An Empirical Study on Industrial Ecological Efficiency in Arid Resource Exploitation Region of Northwest China

Xudong Zhou (395297965@qq.com)
Luzhou Vocational and Technical College https://orcid.org/0000-0001-8683-6746
Zhengkai Xue
Luzhou Vocational and Technical College
Jumeniyaz Seydehmet
Luzhou Vocational and Technical College

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An empirical study on industrial ecological efficiency in arid resource exploitation region of northwest China

Xudong Zhou*[a] Zhengkai Xue[a] Jumeniyaz Seydehmet[b]

a Luzhou Vocational and Technical College; Luzhou, Sichuan Province, China,

b Jumeniyaz Seydehmet1. Collage of Geographical Science and Tourism, Xinjiang Normal University, Urumqi, Xinjiang, China.

Abstract[1]

Located in the northwest of China, Xinjiang is a typical arid desert area and mineral resources development zone. Lacking water resources and a fragile ecological environment restricts the sustainable development of the region. Based on the industrial panel data of Xinjiang from 2001 to 2015, this paper uses the Undesirable Output SBM model, Malmquist index model, and Tobit regression model to comprehensively and systematically measure and evaluate the industrial eco-efficiency and its change characteristics from provincial, regional and prefectural levels. The results show that:(1) The level of industrial eco-efficiency in Xinjiang is generally low, lower than the national average, but it has been rising steadily over time, from 0.36 in 2001 to 1.00 in 2008, and from 0.41 in the "Tenth Five-Year Plan" period to 0.99 in the "Twelfth Five-Year Plan" period. (2)

[1] [1] * Corresponding author. Luzhou Vocational and Technical College, Luzhou , Sichuan ,China
Email: 510279120@qq.com

The industrial ecological efficiency of Xinjiang is not balanced in space. Northern Xinjiang is larger than that of eastern Xinjiang and southern Xinjiang. The 14 prefectures have uneven and asynchronous development, which can be divided into two development modes: industrial region and agriculture and animal husbandry region. (3) Through the decomposition analysis of the Malmquist index, it is found that the technology progress index is the restriction factor of the changing trend of TFP, while the technical efficiency index and the pure technical efficiency index are the promoting factors. (4) The main factors causing the loss of ecological efficiency are industrial sulfur dioxide emissions, industrial nitrogen oxide emissions, total industrial water consumption, general industrial solid waste. It can be seen that the emission of air pollutants and excessive industrial water are the main problems in the region. (5) Industrial ecological efficiency is positively correlated with industrial development level, scientific and technological innovation, industrial structure, and environmental planning, and negatively correlated with opening up and industrial agglomeration degree. (6) Xinjiang is an extremely arid and water-scarce region. These are the key and prerequisite of saving water resources and strengthening the comprehensive utilization of water resources. Water- saving should be given top priority no matter in industrial areas, or agricultural and animal husbandry areas.

Keywords: Industrial ecological efficiency, SBM-Undesirable model, Malmquist index; Input-output redundancy, Arid and resource-developing regions

1. Background

Since the implementation of the "Tenth Five-Year Plan" in 2001, Xinjiang has witnessed rapid economic development with an average growth rate of 17% in industrial GDP. However, many problems have been exposed. Xinjiang is located on the western border of China and the hinterland of Eurasia (Fig1), with desert area accounting for nearly 60% of China's desert area. It is one of the world's drought centers with a fragile ecological environment. Xinjiang is an important corridor of the Silk Road Economic Belt. Meanwhile, coal, oil, natural gas, and other mineral resources are abundant (Ma, 2013), and about 60% of prefectures in Xinjiang are listed as resource-based prefectures and regions by the Chinese government (2013). Problems such as excessive resource consumption, environmental pollution, and ecological imbalance are becoming increasingly serious, which have become the bottleneck that further restricts the sustainable development of Xinjiang. Therefore, it is very important to scientifically measure the ecological level and efficiency of economic development in this region, which is also the focus of policymakers at all levels. Ecological efficiency is the ratio of increased value to increased environmental impact (Schaltegger et al., 1990), which has gained high attention in the study of sustainable development (Jollands et al., 2004). It has become one of the research hotspots of Chinese and foreign scholars and industrial ecology (Hahn et al.,2010; Lv et al., 2006) and has become an important analytical tool to measure sustainable development.

Industrial ecological efficiency is defined as the ratio of the total amount of products produced by industrial enterprises in a certain region to resource consumption and environmental impact (Gao et al.,2011). At first, it was applied to the enterprise level. With the deepening of the research, it gradually developed to the micro and macro aspects. Foreign countries focused on the micro aspects such as the research on industrial enterprises and products. (Dahlstrom et al., 2005) focused on the trend of eco-efficiency in the steel and aluminum industry; (Huppes et al., 2007) focused on the Dutch oil and gas products; (Korhonen et al., 2004) focused on the ecological efficiency of the power plant, (Aanand Dave et al., 2016) focused on the application of eco-efficiency model in furniture manufacturers. In contrast, China focuses on large scale studies in cities and regions. (Gao et al., 2004) (Lu et al., 2004), and (Wang et al., 2016) measured and evaluated the industrial ecological efficiency of 30 provinces in China Other scholars have studied the industrial ecological efficiency in Beijing (Wang et al., 2008), Shandong (Lu et al., 2014)], Sichuan (Liu et al., 2014) and Hunan (Zhang et al., 2015). The relatively mature research methods of industrial ecological efficiency mainly include traditional data envelopment analysis (DEA) (Gao et al., 2011&Wang et al., 2011) and super- efficiency DEA model method (Fu et al., 2013&Li et al., 2018). However, the traditional DEA model does not consider the slack of input and output in the evaluation of ecological efficiency, and it may lead to the deviation of ecological efficiency measurement due to the choice of radial and Angle (Hu.,2016 &Pan et al., 2013). Therefore, non-radial and non-angular SBM models have been gradually applied and developed in recent years. Dan Pan and Ruiyao Ying used the SBM-Undesirable model to measure the spatial and temporal distribution of agricultural eco-efficiency in 30 provinces of China (Pan et al., 2013). Biao Hu and Yeteng Fu (Hu et al., 2016) conducted an empirical study on the ecological efficiency of 30 provinces in China. Xiaodong Ma et al. (Ma et al., 2018), Yong Zhou et al. (Zhou et al., 2020) and Song Hu et al. (Hu, 2016) respectively applied and discussed the SBM model.

At present, there are few and incomplete research data on industrial ecological efficiency in Xinjiang. Weiping Jia (Jia,2016) took Tianye of Xinjiang as the research object and discussed the connotation and application of ecological efficiency of the Chlor-alkali chemical industry in Xinjiang. This paper mainly uses the SBM model, Malmquist Index, and Tobit model to comprehensively and systematically measure and evaluate the industrial eco-efficiency and its change characteristics from provincial, regional and prefectural levels. The goal of the present study was to explore annual change trends in industrial ecological efficiency, spatial distribution patterns, and analyze the existing shortcomings, explore the ways of improvement and promotion, to provide a reference for the sustainable development of resource-developing prefectures located in arid areas.

2. Materials and methods

2.1 Research Methods

2.1.1 SBM-Undesirable model

SBM-Undesirable model proposed by (Jia, 2016 &Tone,2001) Tone is a method to measure ecological efficiency. Compared with the traditional data envelope analysis model, the SBM model can take wastewater, waste gas, solid waste, and other unexpected outputs generated in the process of economic development into account, making the calculation results more accurate and effective. It effectively solves the difficulties encountered by the traditional DEA model when the input and output elements increase and the corresponding slack is considered, and the deviation of ecological efficiency calculation is caused by the choice of radial and Angle. The model formula is as follows:

$$Min\rho = \frac{1-\frac{1}{N}\sum_{n=1}^{N} S_n^x/X_{n0}}{1+\frac{1}{M+1}\left(\sum_{m=1}^{M} S_m^y/y_{m0} + \sum_{i=1}^{I} S_i^U/U_{i0}\right)}$$

$$s.t. \sum_{n=1}^{N} Z_k X_{nk} + S_n^x = X_{n0}, n = 1,2,\dots,N; \sum_{k=1}^{K} Z_k y_{mk} - S_m^y = y_{m0}, n = 1,2,\dots,M$$

$$\sum_{k=1}^{K} Z_k U_{mk} + S_i^u = U_{i0}, i = 1,2,\dots,I; \sum_{k=1}^{K} Z_k = 1;\ Z_k \ge 0; S_n^x \ge 0; S_m^y \ge 0; S_i^u \ge 0$$

Here, Xn0 represents the input variable of DMU, Ym0 represents the expected output variable of DMU, and UI0 represents the unexpected output variable of DMU. ρ denotes the ecological efficiency value, ρ ranges between 0 and 1, ρ =1 means DMU reaches the effective front.

2.1.2. The Malmquist index

The Swedish economist the Malmquist (Malmquist, 1953) first proposed the Malmquist index in 1953. In 1982, Caves proposed that the Malmquist index represented the total factor production efficiency under multi-input and multi-output conditions, and integrated the index into the DEA model to calculate the total factor productivity of the production sector (Caves, 1982). The basic principles of this implementation are as follows:

The Malmquist index from time interval t to t+1 can be expressed as (Färe, 1997):

$$
\begin{aligned}
\mathrm{TFP} &= \left[\frac{D^{t}\left(x_{t+1} \bullet y_{t+1}\right)}{D^{t}\left(x_{t} \bullet y_{t}\right)} \times \frac{D^{t+1}\left(X_{t+1} \bullet y_{t+1}\right)}{D^{t+1}\left(x_{t} \bullet y_{t}\right)}\right]^{\frac{1}{2}} \\
&= \left[\frac{D^{t}\left(x_{t+1} \bullet y_{t+1}\right)}{D^{t+1}\left(x_{t+1} \bullet y_{t+1}\right)} \times \frac{D^{t}\left(X_{t} \bullet y_{t}\right)}{D^{t+1}\left(x_{t} \bullet y_{t}\right)}\right]^{\frac{1}{2}} \times \frac{D^{t+1}\left(x_{t+1} \bullet y_{t+1}\right)}{D^{t}\left(x_{t} \bullet y_{t}\right)} \\
&= \mathrm{TC} \times \mathrm{EC} \\
&= \mathrm{TC} \times \mathrm{PE} \times \mathrm{SE}
\end{aligned}
$$

Here the variation in the Malmquist index is the total factor productivity (TFP) variation and represents the change in the degree of productivity for a decision unit from t to t+1. TFP > 1 indicates an increase in productivity, whereas TFP < 1 indicates a decrease in productivity. The TFP can be subdivided into technical change (TC) and efficiency change (EC). TC refers to the contribution of moving the production frontier to productivity, while EC is the contribution from changing technical efficiency to productivity between the period encompassed by t and t+1. EC can be further divided into PE (pure technical efficiency) and SE (scale efficiency).

2.1.3. Tobit Model

The ecological efficiency estimated by the DEA model is not only affected by the input and output indicators that are selected, but also by other factors. Collet (Collet, 1998) developed a two-step method based on the DEA to identify the factors that influence ecological efficiency and their relative contributions. The first step is to evaluate the efficiency of decision-making units by the DEA. Then, a regression model is established that uses the estimated efficiency value as the dependent variable, and influential factors as the independent variables. The orientation and intensity of the influential factors on environmental efficiencies are then determined by the coefficients of the independent variables.

The Tobit model can be written as:

$$y_i = \begin{cases} y_i^* = x_i\beta + \varepsilon_i & y_i^* \geq 0 \\ 0 & y_i^* \leq 0 \end{cases}$$

Here x_i is the independent variable, y_i is the observed dependent variable, y_i^* is the latent variable, β is the correlation coefficient,ε_i is the independent variable. The disturbance term is ε_i -N (0, σ2).

2.2 Selection of Evaluation Indicators and Data Source

Environmental, economic and resource factors were considered here concerning previous studies (Lu et al., 2017; Wang et al., 2011 & Wang et al., 2008). Three types of resource consumption indexes, namely, energy consumption, electricity consumption, and water resource consumption, were selected as input indexes; three types of environmental pollution indexes, namely, exhaust gas discharge, wastewater discharge, and solid waste discharge, were selected as Undesirable Output indexes; and economic value was selected as expected output indexes. The evaluation index system of industrial ecological efficiency is constructed (See Table 1）. The input and output data used in this study were acquired from the Statistical Yearbooks of Xinjiang Uygur Autonomous Region, the

Yearbooks of Xinjiang Environmental Statistics, Statistical Communique of Xinjiang Uygur Autonomous Region on National Economic and Social Development, and statistical yearbooks of the Prefectures.

The research object is Xinjiang and its jurisdiction 14 prefectures. According to the distribution of Xinjiang can be divided into three areas (see Fig1): northern Xinjiang region: including the Urumqi, Changji hui autonomous prefecture (Hereinafter referred to as Changji Prefecture), Karamay city, Yili Kazak autonomous prefecture (Hereinafter referred to as Yili Prefecture), Altay prefecture, Tacheng prefecture, Bortala Mongolia Autonomous Prefecture (Hereafter referred to as BoZhou); Southern Xinjiang region: Bayingol Mongolian Autonomous Prefecture (Hereafter referred to as Bazhou), Aksu Prefecture, Kashi Prefecture, Hotan Prefecture, Kizilsu Kirgiz Autonomous Prefecture (Hereafter referred to as Kizl); Eastern Xinjiang region: Includes Hami city and Turpan city.

Table 1. Evaluation indices are used to assess ecological efficiency

Index	**Category**	**Specific index**	**Content**
Input indicators	Resource factors	Energy consumption	Industrial energyconsumed(104 t)
		Power consumption	Industrial electricity consumption(10^8kwh)
		Water consumption	Industrial water(10^8m^3)
Undesired output indicators	Environmental factors	Exhaust emission	SO_2 (t), NO_x (t)
		Wastewater discharge	NH_3-N (t), COD (t)

		Solid waste discharge	General industrial solid waste(10^4t)
Desired output indicators	Economic factors	Total economic development	Gross industrial product (10^8yuan RMB)

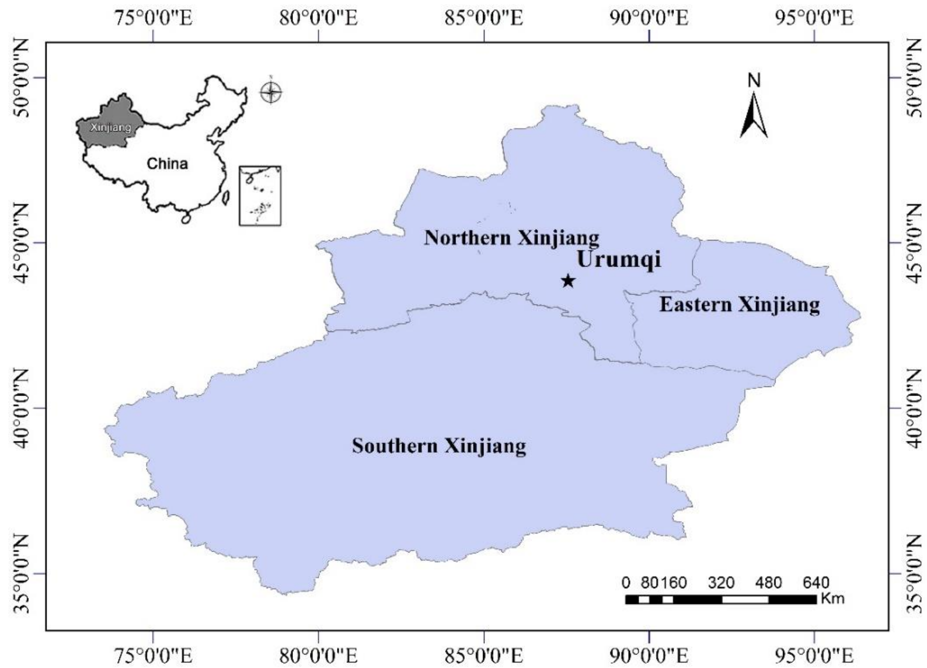

Fig. 1 Study area diagram

3. Results and analysis

The SBM-Undesirable model is adopted, and DEAP2.1 software and DEA-Solver Pro software are used to measure and analyze the industrial eco-efficiency of Xinjiang from 2001 to 2015, from the static and dynamic aspects, as well as from the provincial, regional and prefectural levels, to find out the temporal and spatial variation rule. The results are as follows.

3.1 Static ecological efficiency measurement and analysis

3.1.1 provincial-level measurement and analysis

(1) Comparison and analysis with other provinces. The industrial ecological efficiency of 31 provinces and cities in China is measured and analyzed by using the SBM model, and the gap between Xinjiang and other provinces in China is compared. As can be seen from Fig 2, the national average of industrial ecological efficiency is 0.67, among which only 6 provinces reach the frontier of effective production. The industrial ecological efficiency of Xinjiang is 0.59, ranking the 17th in the country, which is lower than the national average. The industrial ecological efficiency is still low and in a state of inefficiency. It shows that the industrial development of Xinjiang has some problems such as unreasonable resource allocation and unbalanced input-output.

