency, Yu (2016) et al. argued that technological progress can improve eco-efficiency in China's paper industry [19]; Ren (2016) et al. explored the regional heterogeneity of the effects of different types of environmental regulations on eco-efficiency in different regions of China [20]; Chen (2016) and Elliott (2017) explored the provincial and national levels, respectively there is a negative relationship between urbanization and eco-efficiency [21, 22]; Wu et al. (2016) argued that the expansion of economic scale is a favorable condition for improving regional eco-efficiency [23]; Sun (2020) argued that the improvement of energy eco-efficiency depends on efficiency improvement and requires adequate adjustment of industrial structure and the role of transportation infrastructure [24]; Li (2021) used Tobit model to test the effect of energy consumption structure and industrial structure have inhibitory effects on energy eco-efficiency [25].

Much research have been done on energy eco-efficiency, and some valuable results have been obtained, but there are also places for improvement. On the one hand, existing studies have mainly considered economic environmental factors and evaluated eco-efficiency or energy and environmental efficiency at the national or specific regional level, lacking systematic studies on energy eco-efficiency at the micro-enterprise level. On the other hand, energy plays an important strategic position in the national economic development. Energy and environmental problems have become a common challenge for human society, but few studies have focused on energy eco-efficiency studies with oil and gas resource-based enterprises. Therefore, this paper takes Chinese 60 listed oil and gas resource-based enterprises as research objects. Firstly, DEA-SBM model and Malmquist-Luenberger index model are constructed to evaluate the energy eco-efficiency level from two dimensions: static and dynamic. Secondly, a Tobit regression model is constructed to analyze the influencing factors of energy eco-efficiency. This study helps to provide a theoretical basis and practical reference for improving the energy eco-efficiency of oil and gas resource-based enterprises.

Material and Methods

DEA-SBM Model

In the actual production process, the changes of input and output factors are often flexible, and the output of each factor does not follow the same proportional changes of the input, so the non-radial model is often more meaningful when measuring the efficiency of the decision-making unit (DMU) (Wang and Yuan, 2019) [26]. At the same time, the angle of change of output is not always in the same direction when non-desired output is considered. Theoretically, it is often better to have more desired output and less undesired output. In order to solve the realistic problem of non-radial non-angle in efficiency measurement, Tone (2004) proposed a DEA-SBM model based on slack variables, which is beneficial for enterprises to solve the efficiency evaluation of DMUs considering non-desired outputs, which fits with this paper to study static energy eco-efficiency. The model is expressed as follows [14].

$$\rho = min \frac{1 - \frac{1}{N}\sum_{n=1}^{N} S_n^x / x_{k'n}^{t'}}{1 + \frac{1}{M+1}(\sum_{m=1}^{M} S_m^y / y_{k'm}^{t'} + \sum_{I=1}^{I} S_t^b / b_{k't}^{t'})}$$
$$\sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t x_{kn}^t + s_n^x = x_{k'n}^{t'}, n = 1, \ldots N$$
$$\sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t y_{km}^t - s_m^y = y_{k'm}^{t'}, m = 1, \ldots M$$
$$\sum_{t=1}^{T}\sum_{k=1}^{K} z_k^t b_i^t + s_i^b = b_{k'i}^{t'}, i = 1, \ldots I$$
$$Z_k^t \geq 0$$
$$S_n^x \geq 0$$
$$S_m^y \geq 0$$
$$S_i^b \geq 0$$
$$k = 1, \ldots, K \quad (1)$$

where ρ(0≤ρ≤1) is the target efficiency value of the decision unit, ρ = 1 indicates that the DMU is effective, ρ<1 indicates the efficiency loss, and the closer its value to 0 means the greater the loss of efficiency and the greater the room for improvement. z^t_k is the weight coefficient, *N* is the number of factor inputs, *M* and *I* represent the number of desired and non-desired outputs, respectively; s^x_n, s^y_n, and s^p_i denote the slack variables for input elements, desired and undesired outputs, respectively, which are monotonically decreasing. $x^{t'}_{k'n}$, $y^{t'}_{k'm}$ and $b^{t'}_{k'i}$ represent the input, desired and undesired outputs for the decision unit k at time point t.

Malmquist-Luenberger Index Model

Static energy eco-efficiency considering non-desired outputs reflects the degree of efficient use of input factors in DMUs at a specific time point and current technological capacity. To understand the variation of DMU efficiency over a certain period of time, to find out the reasons for efficiency changes, and to measure the space for efficiency growth, it is necessary to use dynamic efficiency evaluation (Chen et al., 2022) [27]. Dynamic efficiency is also known as total factor productivity (TFP) or the rate of technological progress. It reflects the trend of static efficiency of the decision unit over time and is used to analyze the progress of production technology capabilities. A more mature and widely used efficiency index method is the DEA-Malmquist index. It does not need to preset a specific production function, has no strict requirements on the dimensionality of data, and can accommodate more different types of input-output indicators (Li and Jing, 2021a; Li et al., 2022) [28, 29]. Moreover, the index can be further decomposed into EC and TC, so as to make more reasonable judgments and explanations on the intrinsic causes of efficiency progress and propose more targeted improvement measures. However, the traditional Malmquist does not consider non-desired outputs, Chung et al., (1995b) combined the directional distance function with Malmquist and proposed the Malmquist-Luenberger index (ML) model for addressing non-desired outputs [6].

$$ML_t^{t+1} = \frac{1+\vec{D}_0^t(x^t,y^t,b^t;y^t,-b^t)}{1+\overrightarrow{D_0^t}(x^{t+1},y^{t+1},b^{t+1};y^{t+1},-b^{t+1})} \times \frac{1+\vec{D}_0^{t+1}(x^t,y^t,b^t;y^t,-b^t)}{1+\overrightarrow{D_0^{t+1}}(x^{t+1},y^{t+1},b^{t+1};y^{t+1},-b^{t+1})} \quad (2)$$

In equation (2), the directional distance function is $g^t = (y^t - b^t)$, and the non-desired output y^t is in a free state, while the non-desired output b^t is in a weak disposition. If ML>1, the green growth efficiency is in the growth state; if ML<1, the green growth efficiency is decreasing; if ML = 1, the green growth efficiency is in a more stable state. the ML index is decomposed into technical change index (EFFch) and technical progress index (TEch), and their numerical judgment criteria are the same as ML index. The expressions are as follows.

$$ML_t^{t+1} = EFFch \times TEch \quad (3)$$

$$EEFch_t^{t+1} = \frac{1+\vec{D}_0^t(x^t,y^t,b^t;y^t,-b^t)}{1+\overrightarrow{D_0^{t+1}}(x^{t+1},y^{t+1},b^{t+1};y^{t+1},-b^{t+1})} \quad (4)$$

$$TEch_t^{t+1} = \{\frac{1+\vec{D}_0^{t+1}(x^t,y^t,b^t;y^t,-b^t)}{1+\overrightarrow{D_0^t}(x^t,y^t,b^t;y^t,-b^t)} \times \frac{1+\vec{D}_0^{t+1}(x^{t+1},y^{t+1},b^{t+1};y^{t+1},-b^{t+1})}{1+\overrightarrow{D_0^t}(x^{t+1},y^{t+1},b^{t+1};y^{t+1},-b^{t+1})}\}1/2 \quad (5)$$

Tobit Regression Model

In order to measure the degree of influence of different factors on the energy eco-efficiency of oil and gas resource-based enterprises, a regression model was constructed. The SBM model produces efficiency values between 0 and 1. If the least squares method is used, the data will be incomplete and thus the measurement will be biased, so the Tobit model is used for the analysis (Li and Jing, 2021b) [18]. In this paper, a Tobit regression model is chosen, where y_i represents the value of the energy ecological index of the firm i, β_0 is the constant term, β_1, β_2, β_3, ..., β_n is the coefficient to be estimated for the equation, the explanatory variable is x_n, and the error term is μ_i.

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n + \mu_i \quad (6)$$

Indicator Acquisition

Energy eco-efficiency. The design of energy eco-efficiency indicators for oil and gas resource-based enterprises is based on the theory of circular economy and sustainable development, with the reduction of waste and resource input and the improvement of energy utilization efficiency as the goal. Every step of energy development, transportation and utilization is dependent on the support of capital and labor. Therefore, combining with the existing research results (Chen et al., 2021) [30], this paper selects energy, labor, capital as input indicators, and divides the output indicators into desired and undesired outputs to establish an energy eco-efficiency model.

According to Wang and Dai (2014), Feng and Zang (2020) [31, 32], total assets are the total amount of current assets and current assets. Oil and gas resource-based enterprises need to maintain a certain amount of monetary capital and various production equipment in the process of operation, so the level of assets is an important component of the normal operation of the enterprise, total assets are treated as capital input in this paper. Employee wages are the various salaries paid to employees by enterprises according to relevant regulations, reflecting the labor input of enterprises, this is consistent with the index chosen by Wang et al. (2021) [33]. With reference to Xia and Wang (2019), electricity consumption is the main component of energy consumption in the production activities of companies [34]. Therefore, considering the availability of data, industrial electricity consumption is taken as the energy input in this paper. Total industrial output value is the total amount of industrial products produced or sold by industrial enterprises in a certain period in monetary terms, which reflects the output level of industrial production activities in a certain period, so the total industrial output value is taken as the expected output (Chen et al., 2021) [35]. Undesired outputs are the substances that accompany economic outputs and have adverse effects on the ecological environment. For oil and gas resource-based enterprises, undesired output refers to the waste gas, waste water, and waste residue produced by the enterprises in the production process (Fang et al., 2017; Xu and Zhao, 2020) [36, 37].

Energy eco-efficiency is an indicator that integrates both economic and environmental factors, and it is closely related to the economic level, social development, ecological environment, and scientific and technological innovation (Zhao and Liu, 2020; Li et al., 2021) [38, 39]. Therefore, in order to further study the influencing factors of energy eco-efficiency, this paper mainly discusses the influencing factors of energy eco-efficiency of oil and gas resource-based enterprises from four aspects: the level of economic development, the scale of enterprises, the level of scientific and technological innovation and the degree of energy consumption.

Economic development (ED). According to the environmental Kuznets theory, there is a dynamic game between economic growth and environmental development, which will have an impact on the energy eco-efficiency of enterprises. In the existing studies, it has been shown that economic development drives corporate eco-efficiency (Yang and Zhang, 2017; Chen and Su, 2018) [40, 41]. GDP per capita can eliminate the influence of population size on economic development, drawing on Xu and Cui (2021), GDP per capita is chosen to measure the level of economic development in this paper [42].