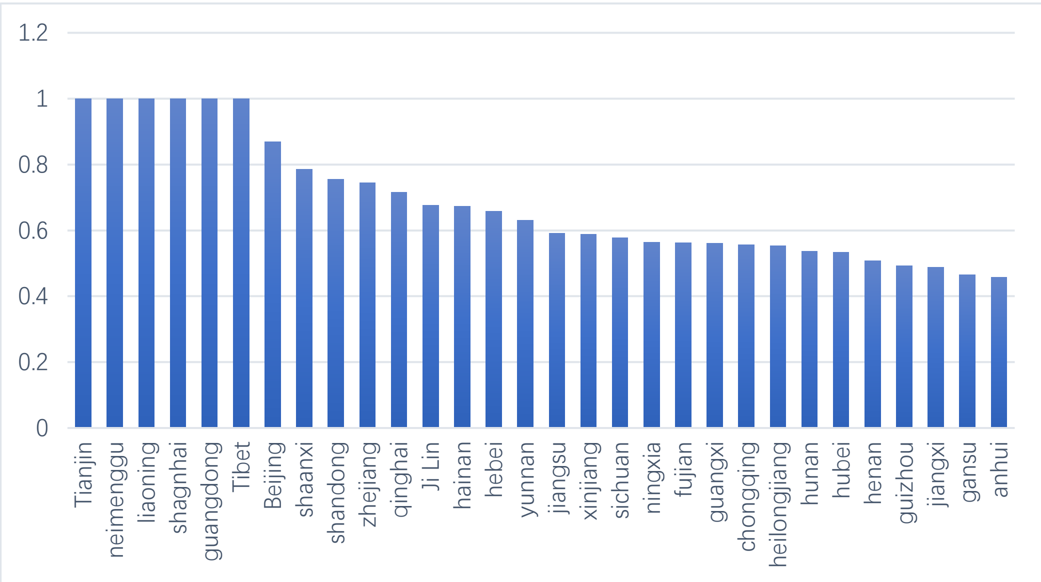

Fig 2 Comparison of industrial eco-efficiency in different provinces in China

(2) Time series change analysis of industrial eco-efficiency in Xinjiang is shown in Figs 3-4. From 2001 to 2015, the overall industrial eco-efficiency of Xinjiang showed a continuous upward trend, increasing from 0.36 in 2001 to 1.00 in 2008, the first peak, reaching the effective production frontier, but there was a sudden and brief decline in 2009, and then it has been kept at the effective production frontier since 2010. According to the analysis of the changes of the industrial ecological

efficiency in the three five-year plans, the ecological efficiency has been rising steadily from 0.41 in the "Tenth Five-Year Plan" period to 0.82 in the "Eleventh Five-Year Plan" period and then to 0.99 in the "Twelfth Five-Year Plan" period. It shows that since 2001, Xinjiang has gradually realized the coordinated development of industrial economic growth, resource conservation, and environmental protection through a series of energy conservation and emission reduction measures and the three five-year plans, especially since 2008, in the middle of the Eleventh Five-Year Plan, industrial production has entered a new development mode. The industrial ecological efficiency has reached the effective production frontier for six consecutive years, realizing the stable, coordinated, and sustainable development of industrial production. This is mainly due to the strong support given by the central government to the economic development of Xinjiang since 2010. The central government has held two symposiums on work in Xinjiang and implemented the policy of aiding Xinjiang in 19 provinces and cities.

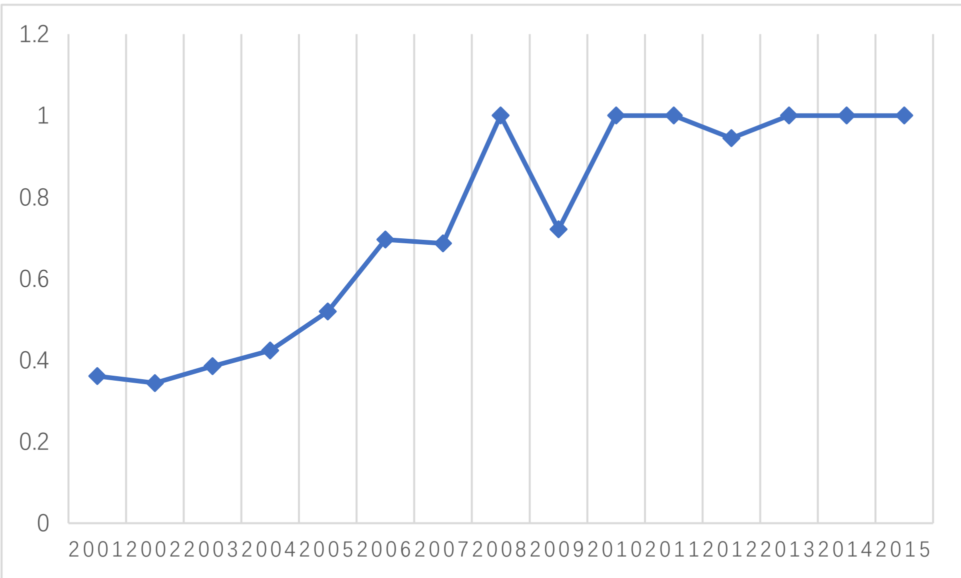

Fig.3 The change trend of industrial eco-efficiency in Xinjiang from 2001 to 2015

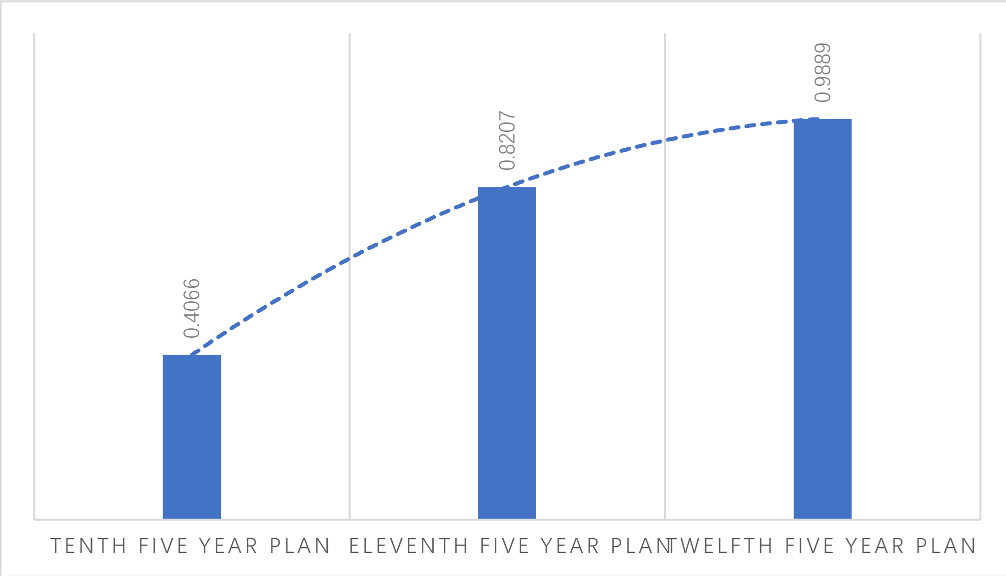

Fig 4 Variation trend of industrial eco-efficiency during the "Tenth five- year plan" to the "Twelfth five-year plan"

3.1.2 Area level measurement and analysis

Xinjiang is divided into three regions: northern Xinjiang, eastern Xinjiang, and southern Xinjiang, and the temporal and spatial changes of ecological efficiency in different regions are measured and analyzed. The results are shown in Figs 5-6.

(1) Spatial difference analysis. The average industrial ecological efficiency of the three regions in northern Xinjiang, eastern Xinjiang, and southern Xinjiang is 0.66, 0.64, and 0.62 respectively, indicating that northern Xinjiang is greater than that of eastern Xinjiang and southern Xinjiang.

(2) Time change trend analysis. From 2001 to 2015, the industrial eco-efficiency in eastern Xinjiang first declined slightly and then increased, from 0.65 in 2001 to 0.59 in 2007 and then to 1.00 in 2015, with an overall increase of 52.93%. Since 2001, northern Xinjiang has been rising in a "W" shape with a rising rate of 12.00%. The industrial ecological efficiency in southern Xinjiang fluctuated frequently, with a slight increase of 20.73% in the end. From the "10th five-year plan " to "11th five-year plan" to "12th five-year" period, the ecological efficiency value changes from

0.57 to 0.60 and 0.68 in northern Xinjiang, from 0.63 to 0.62 to 0.74 in eastern Xinjiang, from 0.56 to 0.59 and 0.76 in southern Xinjiang, except the east during the period of "11th five-year plan" ecological efficiency declined slightly. In general, in three regions from the "10th five-year plan " to the 12th five-year" period, the industrial ecological efficiency showed a trend of stage rise.

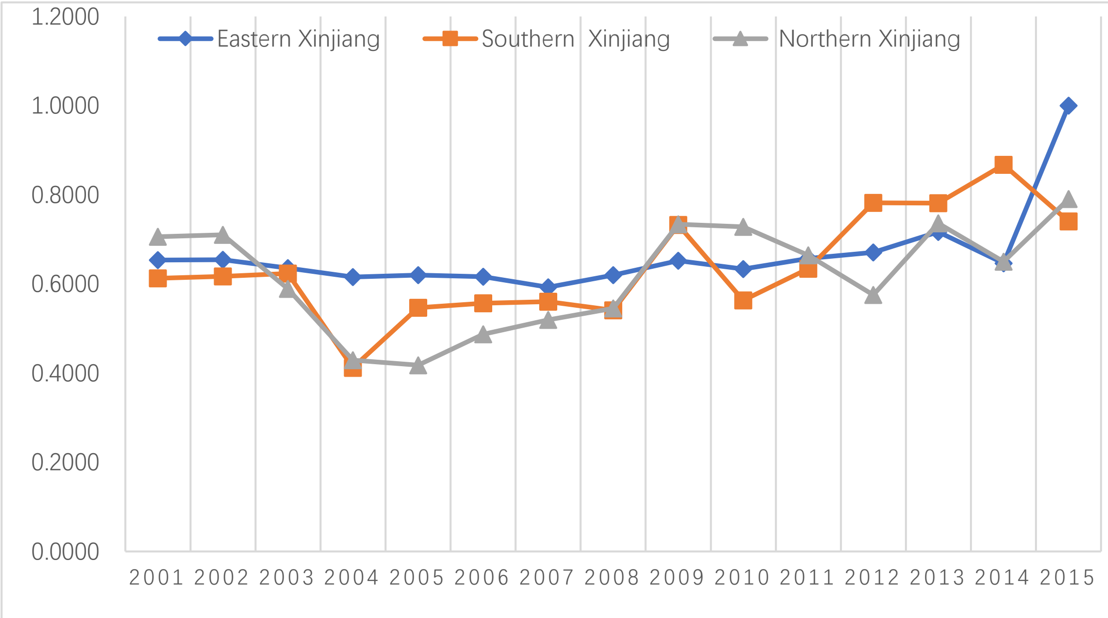

Fig 5 variation trend of industrial eco-efficiency in different regions of Xinjiang from 2001 to 2015

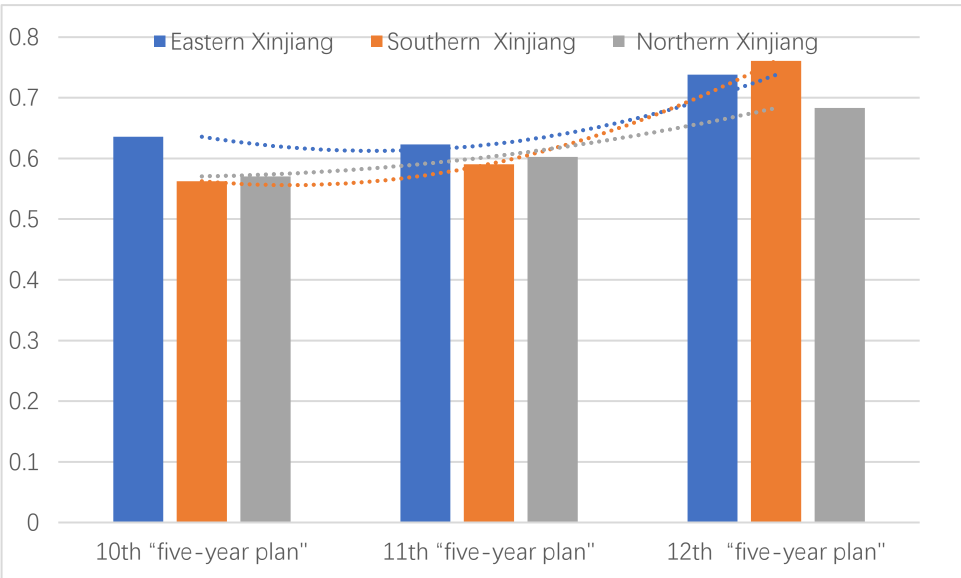

Fig 6 variation trend of industrial eco-efficiency in different regions during the "Tenth five- year plan" to the "Twelfth five- year plan"

3.1.3 Prefectures level measurement and analysis

Xinjiang is divided into 14 districts, and measurement analysis of the ecological efficiency between prefectures is carried out, and the results are shown in Fig 7.

The average industrial ecological efficiency of the 14 prefectures was 0.66, among which the industrial ecological efficiency of Karamay, Turpan, Aletai, Bazhou, Hetian , and Kezhou was 1.00, reaching the frontier of effective production, indicating that the industrial input and output of these six prefectures had reached the optimal level. The industrial ecological efficiency of Urumqi is basically at the average level, while the industrial ecological efficiency of the other 7 prefectures is lower than the average, which belongs to the non-efficient region. The number of such prefectures is large, accounting for 50%. Generally speaking, the development of industrial ecological efficiency in different regions of Xinjiang is unbalanced. It can be divided into two categories. The first category is industrial developed areas, such as Karamay City, Urumqi City , and Changji Prefecture, which need to further improve cleaner production, energy conservation and emission reduction. The second category is agriculture and animal husbandry areas, such as Kezhou, Altay region, Yili Prefecture, Hotan, and other places, which need to further strengthen scientific and technological research and development and promotion efforts, further strengthen and improve energy-saving and cost-reducing.

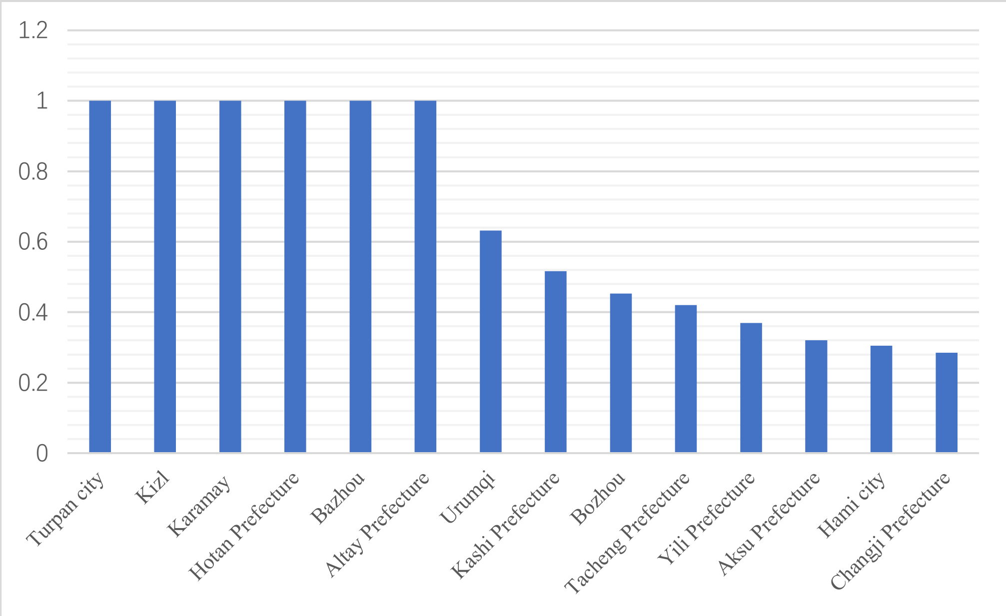

Fig.7 Industrial eco-efficiency of 14 prefectures in Xinjiang

3.2 Dynamic ecological efficiency measurement and analysis

To better clarify the ecological efficiency change trend in Xinjiang, the DEA-Malmquist index model was used to calculate the ecological efficiency variations of 14 prefectures from 2001 to 2015. The Malmquist index included comprehensive technical efficiency (EC), technical progress (TC), pure technical efficiency (PE), scale efficiency (SE), and total factor productivity (TFP).

(1) Total factor productivity (TFP) was at a low level from 2001 to 2015. The mean value was 0.982 and the average annual decline was 1.8%. Among them, six years of TFP was above 1.0, accounting for 42.8%. The rest of the years are below 1.0, showing that industrial ecology efficiency development in Xinjiang is unstable and the fluctuation is large. It is mainly affected by technical progress and technical efficiency, and it still needs to be improved and perfected.

(2) By analyzing the decomposition changes of each index, the average value of the technical progress is 0.967, among which 6 years are greater than 1, showing an increasing trend, but the overall trend is down. The average annual decline rate is 3.3%, basically synchronous with the

change of the TFP index, which is the main influence and restriction factor of the industrial ecological efficiency. Both the comprehensive efficiency and the pure technical efficiency are greater than 1. The overall trend is increasing, and the average growth range is 1.6%. It contributes the most to the improvement of industrial ecological efficiency and is the main factor in promoting the improvement of industrial ecological efficiency.

The comprehensive analysis shows that the technical progress index is the main restriction factor of the trend of TFP change, while the technical efficiency index is the promoting factor. It shows that the industrial technology level of Xinjiang is relatively backward, and we should attach great importance to the research and development and introduction of new industrial technology in the future.

Table 2 Malmquist index of industrial eco-efficiency in Xinjiang from 2001 to 2015

Year	EC	TC	PE	SE	TFP
2001-2002	1.027	0.923	1.027	1.000	0.948
2002-2003	0.451	2.680	0.451	1.000	1.208
2003-2004	1.279	0.695	1.279	1.000	0.889
2004-2005	1.041	1.012	1.041	1.000	1.066
2005-2006	0.850	1.253	0.850	1.000	1.114
2006-2007	1.367	0.765	1.367	1.000	1.04
2007-2008	0.881	1.100	0.881	1.000	0.957
2008-2009	0.828	1.156	0.828	1.000	0.957
2009-2010	1.650	0.607	1.650	1.000	1.001
2010-2011	0.698	1.069	0.698	1.000	0.746

2011-2012	0.817	0.910	0.817	1.000	0.743
2012-2013	1.001	0.842	1.001	1.000	0.843
2013-2014	0.984	0.995	0.984	1.000	0.98
2014-2015	2.576	0.594	2.576	1.000	1.529
Mean	1.016	0.967	1.016	1.000	0.982

3.2.2 Spatial distribution analysis

To further analyze the composition and causes of the Malmquist index changes in Xinjiang, Malmquist indexes of 14 Prefectures in Xinjiang were decomposed and analyzed, as shown in Table 3.