Enterprise size (ES). The larger the firm, the more attention it receives from the public and the media. In order to prevent the negative effects of excessive pollutant emissions, companies will take energy-saving and environmental protection measures to obtain to maintain their good reputation (Wang et al., 2021) [43]. This paper represents ES by total assets at the end of the year. From the available studies, its effect on energy eco-efficiency is generally positive (Han and Li, 2014) [44].

Technological Innovation (TEI). Technological innovation can improve the production technology of enterprises, reduce their costs, and also enhance their ability to prevent pollution. In general, the effect of technological innovation on efficiency enhancement and eco-improvement is positive and effective (Feng and Zang, 2020) [32]. Referring to Zhang et al. (2017) [45], the ratio of R&D expenditure to total enterprise expenditure is used to measure the level of technological innovation.

Energy consumption (EC). Energy consumption is an important factor contributing to pollutant generation. The development of production and business activities in enterprises requires the consumption of large amounts of electricity and other fossil energy sources, which may have a significant negative impact on energy eco-efficiency (Yi and Liu, 2020; Chen et al., 2021) [35, 46]. In this paper, when measuring the degree of energy consumption of oil and gas resource-based enterprises, the ratio of crude oil and natural gas consumption to the total industrial integrated energy consumption is used to express.

Data Source

Oil and gas resource-based companies are energy companies whose main business is oil and gas exploration and development, production and operation services, engineering technology operation, engineering construction and oil and gas equipment manufacturing. According to the industry classification criteria of Sina Finance website and CITIC Securities, this paper selects 60 representative listed oil and gas resource-based companies, including Sinopec, PetroChina, and CNOOC. The relevant data are mainly collected from Guotaian and Wande databases, and the missing data are collated through financial reports, sustainability reports, and annual reports of oil and gas companies published on Juchao website, Hexun website, and the official websites of oil and gas companies.

Results and Discussion

Analysis of Energy Eco-Efficiency

Evaluation of Static Energy Eco-Efficiency

According to the SBM model, the static energy eco-efficiency of oil and gas resource-based enterprises is calculated using DEA-SOLVER Pro5.0 software, and the results are shown in Table 1. 2011-2019, the energy eco-efficiency of oil and gas resource-based enterprises was not high, and there is a lot of room for improvement. Since the 21st century, China's oil and gas industry has developed rapidly, with an increased share of technological investment and the continuous implementation of policies to remove production capacity, which has achieved high efficiency in resource development and utilization. However, in terms of time, only enterprise 24 and enterprise 59 have achieved DEA validity in 2019, indicating that the enterprises are of reasonable size and high technology level, and the input factors have achieved optimal output. Overall energy eco-efficiency is far below the ideal efficiency value,

Table 1. Energy eco-efficiency values of oil and gas resource-based enterprises.

Enterprise number	2011	2012	2013	2014	2015	2016	2017	2018	2019	Mean value
1	1.000	0.851	0.793	1.000	0.634	0.612	0.500	0.464	0.589	0.716
2	1.000	1.000	1.000	0.795	0.683	0.579	0.624	0.479	0.483	0.738
3	0.522	0.672	0.491	0.672	0.620	0.684	0.632	0.611	0.585	0.610
4	0.296	0.304	0.291	0.275	0.317	0.285	0.280	0.259	0.239	0.283
5	0.226	0.236	0.235	0.234	0.223	0.225	0.343	0.333	0.317	0.264
6	0.305	0.304	0.331	0.330	0.326	0.343	0.348	0.331	0.325	0.327
7	0.734	0.581	0.855	0.740	0.793	0.709	0.650	0.525	0.319	0.656
8	0.418	0.381	0.463	0.445	0.436	0.403	0.883	0.415	0.552	0.488
9	0.130	0.119	0.147	0.235	0.287	0.271	0.235	0.215	0.168	0.201
10	0.185	0.203	0.250	0.293	0.313	0.325	0.278	0.216	0.280	0.260
11	0.108	0.093	0.086	0.209	0.250	0.236	0.048	0.060	0.055	0.127
12	0.521	0.502	0.423	0.423	0.435	0.422	0.400	0.402	0.362	0.432
13	0.217	0.145	0.120	0.123	0.110	0.118	0.164	0.198	0.171	0.152
14	0.516	0.504	0.444	0.599	0.366	0.429	0.526	0.742	0.669	0.533
15	0.220	0.212	0.321	0.272	0.259	0.232	0.249	0.263	0.242	0.252
16	0.441	0.464	0.492	0.422	0.434	0.597	0.356	0.361	0.404	0.441
17	0.216	0.208	0.206	0.209	0.212	0.212	0.202	0.207	0.202	0.208
18	0.331	0.313	0.307	0.221	0.225	0.184	0.279	0.250	0.262	0.264
19	0.461	0.436	0.398	0.400	0.294	0.296	0.279	0.309	0.383	0.362
20	0.786	0.829	0.713	0.708	0.799	0.766	0.593	0.752	0.660	0.734
21	0.730	0.668	0.847	0.661	0.836	0.793	0.651	0.826	0.636	0.739
22	0.572	0.467	0.400	0.381	0.748	0.306	0.721	0.393	0.433	0.491
23	0.420	0.419	0.369	0.198	0.487	0.470	0.193	0.625	0.578	0.418
24	0.543	0.453	0.416	0.441	0.623	0.823	0.774	0.814	0.632	0.613
25	0.807	0.746	0.570	0.827	0.735	0.592	0.537	0.930	0.799	0.727
26	0.281	0.268	0.220	0.205	0.187	0.215	0.266	0.241	0.335	0.246
27	0.400	0.404	0.179	0.373	0.382	0.363	0.336	0.144	0.368	0.328
28	0.997	0.769	0.755	0.994	0.953	0.787	0.792	0.912	0.266	0.803
29	0.271	0.297	0.268	0.292	0.289	0.295	0.291	0.273	0.255	0.281
30	0.162	0.170	0.172	0.118	0.111	0.193	0.039	0.036	0.155	0.128
31	0.237	0.244	0.300	0.319	0.346	0.413	0.525	0.630	0.305	0.369
32	0.287	0.281	0.258	0.263	0.193	0.198	0.240	0.242	0.243	0.245
33	0.221	0.243	0.209	0.214	0.228	0.106	0.207	0.173	0.175	0.197