(1) From 2001 to 2015, the average total factor productivity (TFP) of various prefectures was 0.982. TFP of 6 prefectures was greater than 1.0, and TFP of the other 8 prefectures was less than 1. Although the increase rate of Karamay was 12.6%, it could not hide the overall downward trend of 1.8%. The average drop in prefectures was 1.8%. It is mainly caused by the unbalanced development between prefectures. It is suggested that prefectures based on the industry should learn from the experience of Karamay and Urumqi and make more efforts in cleaner production, energy conservation, emission reduction; and prefectures based on agriculture should learn from the experience of Hotan, Kizl, and Altay. It is necessary to further increase scientific and technological research and promotion, and further strengthen and improve energy-saving and cost-reducing.

(2) By analyzing the decomposition changes of each index, the scale efficiency remains unchanged at 1.00. Both the comprehensive technical efficiency (EC) and pure technical efficiency

index (PE) are all 1.016, and the increase rate is 1.6%. The technology progress index was 0.967, with a decline rate of 3.3%. In particular, the technology progress index in Kashi prefecture declined by 10.3%. It can be seen that the technical progress index is the leading factor for the decline of total factor productivity，It has a restrictive effect on total factor productivity. But the technical efficiency and pure technical efficiency index play a promoting role.

(3) On the whole, TFP shows a downward trend, in which technical efficiency plays a promoting role and technological progress plays a restricting role, while scale efficiency has little influence. In Urumqi, Karamay, Turfan, Changji, and most of the other prefectures, Technological efficiency is the main factor that promotes TFP, while technological progress is the constraint. In Altay and Hotan, both technological progress and technical efficiency play a promoting role, while in Bazhou, technological progress plays a promoting role and technical efficiency plays a restricting role.

Table 3 Malmquist index of ecological efficiency in 14 prefectures of Xinjiang from 2001 to 2015

district	EC	TC	PE	SE	TFP
Urumqi	1.063	0.971	1.063	1.000	1.033
Karamay city	1.135	0.992	1.135	1.000	1.126
Turpan city	1.042	0.970	1.042	1.000	1.011
Hami city	0.985	0.989	0.985	1.000	0.974
Changji Prefecture	1.053	0.911	1.053	1.000	0.959
Yili Prefecture	0.976	0.909	0.976	1.000	0.887
Tacheng Prefecture	0.979	0.938	0.979	1.000	0.918
Altay Prefecture	1.002	1.004	1.002	1.000	1.005

Bozhou	1.000	0.956	1.000	1.000	0.956
Bazhou	0.983	1.014	0.983	1.000	0.996
Aksu Prefecture	0.984	0.962	0.984	1.000	0.947
Kizl	1.000	1.005	1.000	1.000	1.005
Kashi Prefecture	1.019	0.897	1.019	1.000	0.914
Hotan Prefecture	1.013	1.030	1.013	1.000	1.043
Mean	1.016	0.967	1.016	1.000	0.982

3.3 Input-output redundancy analysis

3.3.1 Input-output redundancy results

In this paper, the input redundancy rate is obtained by dividing the slack of each input variable by the corresponding input index value, and the output redundancy rate is obtained by dividing the slack of each output variable by the corresponding output index value. The calculation results are shown in Table 4.

Table 4 Redundancy rate of input-output index of industrial eco-efficiency in different prefectures of Xinjiang

Area	Industrial energy consumed	Industrial electricity consumption	industrial water consumption	Industrial waste gas emissions	SO2	NOx	Industrial wastewater emissions	NH3-N	industrial solid waste	Gross industrial product
Urumqi	-0.00%	-57.75%	-11.47%	-44.7%	-54.43%	-68.81%	-41.64%	-0.00%	-28.59%	0.00%
Hami city	-28.38%	-66.38%	-76.27%	-77.56%	-91.49%	-82.67%	-71.72%	-80.21%	-98.96%	0.00%
Changji Prefecture	-18.68%	-85.66%	-73.77%	-75.13%	-81.54%	-87.41%	-63.17%	-95.09%	-95.31%	0.00%
Yili Prefecture	-0.00%	-67.23%	-85.69%	-70.03%	-71.82%	-65.97%	-43.88%	-67.84%	-89.16%	0.00%
Tacheng Prefecture	-0.00%	-67.14%	-71.29%	-68.33%	-62.55%	-70.56%	-39.65%	-43.46%	-67.75%	0.00%

Bozhou	-14.28%	-47.27%	-72.96%	-64.67%	-64.62%	-37.24%	-37.31%	-58.08%	-30.97%	0.00%
Aksu Prefecture	-34.90%	-51.90%	-79.21%	-64.46%	-64.50%	-72.99%	-62.05%	-95.99%	-90.47%	0.00%
Kashi Prefecture	-0.00%	-30.94%	-74.90%	-72.72%	-74.78%	-67.99%	-48.83%	-0.00%	-11.20%	0.00%
Mean	-12.03%	-59.28%	-68.20%	-63.65%	-70.72%	-69.21%	-51.03%	-55.08%	-64.05%	0.00%

Note: prefectures with invalid ecological efficiency are listed in the table. Karamay, Turfan, Altay, Bazhou, Kizl, and Hotan are not listed in the table due to the balance of resource allocation.

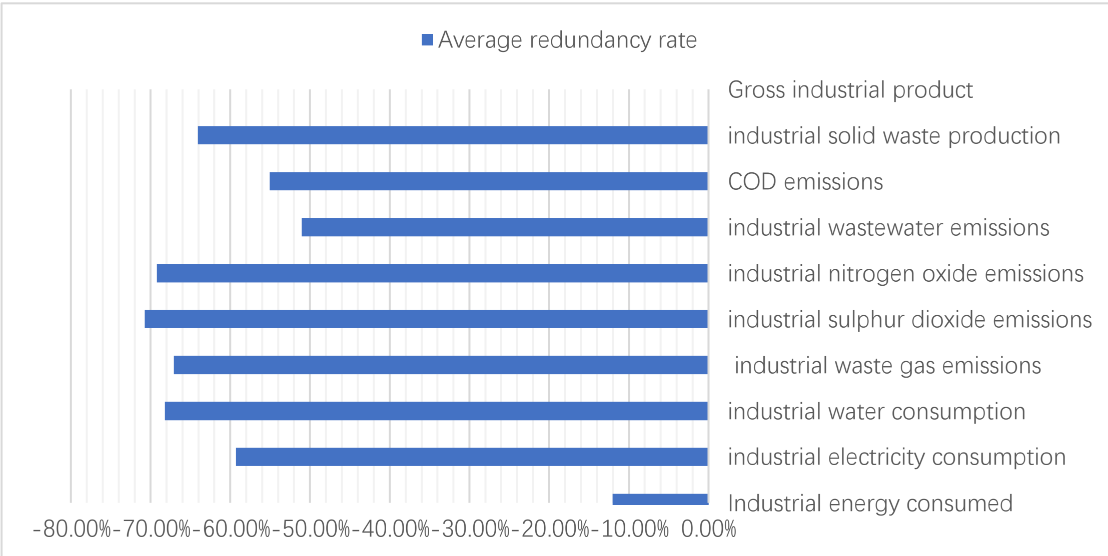

Fig 8 Comparison of redundancy rates of input and output index

The following conclusions can be drawn from Table 4 and Fig 8:

(1) The redundancy rate of the expected output index-industrial gross product in each region is zero, while there is some redundancy in both input and Undesirable Output factors. This shows that the lack of industrial output is not the reason for the loss of industrial ecological efficiency, but the

excessive consumption of resources and excessive discharge of environmental pollutants are the main reasons for the low industrial ecological efficiency in Xinjiang at this stage.

(2) From the average redundancy rate, the main factors causing the loss of ecological efficiency are industrial sulfur dioxide emissions, industrial nitrogen oxide emissions, industrial waste gas emissions, total industrial water consumption, and general industrial solid waste. It can be seen that there is a problem of excessive air pollutant emission in the whole region, which is a typical problem in resource-based cities in the north of China, especially those with mineral resources development. In the future, the industrial development of Xinjiang should continue to make efforts in desulfurization and denitrification. Besides, excessive industrial water use and general industrial solid waste discharge are also important factors causing loss of ecological efficiency. Saving water resources is a fundamental problem in arid areas, so it is urgent to improve the allocation and utilization of water resources in the next step.

(3) Based on the analysis of the redundancy rate in different prefectures, the main factors affecting the loss of ecological efficiency are different.

Industrial production of Hami, Changji, and Aksu prefecture is extensive and belongs to the production mode of high input and high emission. Almost every input and output factor have the problem of excessive redundancy rate. 6 of the 9 input-output factors in Yili Prefecture are excessive; In Tacheng, Bozhou , and Kashi prefecture, there are problems of excessive water and electricity for industrial input elements. The redundancy rate of Urumqi is less than the mean value, and the problem of the excessive input-output index is not too prominent. Excess industrial water is a common problem in all prefectures except Urumqi. We need to take measures to address problems existing in different regions according to local conditions.

3.3.2 Analysis of improvement approaches

3.3.2.1 Analysis of input index of resource consumption

(1) Total industrial energy consumption. Fig 9 shows, industrial energy consumption redundancy rate is higher, areas above average include Hami City, Changji Prefecture, Aksu Prefecture. These regions are relatively developed in the industry in Xinjiang, but compared to Urumqi, Karamay, producing GDP by high energy consumption, which is a relatively extensive and wasteful way of development. In the future, it is necessary to improve the industrial structure adjustment, eliminate backward production capacity, update technology, introduce high and new technology industries, and raise the level of cleaner production.

(2) Industrial electricity consumption. It can be seen from Fig10 that the regions with a high redundancy ratio of industrial electricity consumption are Hami City, Changji Prefecture, Yili Prefecture, and Tacheng Prefecture, which are both industrial-oriented areas such as Hami and Changji Prefecture, and agriculture-oriented areas such as Yili Prefecture and Tacheng Prefecture. Xinjiang is rich in coal and electricity resources：Coal reserves account for 40% of the country's total and the installed power grid had exceeded 50 million kilowatts by the end of the 12th Five-Year Plan. However, controlling industrial electricity consumption, reducing energy consumption, and avoiding waste is still the direction of future efforts.

(3) Industrial water consumption. As can be seen from Fig11, the high redundancy rate of industrial water input is a common problem. Except for Urumqi, the other 7 regions are all overloaded. This is a deadly problem in Xinjiang-an arid and water-scarce region. The direction for improvement in the future is to vigorously develop water-saving industries, water-saving

technologies, and water-saving processes, improve the recycling level of water resources, and eliminate water-consuming enterprises and technologies.

3.3.2.2 Analysis of environmental pollution index of undesired output

(1) Industrial waste gas emission. As can be seen from Figs 12- 14, except Urumqi, the other 7 prefectures all have the problem of excessive redundancy rate of industrial waste gas, sulfur dioxide, and nitrogen oxides emissions. The problem of air pollution has become a common problem throughout the country, having been included in the national environmental pollution battle- "battle to protect the blue sky". At present, the air quality of the whole of China is not optimistic, especially in the northern cities. About 70% of the prefectures in Xinjiang fail to meet the air quality standards. Therefore, the task of controlling the emission of air pollutants is arduous and urgent. Xinjiang is a resource-developing province. Its industries are mainly coal mining, metal mining, limestone mining, and mineral processing, and the amount of industrial waste gas is relatively large. It is a problem to be solved in the future how to improve the quality and efficiency of the existing resource-based enterprises and reduce the emission of waste gas pollutants.

(2) Industrial wastewater emission. As can be seen from Fig15 and 16, Hami, Changji, Aksu, Yili, and Bozhou all have the problem of excessive redundancy rate of COD discharge in industrial wastewater. It is related to local imperfect sewage treatment facilities and the low comprehensive utilization rate of sewage, which is the direction of further adjustment and improvement in these areas in the future.

(3) Industrial solid waste production. As can be seen from Fig 17, Hami City, Changji Prefecture, Aksu, Yili, and Tacheng have the problem of excessive redundancy rate of industrial solid waste production. A large amount of industrial solid waste is mainly produced in mineral mining and

processing enterprises, and the production of tailings, waste rock, and the waste residue is relatively large. In the future, it is necessary to improve the mining rate, recovery rate, and comprehensive utilization rate of solid waste.

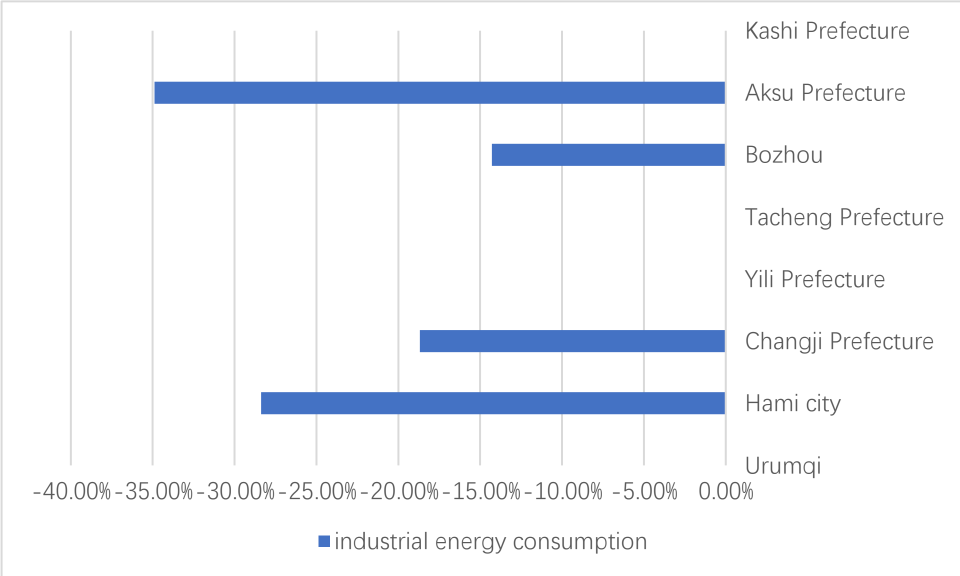

Fig 9 Comparison of redundancy rates of industrial energy consumption in different prefectures

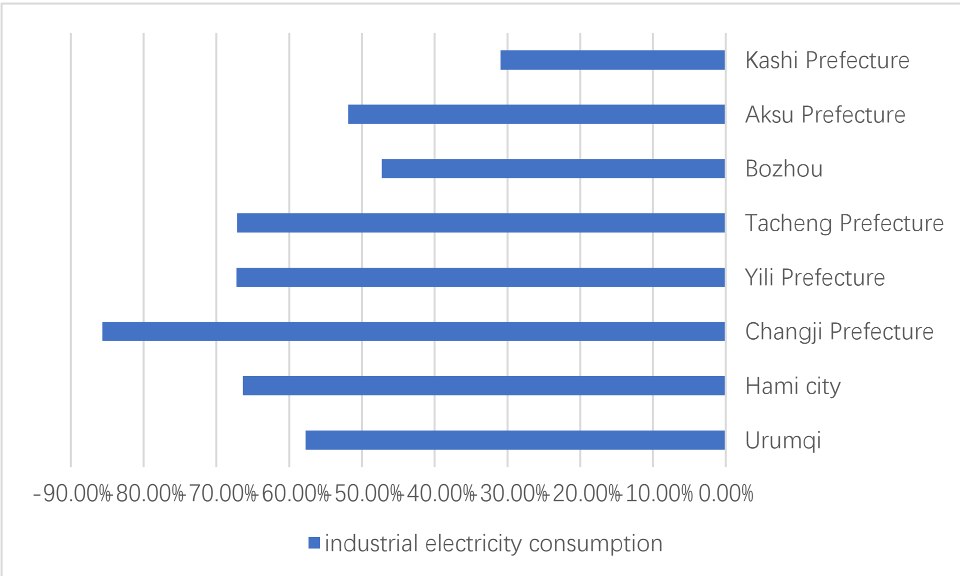

Fig 10 Comparison of redundancy rates of industrial electricity consumption in different prefectures

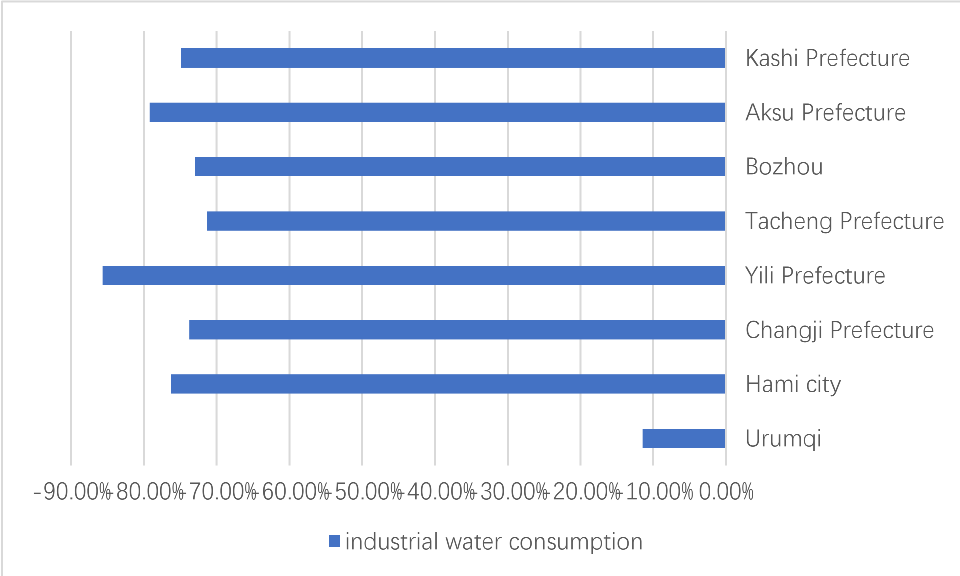

Fig 11 Comparison of redundancy rates of industrial water consumption in different prefectures