Table 1. Continued.

34	0.185	0.222	0.232	0.231	0.173	0.092	0.170	0.190	0.176	0.186
35	0.284	0.265	0.252	0.234	0.220	0.202	0.063	0.036	0.160	0.191
36	0.207	0.202	0.200	0.201	0.162	0.160	0.172	0.162	0.085	0.172
37	0.213	0.385	0.365	0.320	0.268	0.243	0.241	0.220	0.055	0.257
38	0.368	0.372	0.361	0.318	0.098	0.296	0.261	0.242	0.264	0.287
39	0.529	0.209	0.046	0.495	0.471	1.000	0.101	0.073	0.655	0.398
40	0.189	0.217	0.185	0.190	0.158	0.130	0.056	0.117	0.233	0.164
41	0.257	0.233	0.239	0.189	0.202	0.208	0.226	0.196	0.118	0.208
42	0.164	0.119	0.166	0.137	0.131	0.208	0.329	0.199	0.267	0.191
43	1.000	0.367	0.579	0.467	0.447	0.343	1.000	1.000	0.745	0.661
44	0.214	0.209	0.230	0.207	0.241	0.246	0.259	0.257	0.213	0.231
45	0.211	0.144	0.146	0.346	0.416	0.471	0.315	0.275	0.262	0.287
46	0.158	0.165	0.293	0.200	0.147	0.156	0.181	0.196	0.320	0.202
47	0.215	0.209	0.213	0.211	0.212	0.205	0.278	0.216	0.325	0.232
48	0.218	0.202	0.191	0.152	0.148	0.273	0.260	0.234	0.365	0.227
49	0.190	0.181	0.186	0.166	0.181	0.221	0.239	0.233	0.231	0.203
50	0.172	0.193	0.200	0.049	0.181	0.205	0.205	0.212	0.208	0.181
51	0.131	0.137	0.049	0.200	0.194	0.205	0.198	1.000	0.735	0.317
52	0.108	0.070	0.092	0.110	0.147	0.182	0.176	0.173	0.171	0.137
53	0.157	0.151	0.161	0.178	0.174	0.259	0.168	0.180	0.983	0.268
54	0.380	0.321	0.280	0.301	1.000	1.000	1.000	1.000	1.000	0.698
55	0.165	0.113	0.175	0.184	0.106	0.469	0.472	0.415	0.515	0.290
56	0.271	0.662	0.619	0.695	0.561	0.593	0.694	0.619	0.421	0.571
57	0.265	0.252	0.234	0.220	0.202	0.204	0.153	0.197	0.195	0.214
58	0.265	0.246	0.108	0.250	0.166	0.324	0.274	0.307	0.361	0.256
59	0.794	0.662	0.812	1.000	0.439	1.000	1.000	0.827	1.000	0.837
60	0.564	1.000	0.903	1.000	0.502	0.302	0.270	0.363	0.434	0.593
Mean value	0.374	0.355	0.347	0.369	0.358	0.378	0.370	0.380	0.382	—

and technical inputs and outputs cannot be proportional.

As seen in Fig. 1, the energy eco-efficiency value of oil and gas resource-based enterprises fluctuates constantly and is far below 0.5. Previously, oil and gas enterprises were only developing and would not consider the issue of oil and gas reserves, which would lead to rapid depletion of oil wells, serious waste of resources as well as serious environmental damage. Although the government has taken a series of measures to address these problems, they have not been well managed, and companies are still restricted in their development process. At the same time, the technical problems lead to the oil and gas resources cannot realize the maximum utilization value. Therefore, the efficiency of input and output utilization should be strengthened, and the technology level should be improved to promote the development of enterprises.

As can be seen from Fig. 2, from 2011 to 2019, although the energy eco-efficiency of oil and gas resource-based enterprises showed an upward trend, the growth rate was not large and the efficiency value was far below the ideal value of 1. From the regional dimension, the energy eco-efficiency of the central and eastern regions showed a slow decline, and the western region was consistent with the overall change of the country, both showing a linear upward trend, but none of the energy eco-efficiency reached 1, indicating that the energy eco-efficiency policies of each enterprise have not been effectively implemented and the green development issues have been neglected in the actual

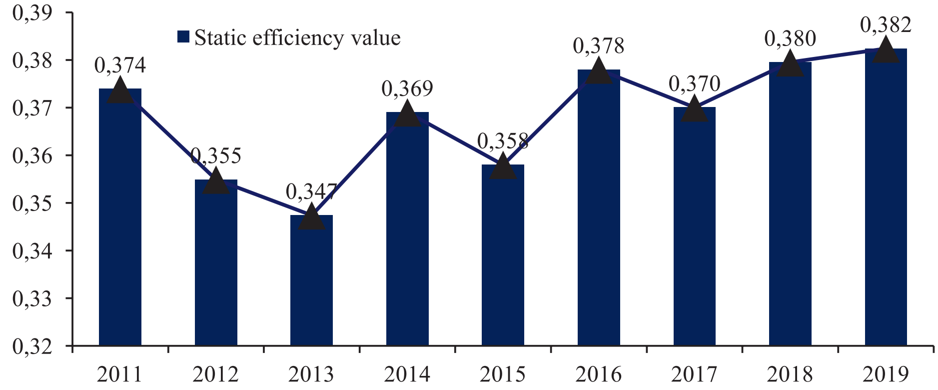

Fig. 1. Trend of static energy eco-efficiency.

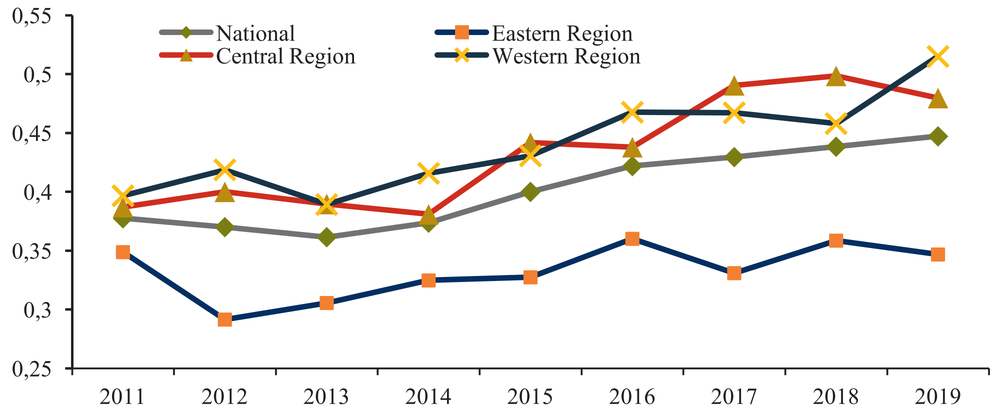

Fig. 2. Trend of static energy eco-efficiency by region.

development process. Therefore, the awareness of coordination between environment and development should be strengthened in the process of enterprise development, and green development should be implemented into actual actions to achieve coordinated development.

Evaluation of Dynamic Energy Eco-Efficiency

According to the ML index model, total factor efficiency (MI) can be decomposed into two indices: technological progress index (TC) and technological efficiency index (EC). TC represents how technological progress affects the energy eco-efficiency of enterprises; EC represents how the combination of factors such as the proficiency of technology users and market environment conditions affect energy eco-efficiency when technology remains stable. The dynamic analysis of energy eco-efficiency of 60 listed oil and gas resource-based enterprises from 2011-2019 can reflect the driving force of economic growth of oil and gas resource-based enterprises. Since total factor productivity is a dynamic evaluation of energy eco-efficiency, total factor productivity values are obtained for only 8 years in a 9-year time period. When the total factor efficiency is greater than 1, it means that the energy eco-efficiency shows a positive development trend, less than 1 indicates a decline in efficiency, and equal to 1 means that the efficiency remains unchanged.

According to Table 2, the average value of total factor productivity from 2011 to 2019 is 0.939, which indicates that enterprises' total factor productivity is in the stage of increasing returns to scale, and the values

Table 2. Decomposition results of energy eco-efficiency from 2012-2019.

Year	MI	TC	EC
2012	0.899	0.927	1.151
2013	0.994	1.137	0.906
2014	0.984	1.025	1.137
2015	0.894	1.615	0.685
2016	0.979	1.332	1.045
2017	0.955	1.422	0.898
2018	0.939	1.026	0.915
2019	0.866	0.882	1.143
Mean value	0.939	1.171	0.985

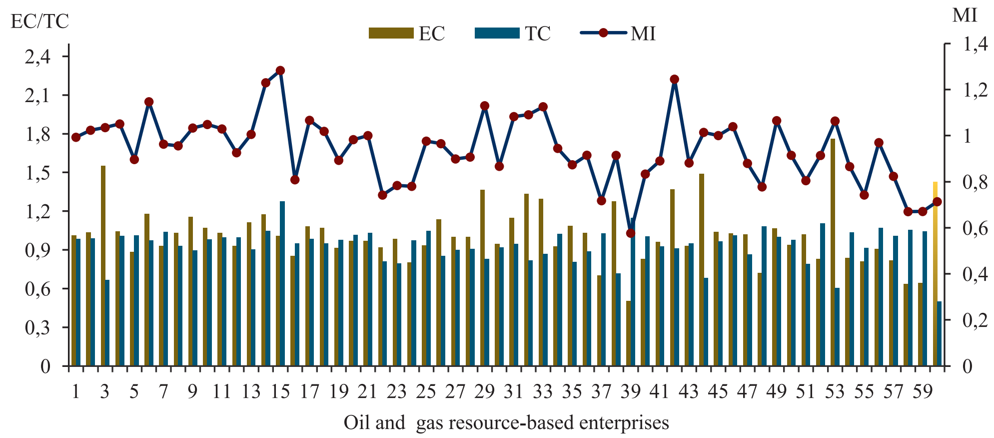

Fig. 3. Dynamics of energy eco-efficiency and decomposition index of each enterprise.

of change in technical progress and pure technical efficiency are 0.985 and 1.171, respectively, which indicate that enterprises' total factor productivity is mainly driven by pure technical efficiency. Technical progress shows a decreasing trend, which indicates that enterprises should pay attention to scientific and technological innovation and continuously strengthen the management level to promote the growth of technical progress.