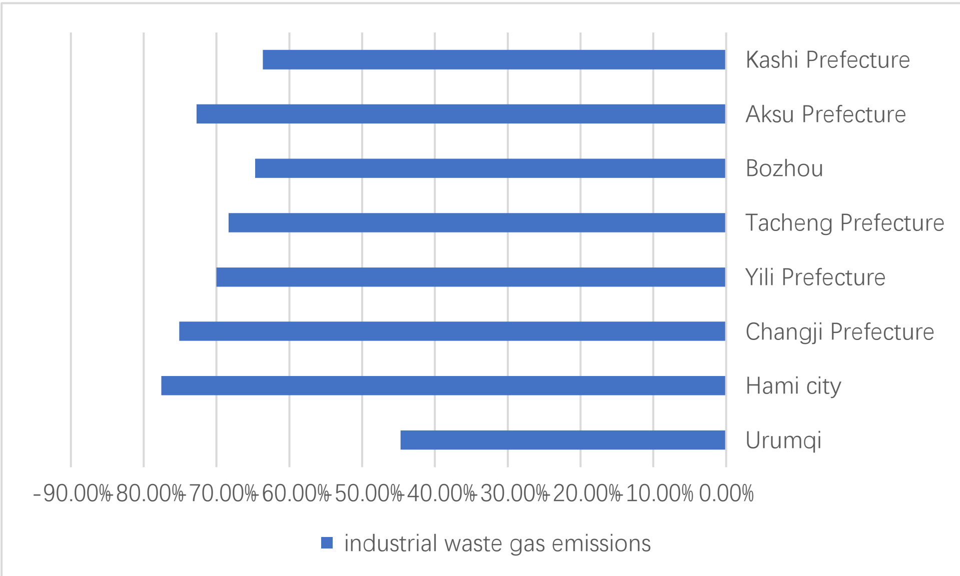

Fig 12 Comparison of redundancy rates of industrial waste gas emissions in different prefectures

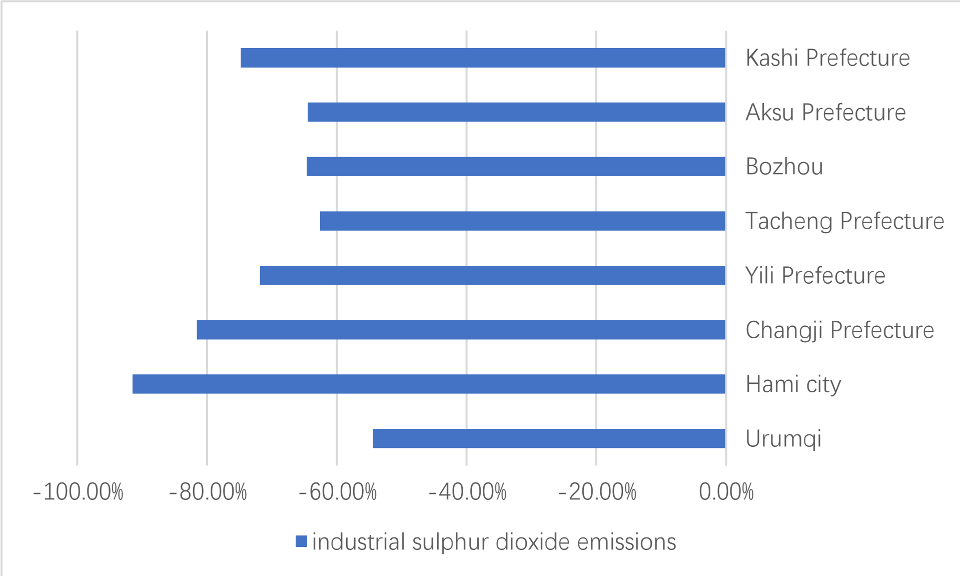

Fig 13 Comparison of redundancy rates of industrial sulphur dioxide emissions in different prefectures

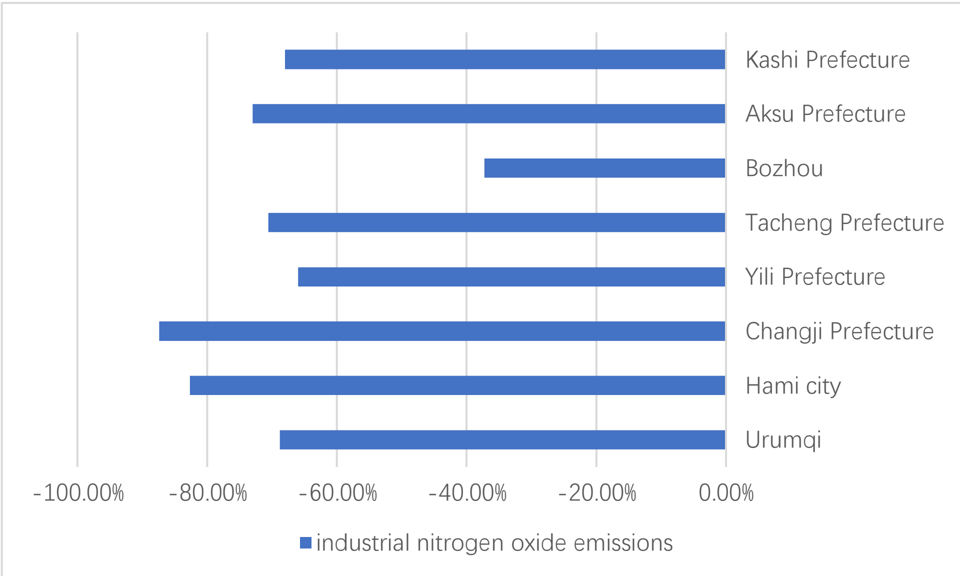

Fig 14 Comparison of redundancy rates of industrial nitrogen oxide emissions in different prefectures

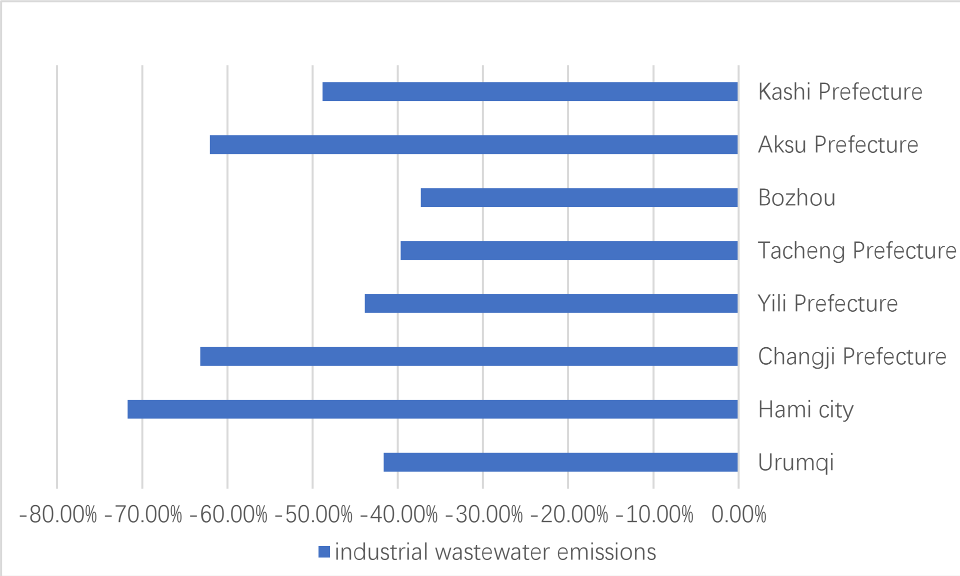

Fig 15 Comparison of redundancy rates of industrial wastewater emissions in different prefectures

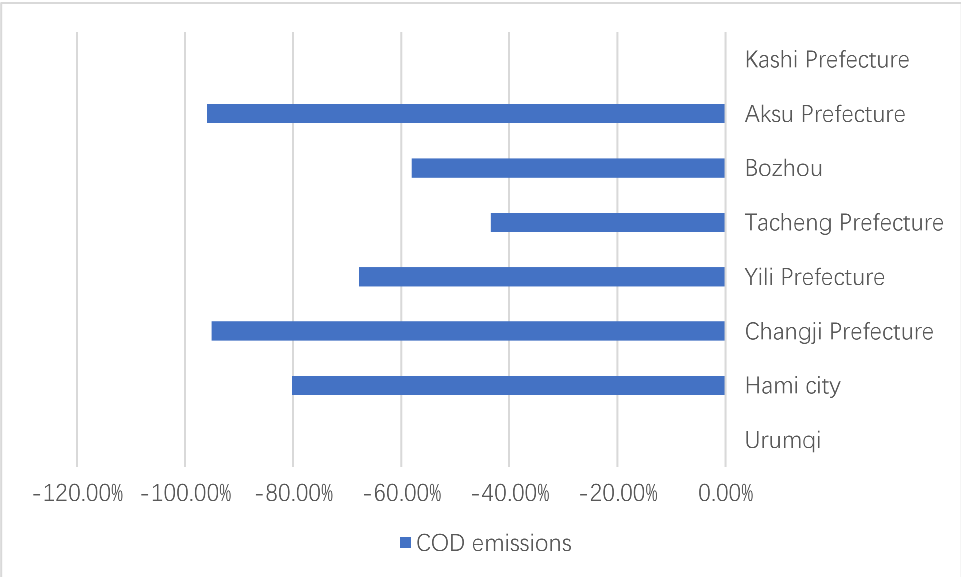

Fig 16 Comparison of redundancy rates of COD emissions in different prefectures

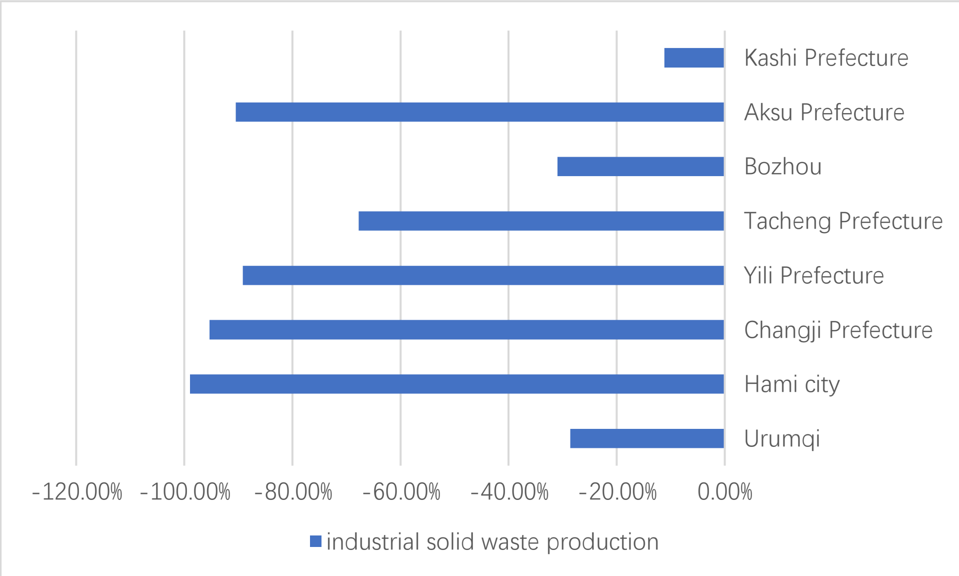

Fig 17 Comparison of redundancy rates of industrial solid waste production in different prefectures

3.4 Analysis of external influencing factors of industrial ecological efficiency

By referring to relevant studies (Lu et al., 2017; Wang et al., 2011 & Wang et al., 2008) and combining with the actual situation of Xinjiang, this paper selects 6 indicators for empirical analysis: (1) Industrial development level (PGDP): Measured by industrial GDP per capita;(2) Opening to the outside world (FIR): measured by the proportion of foreign investment;(3) Environmental planning (EIR): measured by the proportion of investment in environmental protection in the gross industrial product;(4) Scientific and technological innovation (RDR): measured by the proportion of R&D investment in the gross industrial product of large and medium-sized enterprises;(5) Industrial structure (HIR): measured by the proportion of heavy industry;(6) Industrial Agglomeration (IGR): measured by the proportion of industrial GDP in the national. Taking the above 6 indicators as independent variables and the static industrial ecological efficiency value as the dependent variable, the Tobit regression analysis was carried out by using the Stata software and the regression equation was established as follows:

$$ER = \alpha + \beta_1(PGDP) + \ln \beta_2(FIr) + \beta_3(EIr) + \ln \beta_4(RDr) + \ln \beta_5(HIr) + \beta_6(IGr) + \mu$$

In the formula, ER represents industrial ecological efficiency, α is a constant term, β_i is a parameter to be estimated, μ is a random error, and the regression results are shown in Table 5.

Table 5 Tobit regression analysis of influencing factors of industrial eco-efficiency

Explanatory variable	**Coefficient**	**Standard deviation**	**Z statistic**	**Significance**
Constant term	-3.4086	0.1826	-18.670	***
industrial GDP per capita (PGDP)	0.0056	0.0026	2.110	*
the proportion of foreign investment; (FIr)	-0.2293	0.0453	-5.058	***
the proportion of investment in environmental protection (EIr)	0.9324	1.6356	0.570	
the proportion of R&D investment (RDr)	0.2257	0.0895	2.522	*
the proportion of industrial GDP (HIr)	2.1378	0.3331	6.419	***
the proportion of industrial GDP (IGr)	-0.6313	0.4408	-1.432	

***, **, * represent statistical significance at the 0.001, 0.01, and 0.05 levels, respectively.

As can be seen from Table 5, per capita GDP, the proportion of R&D expenditure, the proportion of the heavy industry, the proportion of investment in environmental protection, and industrial ecological efficiency are positively correlated, among them, the first three are significantly positive correlation. It indicates that industrial development level, scientific and technological innovation, and the proportion of heavy industry have an obvious promoting effect on industrial ecological efficiency. The proportion of investment in environmental governance also plays a promoting role, but not obvious. It is necessary to point out that the proportion of heavy industry has a promoting effect on industrial ecological efficiency, which is the result that the economic effect is greater than the pollutant discharge effect. It is consistent with the development model of Karamay Industrial City. It shows that as long as we properly handle the relationship between economic development and environmental protection, we can achieve coordinated development. And proportion of foreign investment, the proportion of industrial GDP in the nation are negatively related to industrial ecological efficiency. The former has a significant negative correlation with industrial ecological efficiency. It shows that if the introduction of backward foreign-funded enterprises or foreign investment with a negative impact on the environment, the impact of opening to the outside world on the environment is negative and is not conducive to the improvement of industrial ecological efficiency., which is consistent with the Jia Jun findings (Jia, 2015).

4. Discussions

4.1 Analysis of the reasons for the gap of industrial eco-efficiency between prefectures. According to the analysis of the industrial ecological efficiency of 14 prefectures, 6 of them reach the effective production frontier. One is at the average level, and 7 of them are all lower than the average value, belonging to the inefficient areas, accounting for 50%.

The first is the analysis of the reasons for the effective areas on the ecological frontier: there are both industrially developed areas, such as Karamay, and agriculture-based areas, such as Turpan and Altay Prefecture. Karamay is a famous oil city in China. Founded in 1958 for petroleum, it has formed a comprehensive oil production base integrating oil extraction and refining. The GDP of the region is second only to that of the capital of Xinjiang, Urumqi. With mature industrial technology, low energy consumption, and low pollutant emission, it has truly achieved energy conservation and emission reduction and is the representative of the advanced industrial city of Xinjiang. Turpan city has also reached the frontier of efficient production. It is an agriculture-oriented area. The agricultural population accounts for more than 70%, and the gross industrial product is at the level of the middle reaches of Xinjiang. The main reason for its high industrial ecological efficiency is that the implementation of water-saving measures has achieved remarkable results. The sewage discharge is only 0.38 tons/ten thousand industrial GDP, which is the lowest in Xinjiang. From the government to the public, there is a strong sense of water-saving. The most famous water-saving project is “karez”. Besides, Kezl, Hotan, and Altay are all typical agricultural and animal husbandry areas, with only a few agricultural and by-product processing industries, and industrial GDP is not high. Among them, Hotan and Kezl respectively rank first and second from last in Gross industrial product in Xinjiang. The main reasons for their high industrial ecological efficiency are low energy consumption and low pollutant emission. Changji Prefecture is the lowest, followed by Hami City, Aksu Prefecture, and Yili Prefecture. There are both industrially developed areas such as Hami City and Changji Prefecture, as well as agriculture-oriented areas such as Yili Prefecture, Tacheng Prefecture, Bozhou, and Kashi Prefecture. There is a big gap between these areas and the areas with high industrial ecological efficiency above, and there is much room for improvement. A lot of work needs to be done in energy-saving, water-saving, and emission reduction.

Generally speaking, the development of industrial eco-efficiency in different regions of Xinjiang is unbalanced, but it has little to do with the level of regional industrial development. The key to improving industrial eco-efficiency is to do a good job in energy conservation and emission reduction of industrial enterprises, no matter the area dominated by industry or by agriculture and animal husbandry.

4.2 The common problem in arid areas is water shortage and the ecological problems caused by water shortage. Through the analysis of input-output redundancy, it can be seen that the redundancy rate of industrial water input in 7 of the 8 inefficient regions is all excessive, which indicates that industrial water excess is a common problem in the industrial development of Xinjiang. Turpan is a city with extreme drought and water shortage. Due to the remarkable effect of water-saving and water recycling measures, the industrial ecological efficiency level is high, reaching the effective ecological frontier. The water resource is a limiting factor for the development of arid areas. Saving water resources and improving the comprehensive utilization efficiency of water resources is the key to improving ecological efficiency. How to improve the distribution and utilization of water resources and improve the recycling level of water resources is urgent.

4.3 Through the analysis of input-output redundancy rate, it can be seen that the excessive emission of air pollutants is the main problem faced by all the prefectures in Xinjiang, which is a typical problem existing in the industrial production of northern resource-based cities, especially those with mineral resources development. Xinjiang is a big province of resource development, and its mineral resources rank second in China (Ma, 2011). 8 of 14 prefectures are listed as resource-based cities and regions by the state (2013), accounting for about 60% of the prefectures in Xinjiang (Fig 18）. Their industrial types are mainly coal mining, metal and limestone mining, and mineral processing industry, which emit a large amount of industrial waste gas. According to research reports, resource-based cities have a great impact on ecological efficiency, resulting in a low level of ecological efficiency (Huang et al., 2015 & Ai et al., 2019). According to the air environment monitoring data of Xinjiang in 2015, among the 19 monitored cities in Xinjiang, only Altay, Tacheng, Bole, and Karamay met the national second-level air quality standard, accounting for 21.1% of the total, and about 80% of the cities failed to meet the standard. Therefore, how to improve the quality and efficiency of the existing resource-oriented enterprises in Xinjiang and reduce the emission of waste gas pollutants is a problem that needs to be solved in the future.

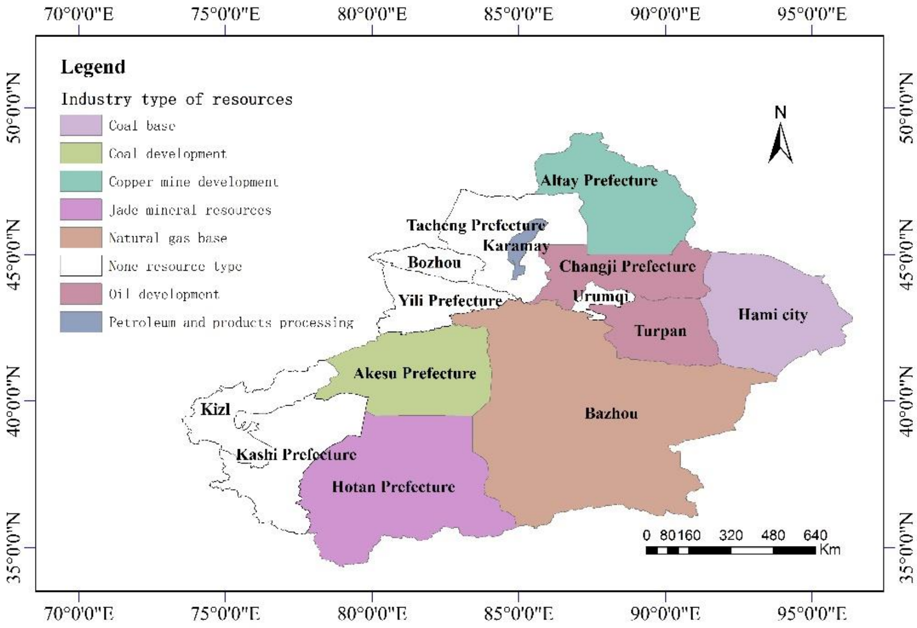

Fig18. Resource prefecture distribution map of Xinjiang

4.4 In this study, the influencing factors of ecological efficiency are summarized into three aspects. Scholars have done a lot of work in these three aspects, and I would like to classify and summarize them here. The first is the internal influencing factors, including resource input index, environmental index, and economic index. The results of this study show that the excessive discharge of industrial sulfur dioxide, industrial nitrogen oxides, industrial waste gas, total industrial water, and general industrial solid waste are the important factors restricting the ecological efficiency of Xinjiang. The second is external factors. The conclusion of this study shows that per capita GDP, the proportion of R&D expenditure, the proportion of the heavy industry, the proportion of investment in environmental protection, and industrial ecological efficiency are positively correlated, while the proportion of foreign investment and proportion of industrial GDP in China is negatively correlated with industrial ecological efficiency. The third is the influence of the Malmquist index. This influence should be adjusted according to local conditions. Different regions have different influence conclusions. This study shows that the technical progress index has an influence and restriction effect on the ecological efficiency of Xinjiang, while the comprehensive technical efficiency index, pure technical efficiency index, and scale efficiency index have a promoting effect on the ecological efficiency of Xinjiang.

4.5 Through the analysis of the influencing factors, this study puts forward the following countermeasures and suggestions to improve the industrial ecological efficiency: first, further improve the level of industrial development. We will mainly implement measures to raise workers' income and increase industrial output; Second, introduce new technology and further improve the level of industrial technology research and development and promotion efforts; Third, strengthen environmental planning and environmental protection management, actively guide enterprises to strengthen the prevention and control of industrial pollution, improve the level of clean production, and implement energy-saving, consumption reduction, and emission reduction; Fourth, we should be cautious in introducing foreign investment, do a good job in the preliminary environmental planning demonstration, and resolutely resist unreasonable demands and additional conditions that are not conducive to environmental protection.

4.6 This study has rich levels, continuous data, comprehensive data, and longtime span, which has important guidance and reference for the study of arid resource areas. In this study, ecological efficiency was measured and analyzed from the provincial level, regional level, and prefectural level. The changing trend of industrial eco-efficiency in Xinjiang is demonstrated from the "Tenth Five

Year Plan", "Eleventh Five Year Plan" and "Twelfth Five Year Plan". It has important guidance and reference for the industrial sustainable development of Xinjiang- an important channel of the Silk Road Economic Belt, and also provides a reference for the research work of other arid resource-based regions.

4.7 Since the environmental pollutant emission data of Xinjiang during the 13th Five-Year Plan period is still in the stage of submission and approval, it cannot be obtained for the time being. To maintain the unity of non-expected emission indicators, the changing trend of industrial ecological efficiency from 2016 to 2020 has not been analyzed this time.

5. Conclusions and suggestions

5.1 The industry ecological efficiency level is low in Xinjiang, lower than the national average, but it shows a steady upward trend over time, from 0.36 in 2001 rose to 1.00 in 2008. Since then, it has remained at the efficient production frontiers. It shows that since 2001, Xinjiang has gradually realized the industrial economic growth, resource-saving, and environmental protection coordination development through a series of measures for energy conservation and emissions reduction through three five-year plans, especially since 2008. In the middle of the Eleventh Five-Year Plan period, industry production entered a new development model. The industrial ecological efficiency has reached the effective production frontier for six consecutive years. The industrial ecological efficiency has reached the effective production frontier for six consecutive years. The stable, coordinated, and sustainable development of industrial production has been realized, which is mainly attributed to the strong support given by the central government to the economic development of Xinjiang since 2010. The central government has held two symposiums on work in

Xinjiang and implemented the policy of aiding Xinjiang in 19 provinces and cities.

5.2 Industrial ecology efficiency exists space imbalance in Xinjiang. The industrial ecology efficiency of Northern Xinjiang is larger than that of Eastern Xinjiang, and the industrial ecology efficiency of Eastern Xinjiang is larger than that of Southern Xinjiang. The 14 prefectures develop unevenly and asynchronously, which can be divided into two development modes: The first type is an area dominated by industrial. Clean production, energy conservation, and emissions reduction are needed to perfect and improve in the future. The second type is the area dominated by agricultural and animal husbandry. It is necessary to further strengthen the research and development and popularization of science and technology, and further strengthen and improve energy-saving and cost-reducing.

5.3 Through the decomposition analysis of the Malmquist index, it is found that the technology progress index is the restriction factor of the changing trend of TFP, while the technical efficiency index and the pure technical efficiency index are the promoting factors. It shows that the application level of industrial technology in Xinjiang has been growing, but the introduction and research and development of industrial technology are not enough and need to be strengthened.

5.4 From the analysis of input-output redundancy, the main factors causing the loss of ecological efficiency are industrial sulfur dioxide emissions, industrial nitrogen oxide emissions, industrial waste gas emissions, total industrial water consumption, and general industrial solid waste. It can be seen that the emission of air pollutants and excessive industrial water are the main problems in the region. In the future, improvements should be made in saving industrial water and reducing the emission of air pollutants.

5.5 From the analysis of influencing factors, industrial development level, scientific and technological innovation, industrial structure, environmental planning, and industrial ecological efficiency are positively correlated, which plays a promoting role in the industrial ecological efficiency, while the opening to the outside world, industrial agglomeration degree, and industrial ecological efficiency are negatively correlated, which plays an inhibiting role in the industrial ecological efficiency. Therefore, to improve the industrial ecological efficiency, it is necessary to further improve the level of industrial development, improve the level of technological research and development in industrial enterprises, promote their popularization, and strengthen environmental planning and environmental protection management. We should be cautious in introducing foreign investment.

5.6 Xinjiang is an extremely arid and water-scarce region. Saving water resources and strengthening the comprehensive utilization of water resources are the key and prerequisite. Water- saving and efficiency should be given top priority in industrial areas, agricultural and animal husbandry areas.

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Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work.

Author Contributions

Xudong Zhou: data curation, formal analysis, funding acquisition, investigation, methodology: project administration, supervision, validation, writing - original draft, writing - review& editing.