In Fig. 3, the green total factor efficiency of most oil and gas resource-based enterprises is less than 1, indicating that the development level of energy eco-efficiency of enterprises is not high and there is still much room for improvement. From the change trend of each year, the indicators have the tendency of short-term fluctuation and small growth, which may be caused by the unstable management level and insufficient motivation of scientific and technological innovation in the process of enterprise development and growth.

Analysis of Factors Influencing Energy Eco-Efficiency

In this paper, the influence factors of energy eco-efficiency of oil and gas resource-based enterprises were analyzed empirically using Tobit analysis with Stata software. As seen in Table 3, each of the four influencing factors is significantly correlated within 1% confidence interval. Among them, the degree of energy consumption is negatively correlated and the rest are positively correlated.

Economic development (ED) has a positive and significant impact on energy eco-efficiency. From the perspective of GDP per capita, the increase in the level of economic development implies the improvement of people's quality of life, which makes stricter requirements at the social environment level and at the individual level. The good atmosphere of social environment and the improvement of individual environmental awareness can interact with each other to promote the regulation of social and corporate environment. Enterprise size (ES) has a positive and significant effect on energy eco-efficiency, indicating that the larger the size of oil and gas resource-based enterprises, the higher the energy eco-efficiency. This is because the larger the size of the enterprise, the more stringent the environmental control will be, and the environmental performance and economic performance will be well improved at the same time. The improvement of science and technology innovation capability (TEI) has a driving effect on the improvement of energy eco-efficiency and is the key factor with a correlation coefficient of 0.102. At 1% significance, energy consumption (EC) has a negative effect on

Table 3. Tobit regression results of the factors influencing energy eco-efficiency.

Variable	Coef.	Std.Err.	t	P>|t|	95% Conf.	Interval
ED	0.061	0.153	5.26	0.000***	0.051	0.083
ES	0.031	0.443	6.95	0.000***	0.022	0.034
TEI	0.102	0.215	7.16	0.000***	0.043	0.207
EC	-0.028	0.082	-3.29	0.001***	-0.036	0.001
cons	0.199	0.026	7.54	0.000***	0.147	0.253

Note: ***, **, and * indicate significant at the 1%, 5%, and 10% levels, respectively.

Table 4. Robustness test results (1).

Variables	Expected sign	Coefficient	Standard deviation	T-value	P-value
ED	+	0.072	0.190	4.24	0.000
ES	+	0.031	0.037	8.32	0.000
TEI	+	0.094	0.105	7.13	0.000
EC	-	-0.021	0.054	-4.98	0.000
cons		0.199	0.027	7.23	0.000

Table 5. Robustness test results (2).

Variables	Expected sign	Coefficient	Standard deviation	T-value	P-value
ED	+	0.071	0.119	4.12	0.000
EN	+	0.080	0.132	6.41	0.000
TEI	+	0.103	0.217	8.15	0.000
EC	-	-0.043	0.143	-4.09	0.000
cons		0.387	0.230	10.01	0.000

energy eco-efficiency. It reflects that in the production activity segment, companies generate a high amount of industrial waste gas and solid waste generation, which can result in a situation of low resource utilization and high level of environmental pollution.

In order to verify the reliability of the above findings, robustness tests were conducted in this paper. The energy eco-efficiency of enterprises is measured by "carbon dioxide emissions from 10,000 yuan of sales revenue", specifically: energy eco-efficiency = revenue from main business/carbon dioxide emissions. At the same time, personnel size can reflect enterprise size to some extent (Wang et al., 2021) [33]. Therefore, this paper chooses the number of employees (EN) of oil and gas resource-based enterprises as a proxy variable for ES. In this paper, the regression analysis was reperformed with energy eco-efficiency as the explanatory variable and TA as the proxy variable, respectively (Tables 4 and Table 5). The regression results show that the direction and significance degree of the regression coefficients of the explanatory variables are basically unchanged, which indicated that the original findings were robust.

Conclusions

Combing the existing domestic and foreign related research on energy eco-efficiency, this paper constructs an energy eco-efficiency evaluation index system for oil and gas resource-based enterprises, and takes 60 oil and gas resource-based enterprises in China as the research objects, and uses the SBM-ML model to evaluate energy eco-efficiency from both static and dynamic perspectives, with the following conclusions.

Firstly, evaluating the energy eco-efficiency level of oil and gas resource-based enterprises in China from a static perspective, it can be concluded that from 2011-2019, the overall energy eco-efficiency did not reach an effective value1, indicating that ecological governance policies have not been effectively implemented in each enterprise. Oil and gas resource-based enterprises have neglected ecological issues in the actual development process, so they should strengthen the awareness of coordinating ecological environment with economic development, implement green development into the actual action process, improve energy utilization rate, and achieve sustainable development.