Jumeniyaz Seydehmet：Drawing, paper ideas

Zhengkai Xue：financial support for the paper

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Figures

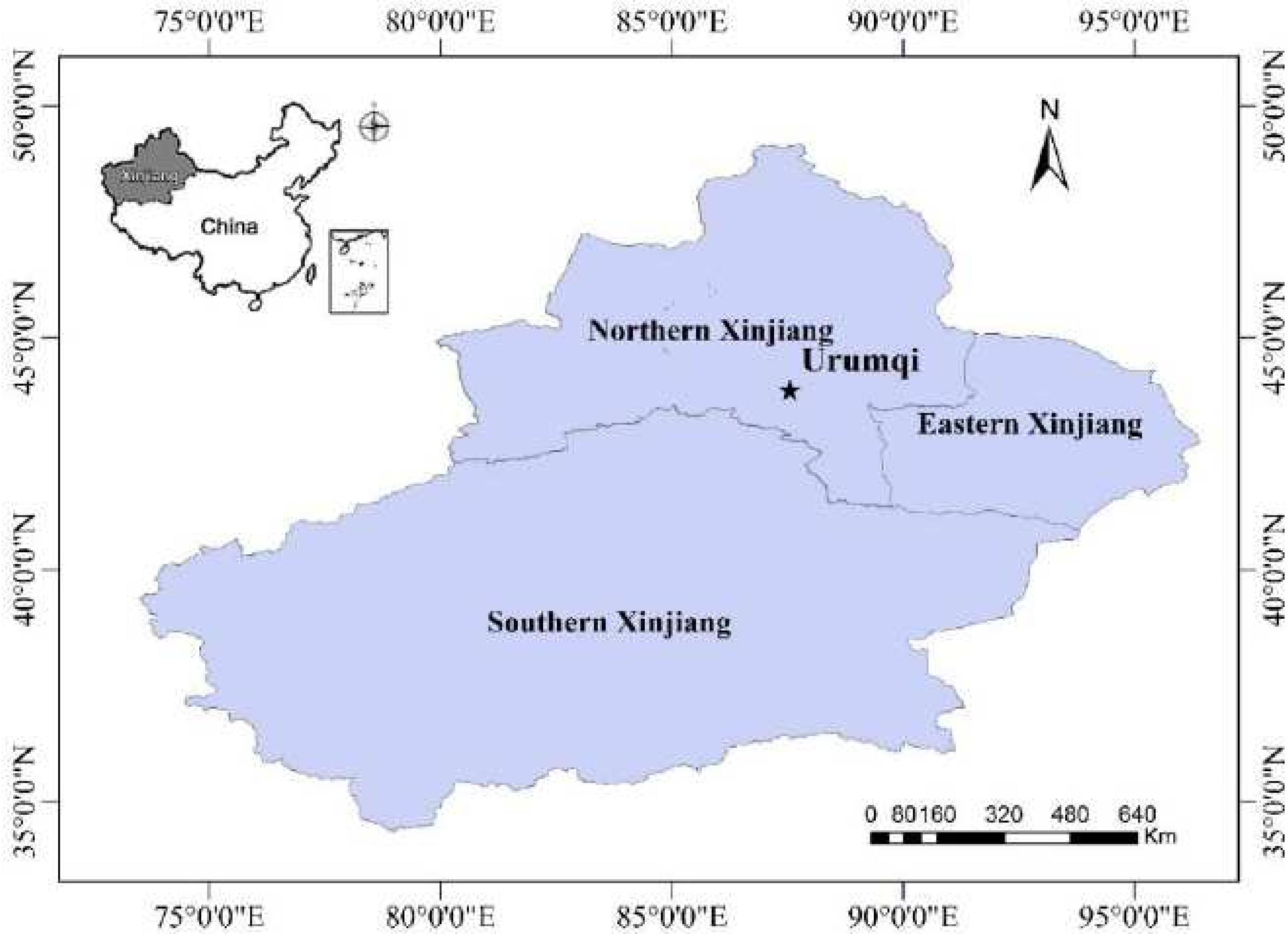

Figure 1

Study area diagram Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

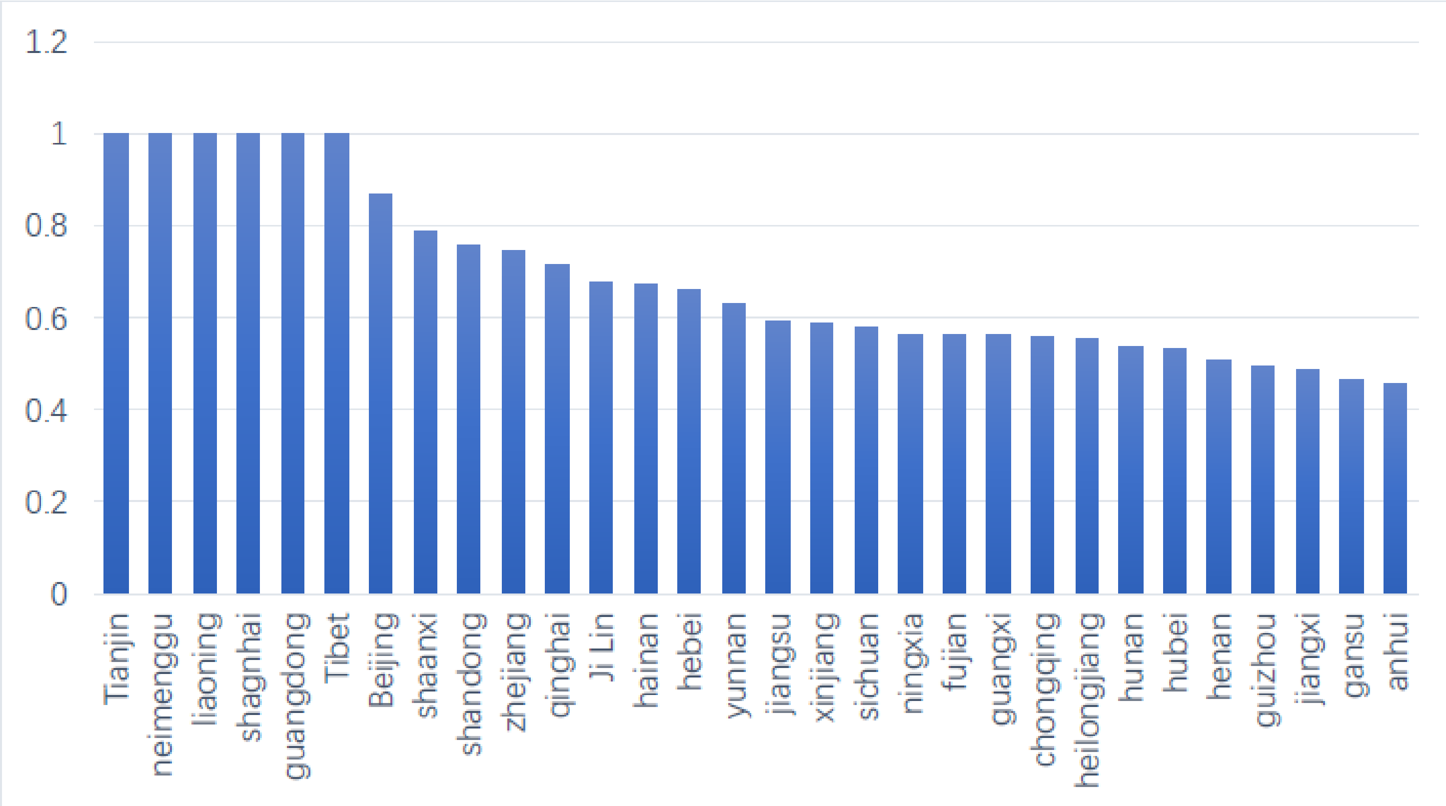

Figure 2

Comparison of industrial eco-efficiency in different provinces in China

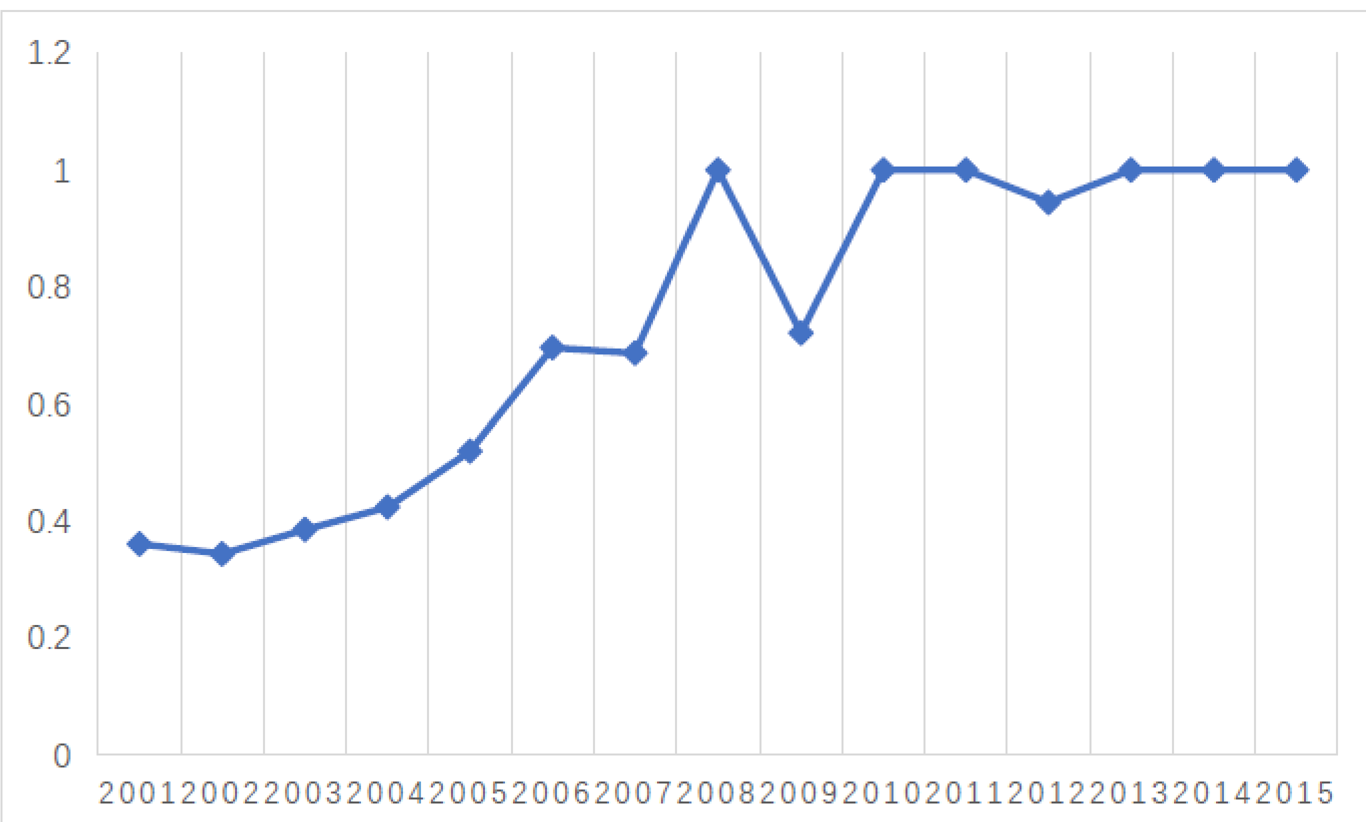

Figure 3

The change trend of industrial eco-efficiency in Xinjiang from 2001 to 2015

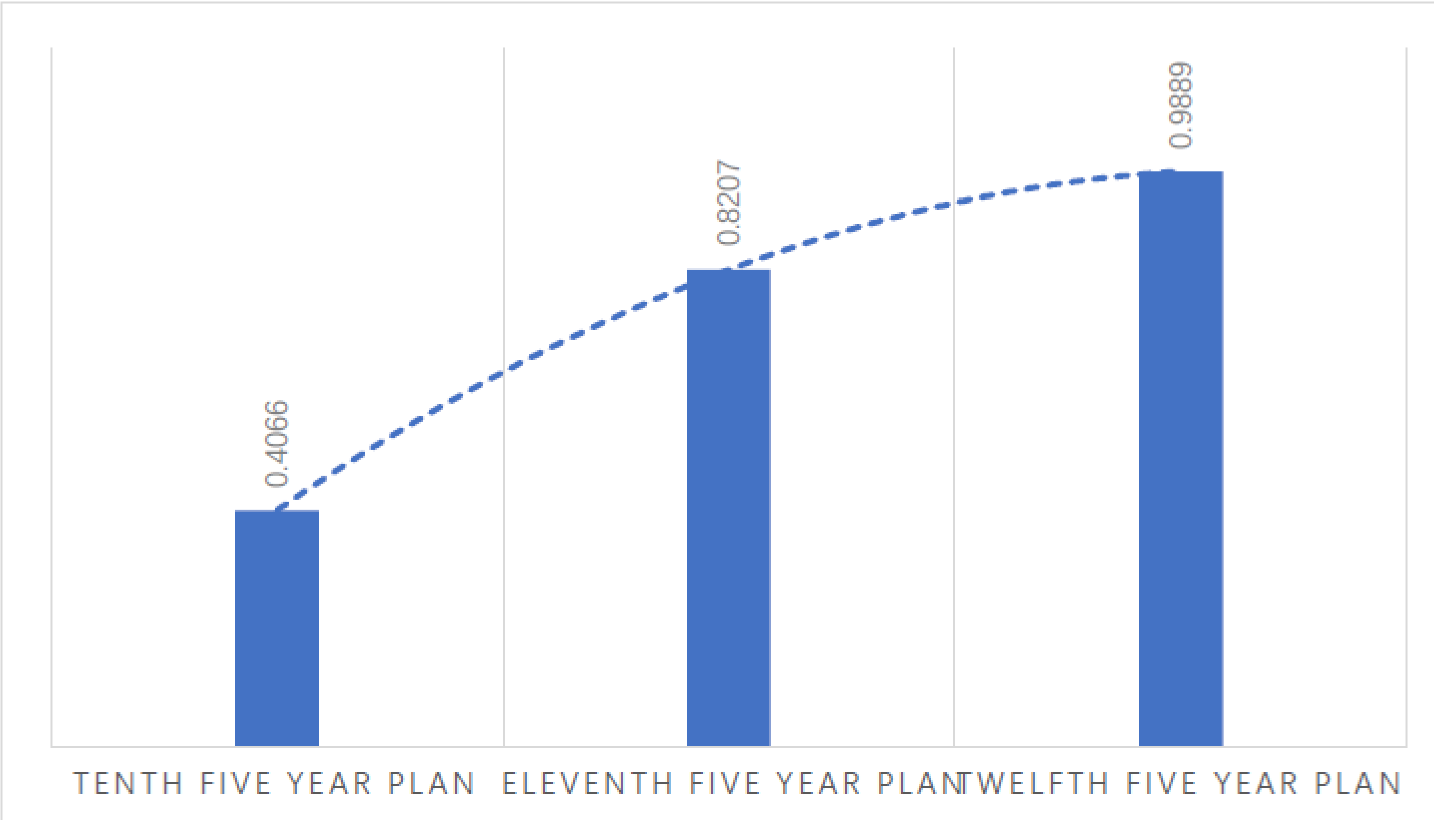

Figure 4

Variation trend of industrial eco-efficiency during the "Tenth five- year plan" to the "Twelfth five- year plan"

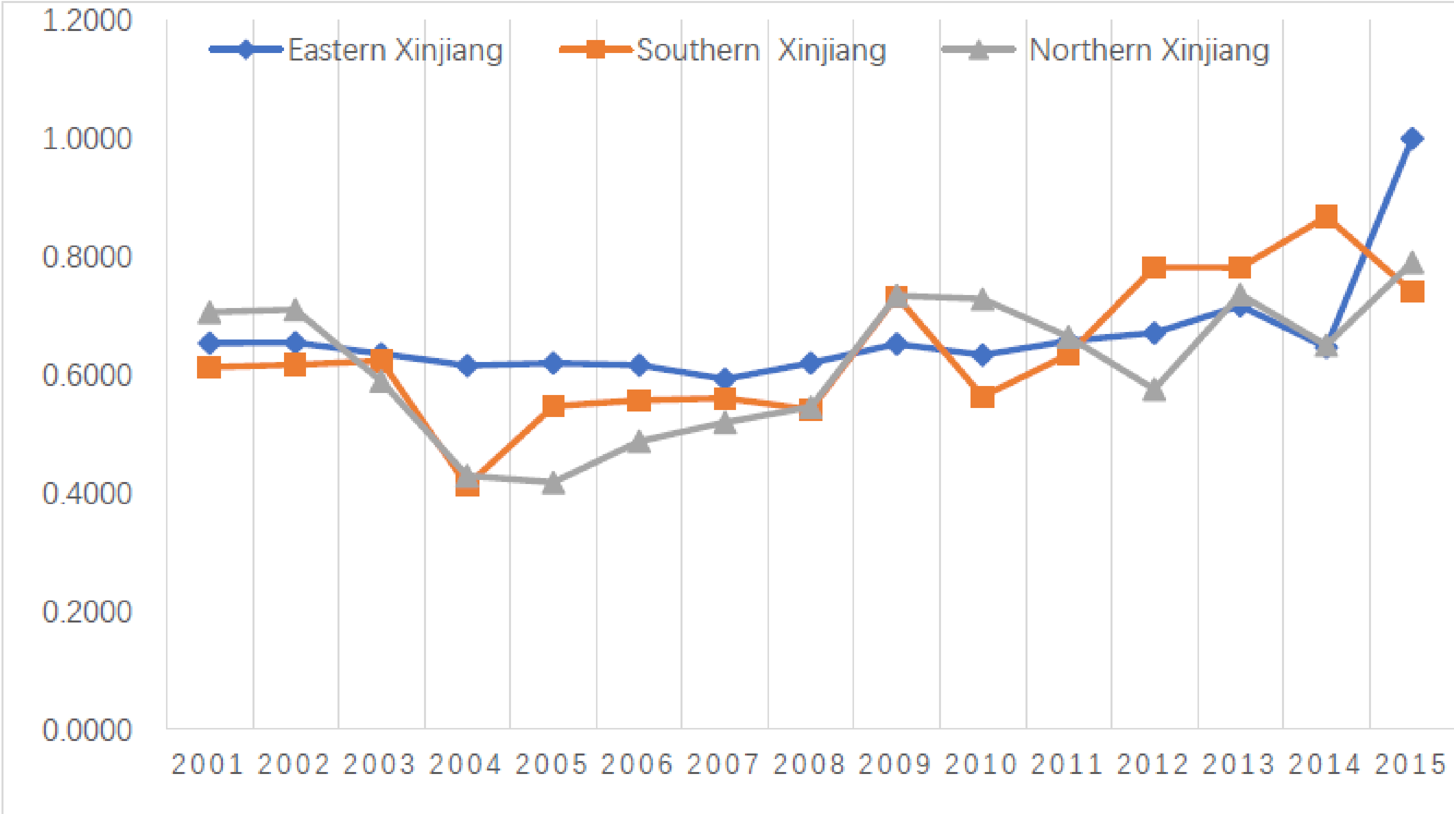

Figure 5

variation trend of industrial eco-efficiency in different regions of Xinjiang from 2001 to 2015

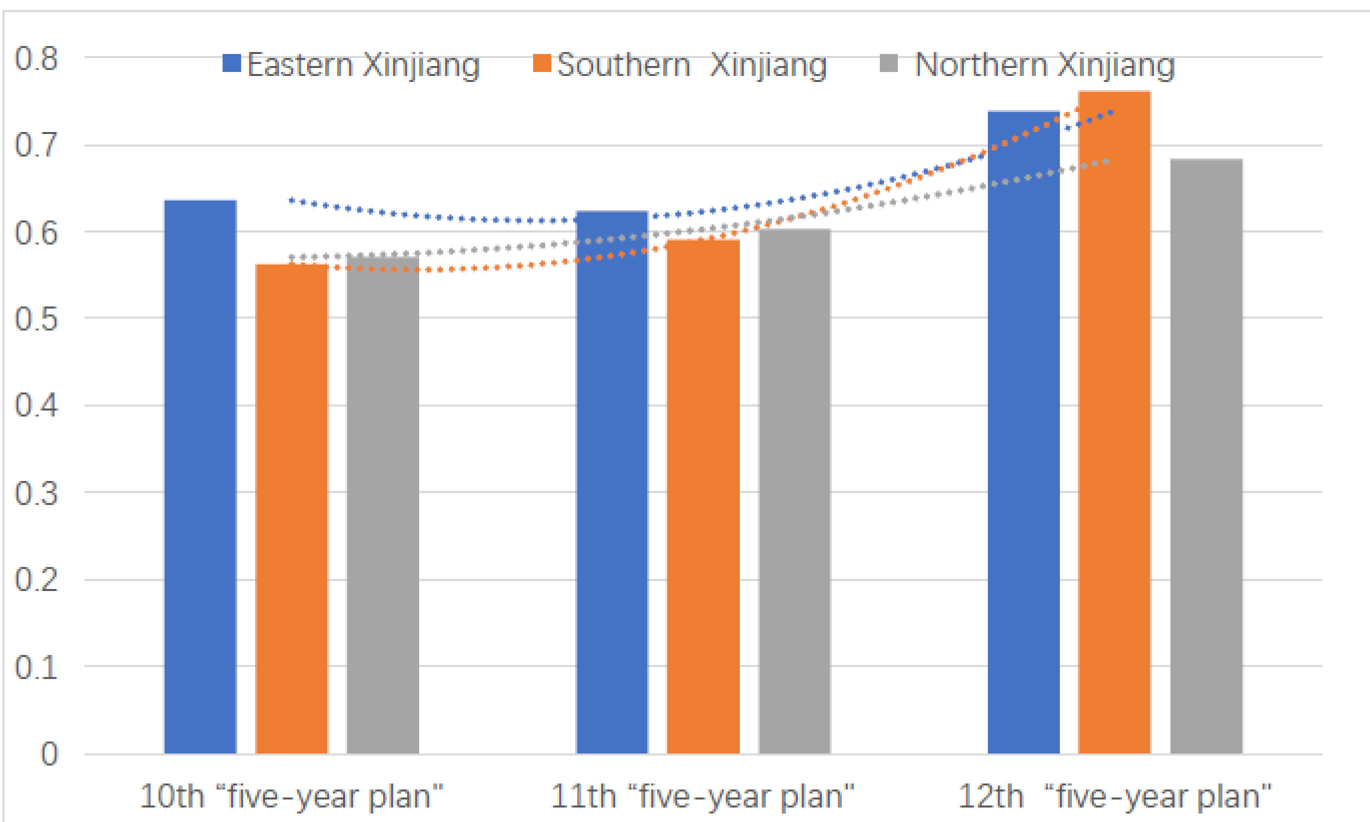

Figure 6

variation trend of industrial eco-efficiency in different regions during the "Tenth five- year plan" to the "Twelfth five- year plan"

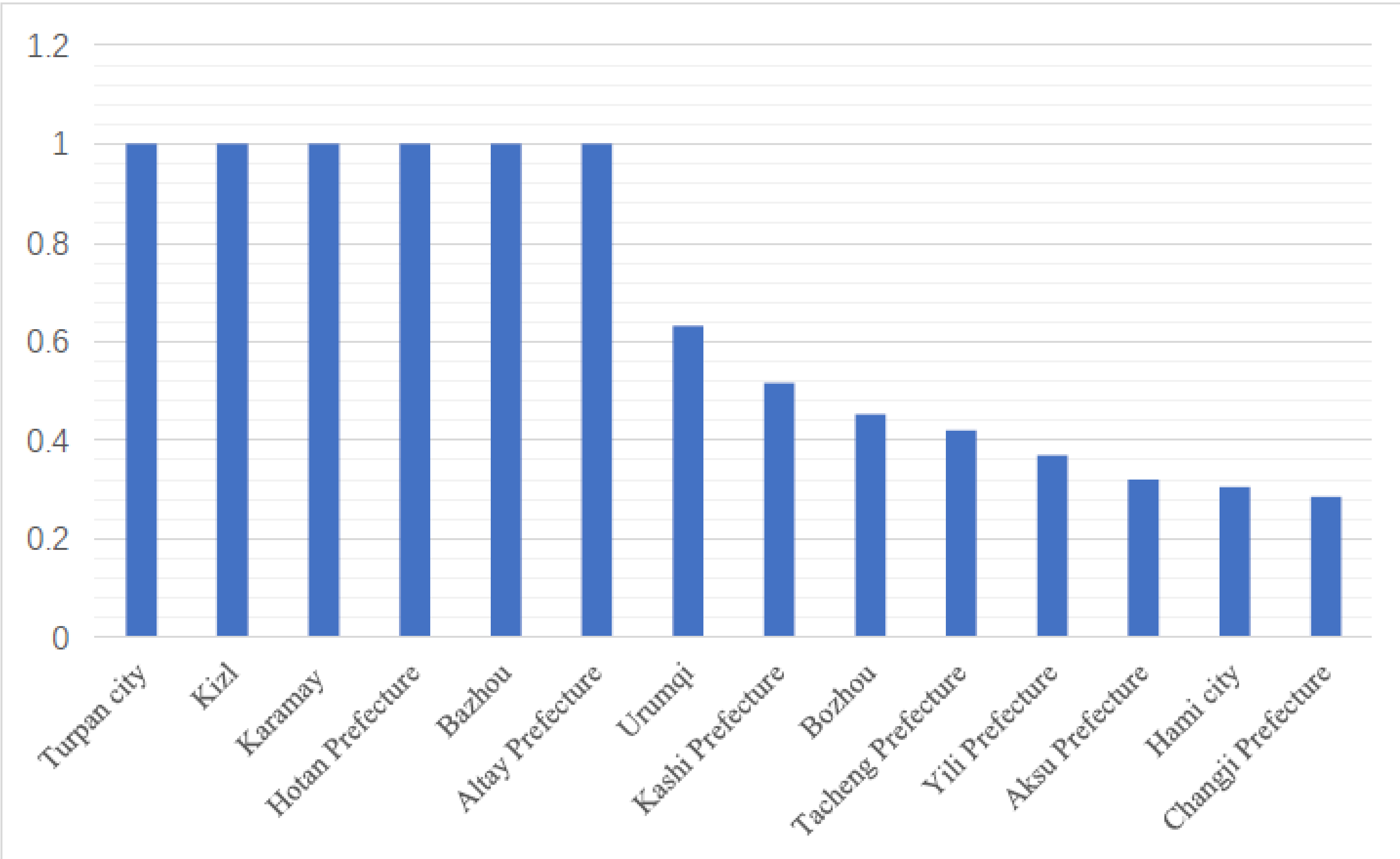

Figure 7

Industrial eco efficiency of 14 prefectures in X injiang

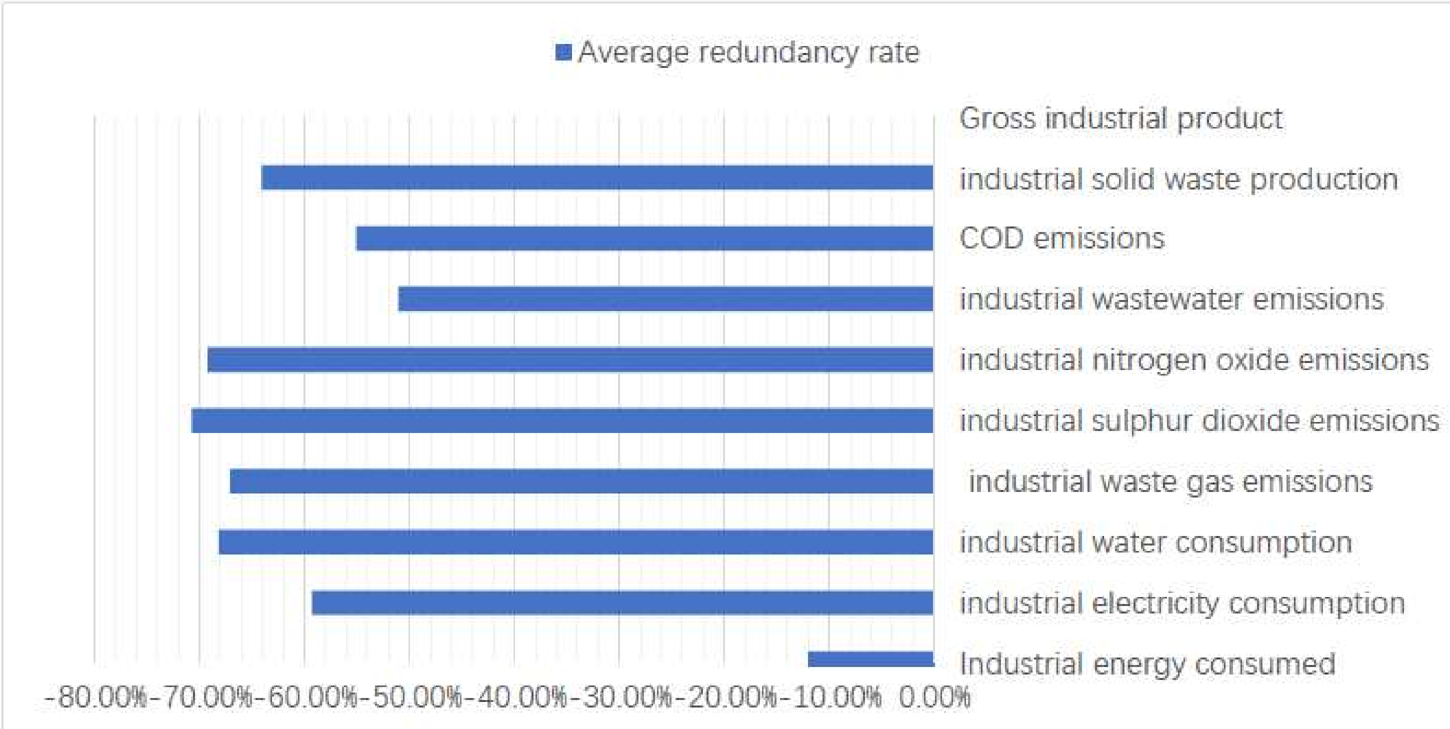

Figure 8

Comparison of redundancy rates of input and output index

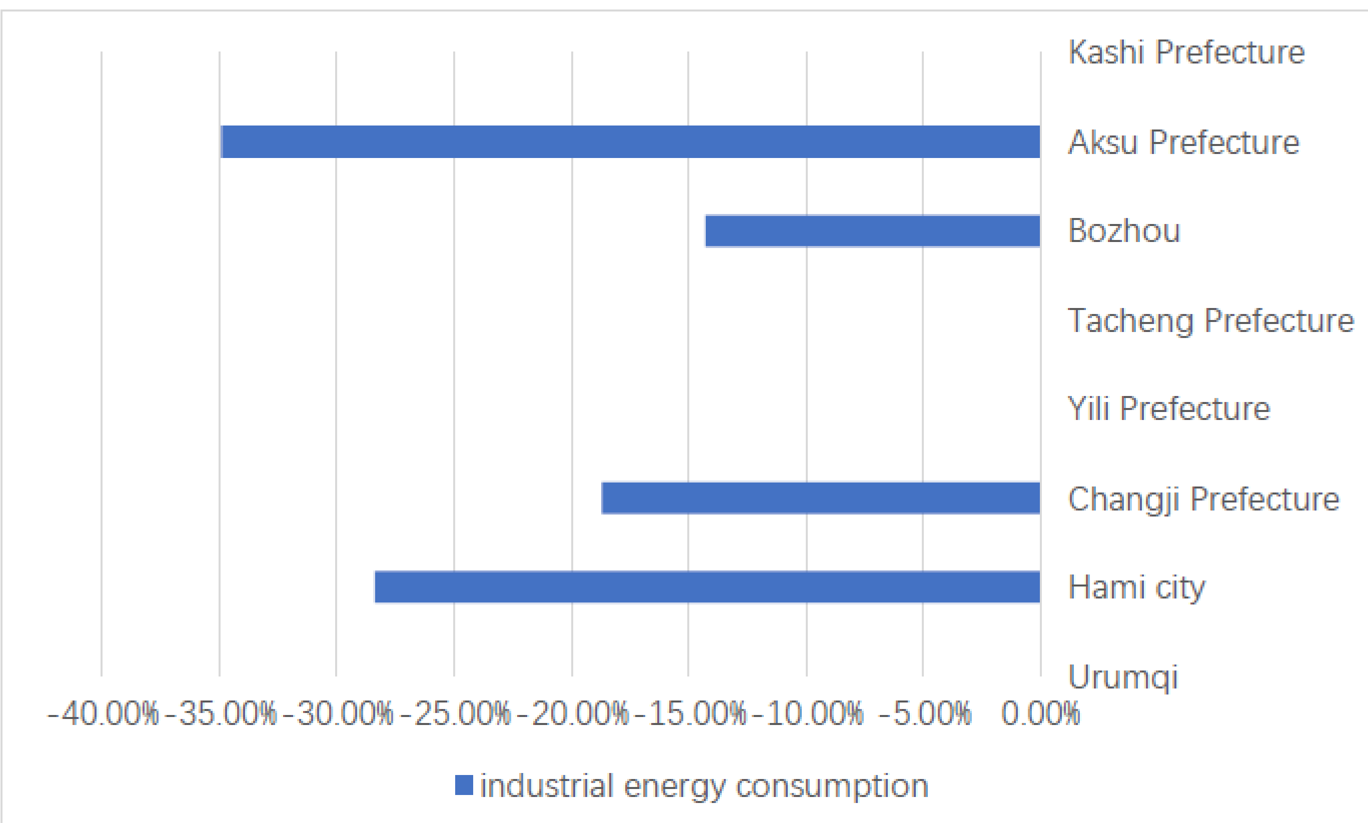

Figure 9

9 Comparison of redundancy rates of industrial energy consumption in different prefectures

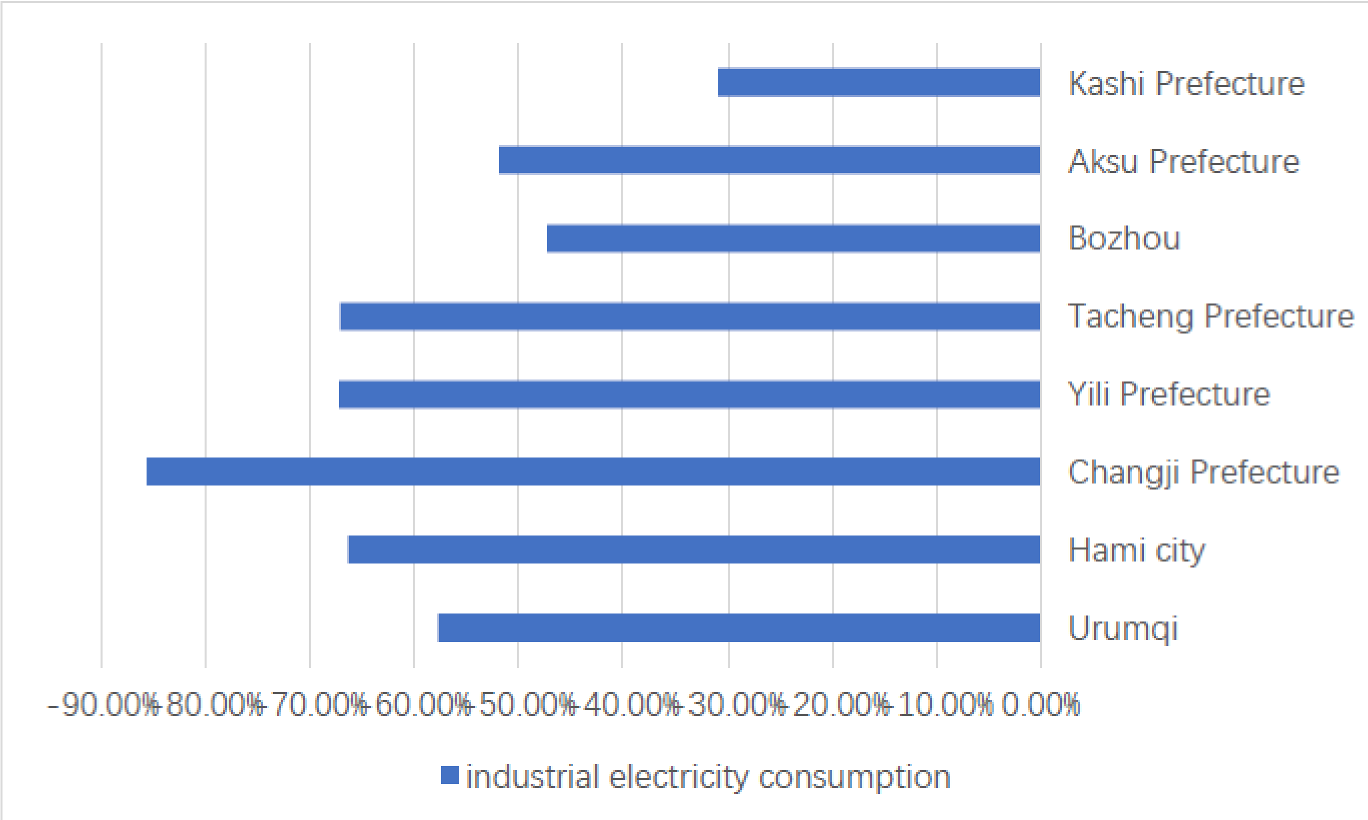

Figure 10

Comparison of redundancy rates of industrial electricity consumption in different prefectures

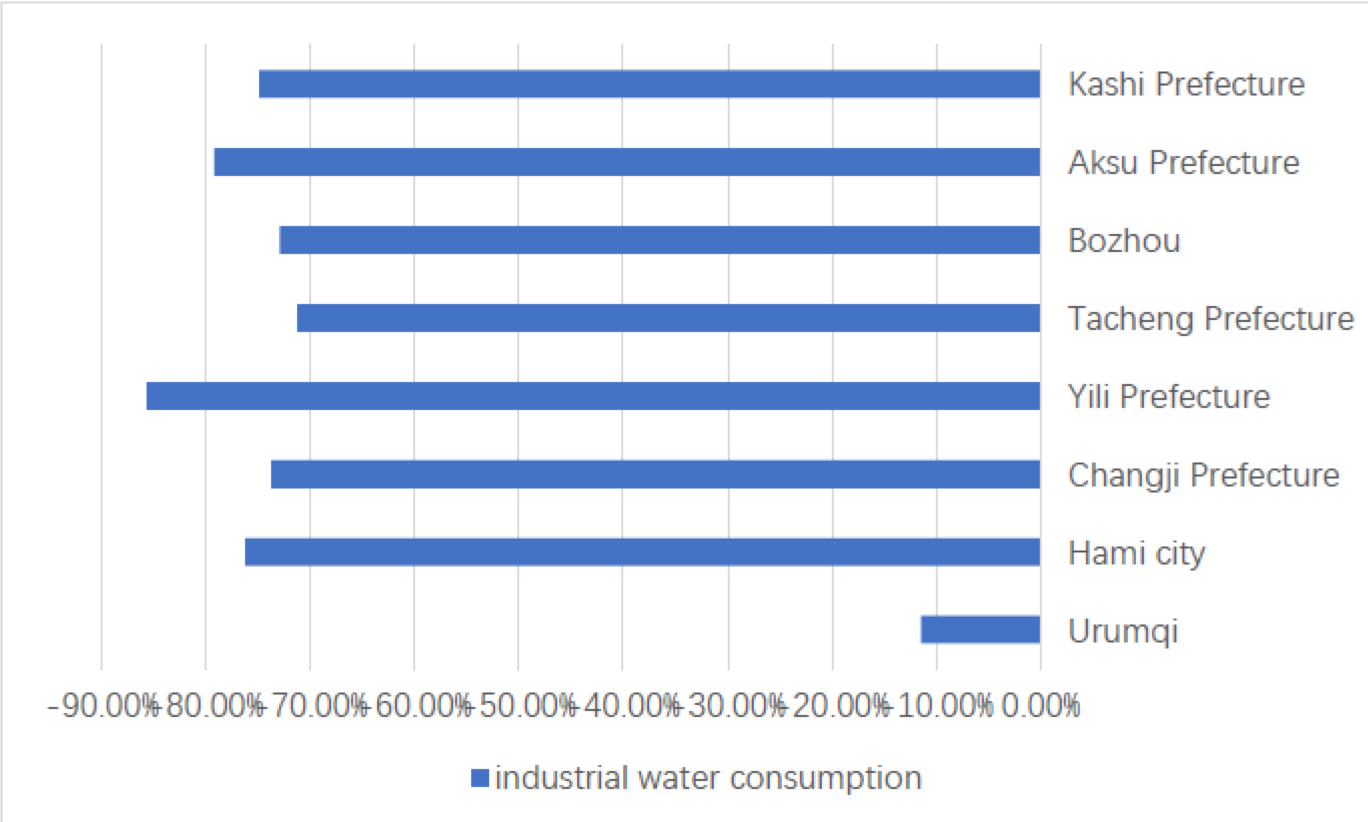

Figure 11

Comparison of redundancy rates of industrial water consumption in different prefectures

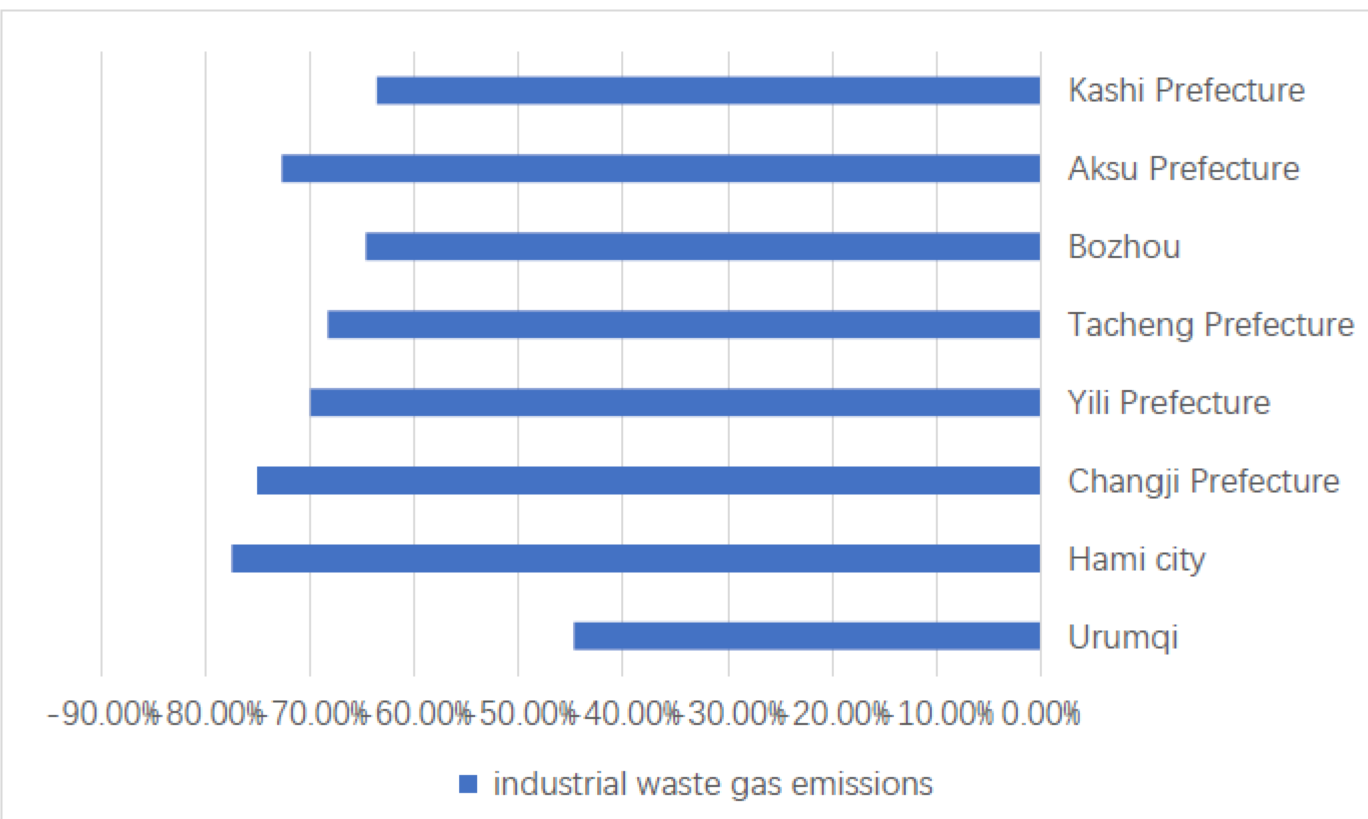

Figure 12

Comparison of redundancy rates of industrial waste gas emissions in different prefectures