Secondly, evaluating the energy eco-efficiency level of oil and gas resource-based enterprises in China from a dynamic perspective, the results show that from 2011-2019, energy eco-efficiency showed a trend of rising and then falling, and energy eco-efficiency has great room for improvement. The total factor productivity of different oil and gas resource-based enterprises has variability. The impact of technological progress on energy eco-efficiency efficiency is greater, while the role of technical efficiency is relatively weaker.

Thirdly, analysis of the factors influencing energy eco-efficiency shows that economic development, enterprise scale and technological innovation are positively related to energy eco-efficiency, and energy consumption is negatively related to energy eco-efficiency. Therefore, when oil and gas resource-based enterprises expand their production scale to pursue economic benefits, it is necessary to enhance the awareness of technological innovation to achieve green and intelligent production, effectively reduce the damage to the ecological environment, improve energy utilization efficiency, and ultimately achieve win-win development of economic growth and ecological protection.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. SUWARNO I., MA'ARIF A. MAHARANI R.N., NURJANAH A., IKHSAN J., MUTIARIN D. IoT-based Lava Flood Early Warning System with Rainfall Intensity Monitoring and Disaster Communication Technology. Emerging Science Journal. **4**, 154, **2021**.
2. EKWUEME B.N. Machine Learning Based Prediction of Urban Flood Susceptibility from Selected Rivers in a Tropical Catchment Area. Civil Engineering Journal. 8, (9), 1857, **2022**.
3. ZHAO Y.M, DONG H.Z. Analysis of spatial and temporal evolution characteristics and influencing factors of industrial energy eco-efficiency in China. Soft Science. **36** (06), 48, **2022**.
4. CUI S.N., WANG, Y.Q., ZHU, Z.W., YU C.Y. The impact of heterogeneous environmental regulation on the energy eco-efficiency of China's energy-mineral cities. Journal of Cleaner Production. **350**, 131553, **2022**.
5. WANG Y.Q., LI Y., GONG Y.F. Study on the coupling interaction between green growth and oil and gas resource-based enterprise growth. Journal of China University of Petroleum (Social Science Edition). **37** (06), 71, **2021**.
6. LI G., LIU J.G., LI T.Q. A study of regional differences in manufacturing energy eco-efficiency considering non-desired outputs - a two-stage analysis based on SBM and Tobit models. China Management Science. **27** (11), 76, **2019**.
7. WANG X.Q., XIA Y.Q, LI H.Z., WU X.Y. Energy eco-efficiency differences and dynamic evolution of China's mining industry. Techno-economics. **39** (09), 110, **2020**.
8. ZHANG R., HU Y.Y., QIE X.T. A study on the dynamic response of energy eco-efficiency of Chinese logistics industry and its influencing factors. Economic Issues. (08), 9, **2021**.
9. ZHOU M., AI J. Inter-provincial energy eco-efficiency assessment in China based on TOPSIS-RSR. Ecological Economics. **35** (03), 45-50+67, **2019**.
10. GUAN W., WANG C.N., XU S.T. Evaluation of energy eco-efficiency and its decoupling analysis from economic growth: A case study of nine provinces and regions in the Yellow River Basin. Resource Development and Market. **38** (1), 23, **2022**.
11. CAO C.H., XI Y.M., CAO X.W. The motivation of energy saving and emission reduction in enterprises and strategy selection. Management Review. 25, (07), 3-10, **2013**.
12. WU Q.S., LI H. Study on the evaluation of energy efficiency in the middle reaches of Yangtze River urban agglomeration. China Population-Resources and Environment. **26** (12), 140, **2016**.
13. LIU Y.S. A comparative study on total factor energy efficiency of G20 countries based on DEA model. Regional and Global Development. **3** (04), 101-120+157-158, **2019**.
14. TONE K., Dealing with undesirable outputs in DEA: A slacks-based measure (SBM) approach. Presentation At NAPW III, Toronto. 44-45, **2004**.
15. TIAN Z., ZHANG H.J., REN F.R. A comparative study on energy efficiency evaluation and influencing factors of three major urban agglomerations in China under environmental constraints. Soft Science. **34** (12), 87, **2020**.
16. CHUANG Y.H., FÄRE R., GROSSKOPF S. Productivity and undesirable outputs: a directional distance function approach. Journal of Environmental Management. **51** (3), 229, **1997**.
17. LU S.J., SHI P.F., DENG C.W., LI X.M., HU Y. Green productivity measurement and spatial and temporal evolution analysis of tourism in the Yangtze River Economic Zone. China Population - Resources and Environment. **29** (7), 19, **2019**.
18. TACHEGA M.A., YAO X., LIU Y., AHMED D., LI H., MINTAH C. Energy efficiency evaluation of oil producing economies in Africa: DEA, Malmquist and multiple regression approaches. Cleaner environmental systems. **2**, 100025, **2021**.
19. YU C., SHI L., WANG Y., CHENG Y., CHENG B.D. The eco-efficiency of pulp and paper industry in China: an assessment based on slacks-based measure and Malmquist–Luenberger index. Journal of Cleaner Production. **127**, 511, **2016**.
20. REN S., LI X., YUAN B., CHEN X. H. The effects of three types of environmental regulation on eco-efficiency: A cross-region analysis in China. Journal of Cleaner Production. **08**, 113, **2016**.
21. CHEN Z.L. Eco-efficiency, urbanization and spatial spillover - A study based on a spatial panel Durbin model. Management Review. **28** (11), 66, **2016**.
22. ELLIOTT RJR, SUN P., ZHU T. The direct and indirect effect of urbanization on energy intensity: A province-level study for China. Energy. **123** 677, **2017**.
23. WU Q.S., LI H. Study on the evaluation of energy efficiency in the middle reaches of Yangtze River urban agglomeration. China Population-Resources and Environment. **26** (12), 140, **2016**.
24. SUN W. Analysis of spatial and temporal differences in urban energy eco-efficiency in the Yellow River Basin and its influencing factors. Journal of Anhui Normal University (Humanities and Social Sciences Edition). 48,

(02), 149, **2020**.
25. LI X.F. Study on the Factors Influencing Total Factor Energy Efficiency in "One Belt and One Road" Related Provinces. Survey World. (03), 49, **2021**.
26. WANG C.H., YUAN J. Efficiency measurement and spatial variation analysis of modern circulation industry in western region-based on non-radial super-efficient three-stage DEA model. Industrial Technology and Economics. (12), 102, **2019**.
27. CHEN X.L., MENG Q.G., SHI J.Y., SHEN W.F. Analysis of eco-efficiency measures and spatial and temporal evolution of eight integrated economic zones in China. Review of Economics and Management. **38** (2), 109, **2022**.
28. LI J., JING Y.J. A study of environmental efficiency measures and influencing factors based on DEA-Malmquist-Tobit model – a case study of Henan Province. Ecological Economics. **37** (2), 132, **2021**.
29. LI J.B., PU H., WU H., WANG Y.Q. Evaluation of mineral resources development efficiency in Sichuan Province based on DEA-Malmquist model. Comprehensive utilization of minerals. (1), 82, **2022**.
30. CHEN J.Q., LIU N., MA X.J. Measurement of energy eco-efficiency and its drivers in eight integrated economic zones of China. China Environmental Science. 41, (5), 2471, **2021**.
31. WANG J.L., DAI S.F. Evaluation of circular economy efficiency of China's iron and steel industry based on DEA-Malquist index. Journal of Hebei University of Economics and Business. **35** (2), 78, **2014**.
32. FENG J.H., ZANG Q.W. A study on the coupling coordination and influencing factors of eco-efficiency and science and technology innovation in industrial enterprises. Technology Economics. **39** (7), 35, **2020**.
33. WANG Y.Q., YAO L.X., CUI S.N., ZHU Z.W. Eco-efficiency Assessment of Chinese Petrochemical Enterprises: A Data Envelopment Analysis Approach. Energy & Environment. **33** (6), 1160, **2022**.
34. XIA Y.Q., WANG X.Q. Evaluation of eco-efficiency of coal enterprises based on DEA-Malmquist. Journal of China Academy of Environmental Management Cadres. **29** (5), 1, **2019**.
35. CHEN N., WANG X.H., YU Y., CAO F. Ping. An empirical study of business performance of ecologically oriented enterprises in China--based on panel data of 15 listed companies. Ecological Economics. **37** (01), 70, **2021**.
36. FANG Q.M., LIU T., LIU X., ZHANG W.N. Research on environmental efficiency in the perspective of enterprise resource ecology. Ecological Economics. **33** (11), 96, **2017**.
37. XU Y.N., ZHAO G.H. Production efficiency, innovation efficiency and eco-efficiency of industrial enterprises - a study based on coupled coordination perspective. Journal of Statistics. **1** (05), 13, **2020**.
38. ZHAO K.J., LIU, X.C. Evaluation of water-energy composite eco-efficiency in the Yellow River Basin and its influencing factors – and a comparison with the Yangtze River Economic Belt. Coal Economic Research. (8), 28, **2020**.
39. LI Q.Y., LIANG L.W., WANG Z.B. Analysis of spatial and temporal differences in eco-efficiency and influencing factors in China. Journal of Resources and Ecology: English Edition. **12** (2), 155, **2021**.
40. YANG H.J., ZHANG C.H. Research on the spatial and temporal evolution of corporate eco-efficiency and its influencing factors. Journal of Kunming University of Science and Technology (Social Science Edition). **17** (05), 55, **2017**.
41. CHEN Y.H., SU K. An empirical study on eco-efficiency and influencing factors of industrial enterprises in Fujian. Journal of Fujian Agriculture and Forestry University (Philosophy and Social Science Edition). **21** (03), 38, **2018**.
42. XU P., CUI S.N. Environmental regulation, resource dependence and economic growth in resource-based regions. Journal of China University of Petroleum: Social Science Edition. **37** (6), 30, **2021**.
43. WANG J.C., YANG M., LI X.Y. Does external pressure promote corporate green innovation? --The dual influence of government regulation and media monitoring. Industrial Economics Review. **12** (04), 66, **2021**.
44. HAN N., LI Y.P. A study on the influencing factors of environmental performance of Chinese manufacturing firms. Journal of Economic Research. (25), 16, **2014**.
45. ZHANG J.Q., BIAN N., FAN F. Analysis of the correlation between new urbanization and science and technology innovation in the middle reaches of Yangtze River urban agglomeration based on PVAR model. Science and Technology Management Research. (16), 103, **2017**.
46. YI X.H., LIU J.D. Evaluation of eco-efficiency in western China and analysis of its influencing factors. Statistics and Decision Making. **36** (01), 105, **2020**.