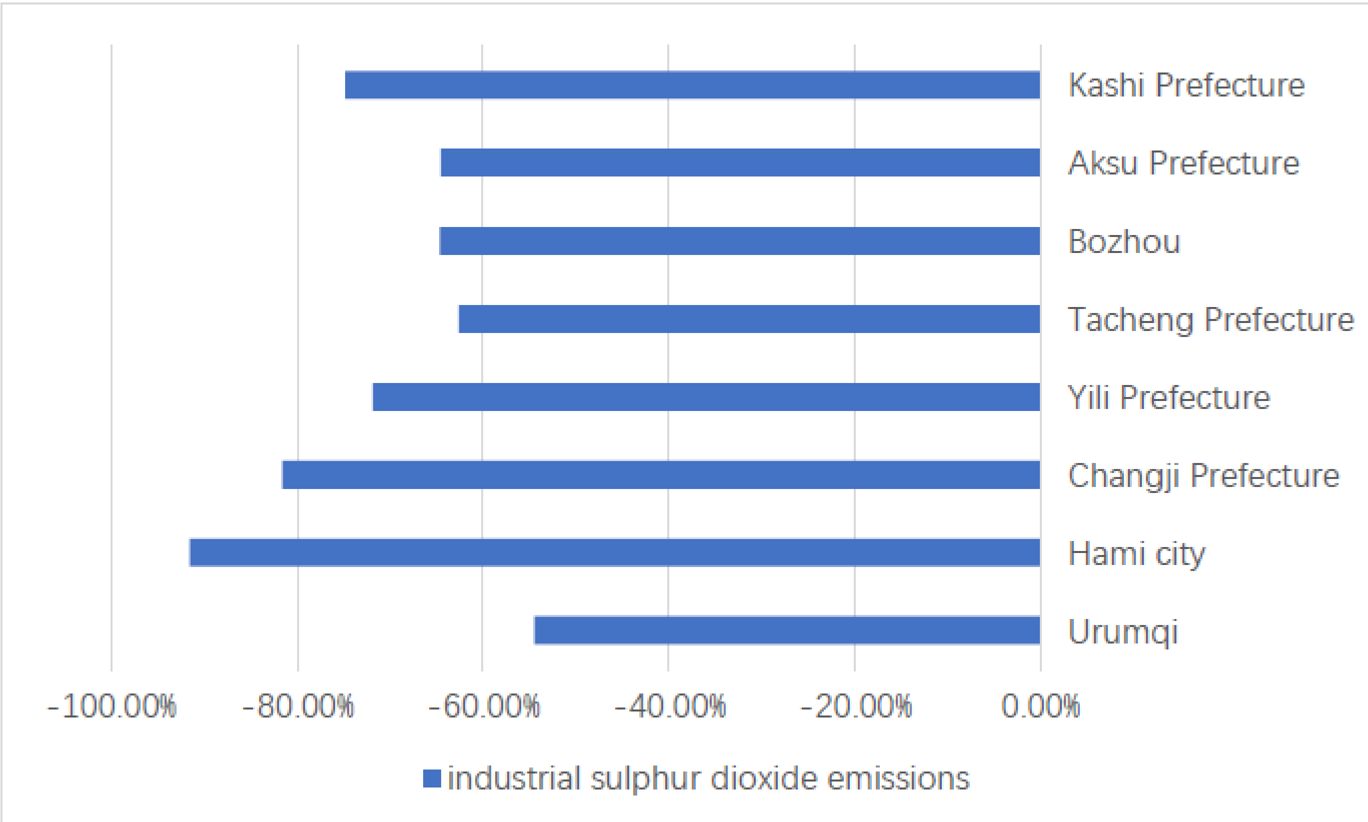

Figure 13

Comparison of redundancy rates of industrial sulphur dioxide emissions in different prefectures

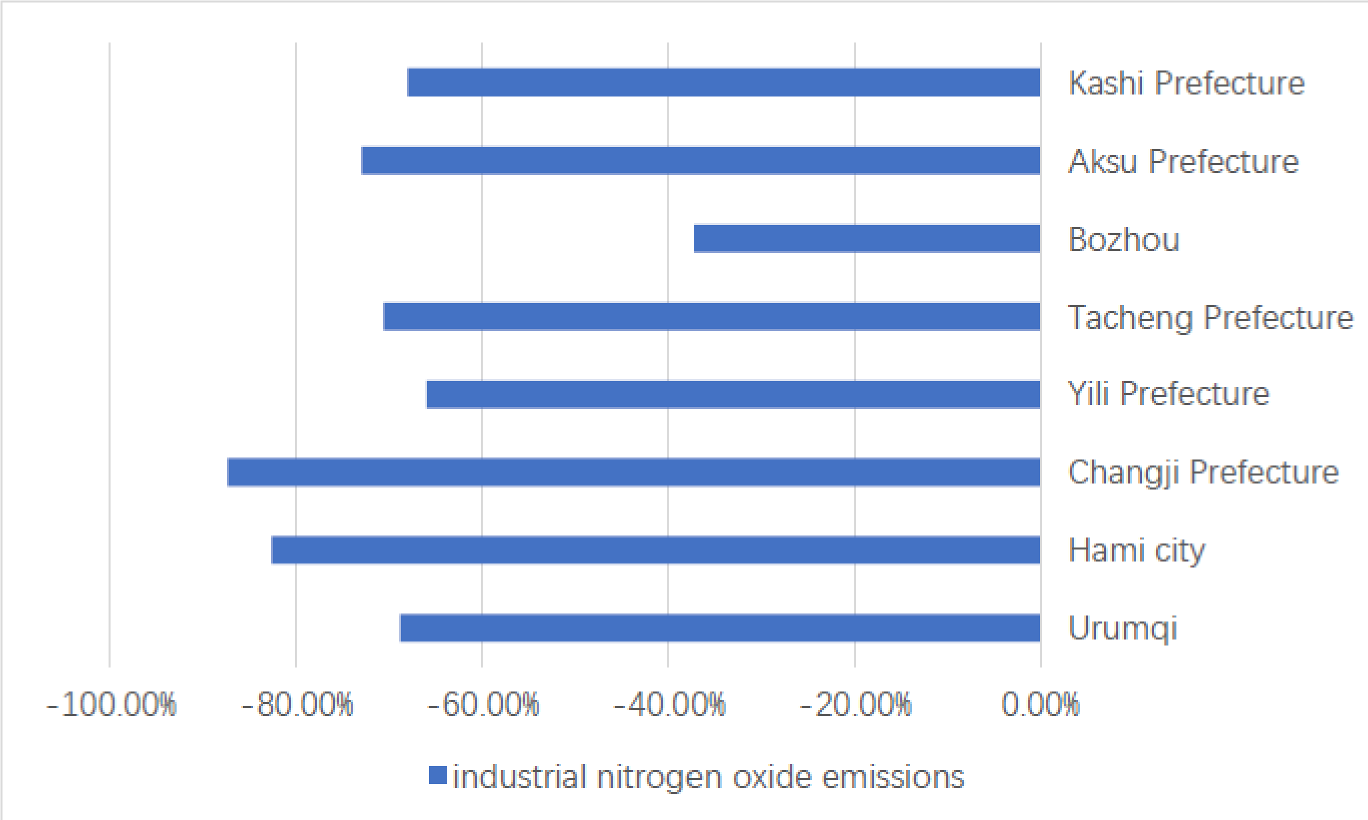

Figure 14

Comparison of redundancy rates of industrial nitrogen oxide emissions in different prefectures

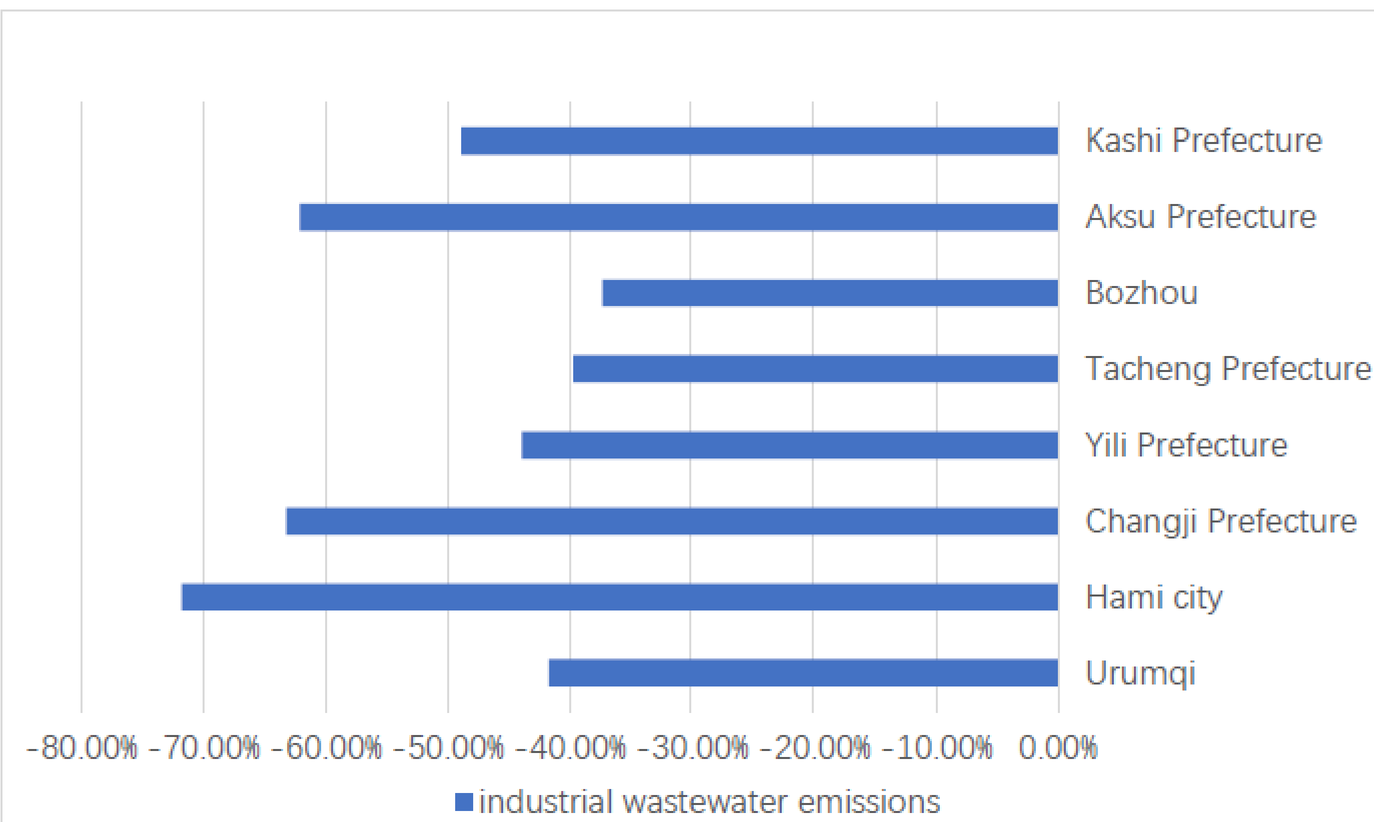

Figure 15

Comparison of redundancy rates of industrial wastewater emissions in different prefectures

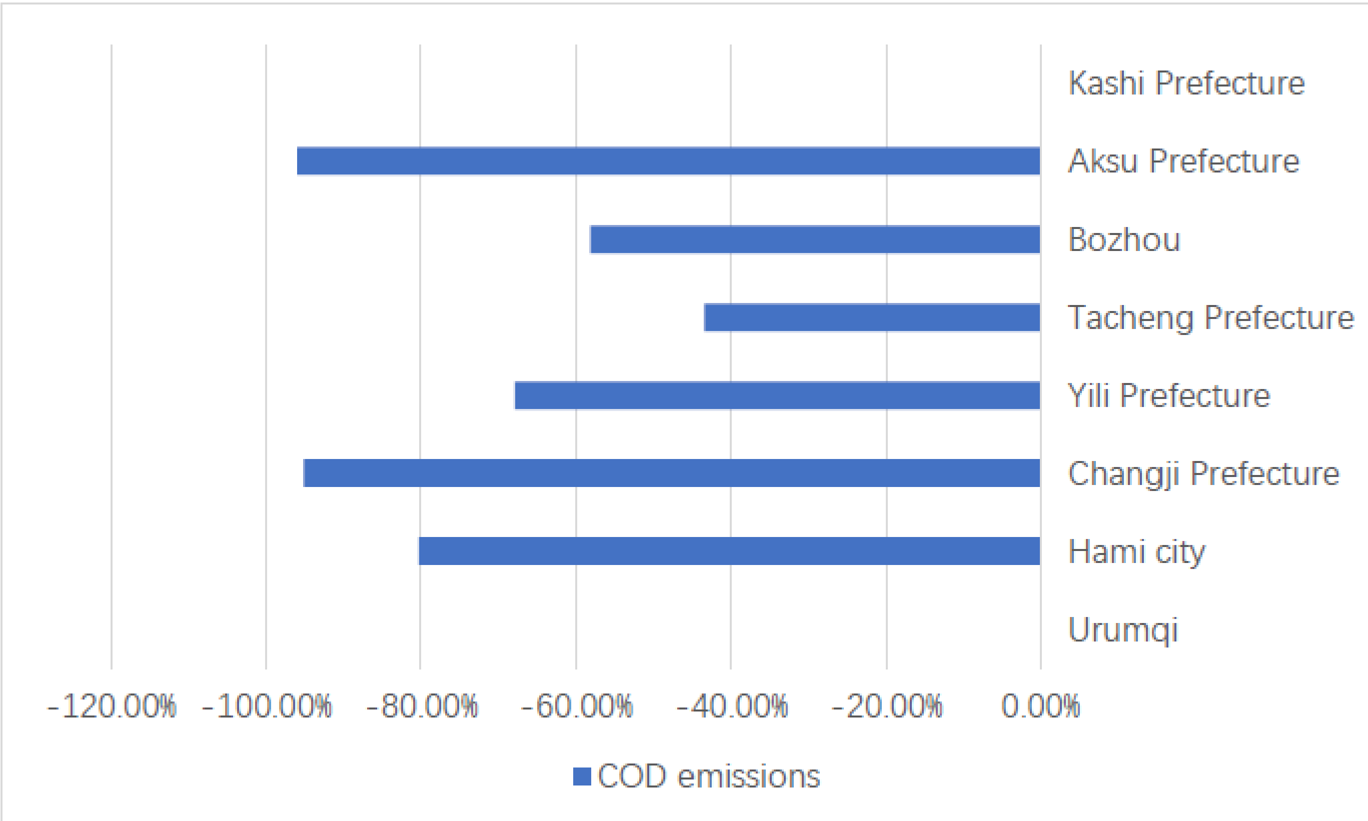

Figure 16

Comparison of redundancy rates of COD emissions in different prefectures

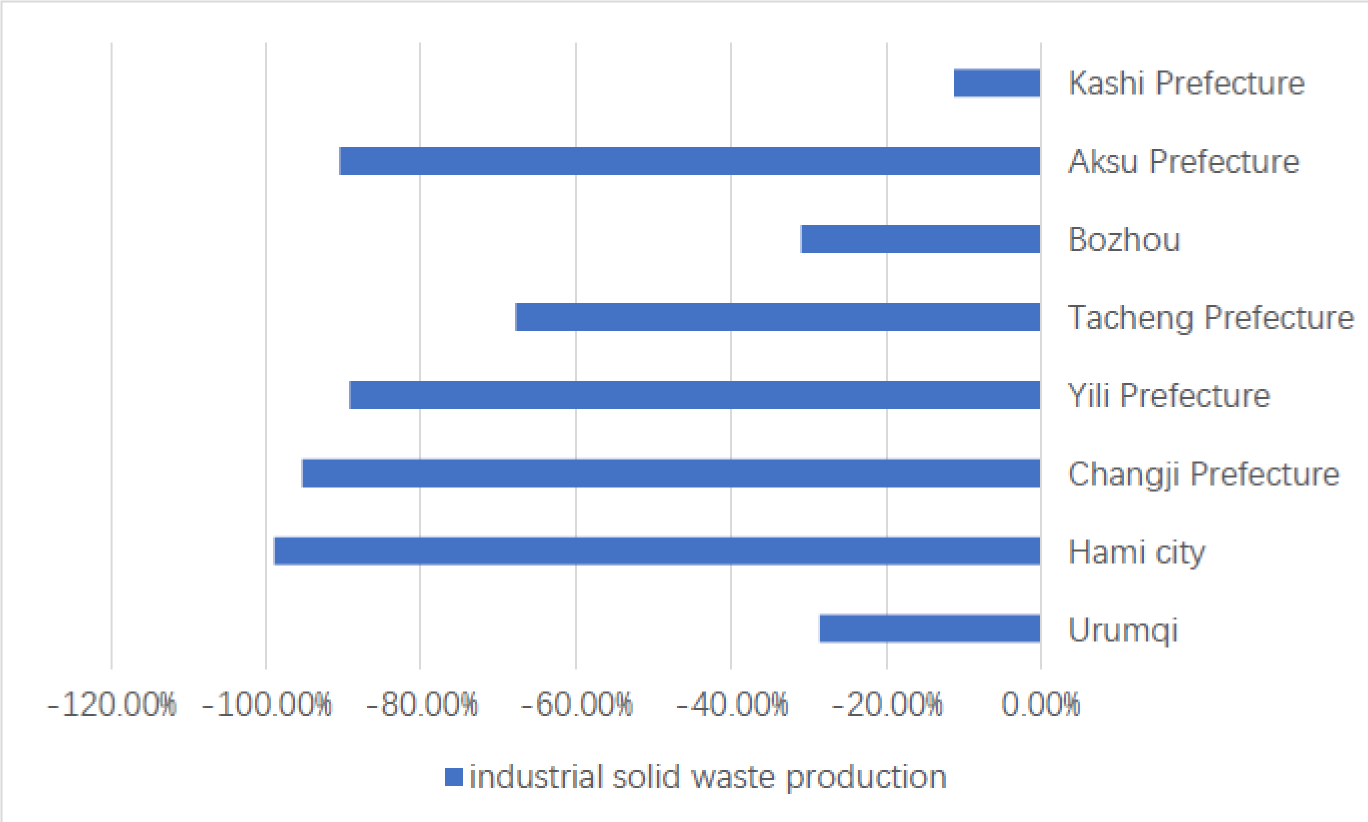

Figure 17

Comparison of redundancy rates of industrial solid waste production in different prefectures

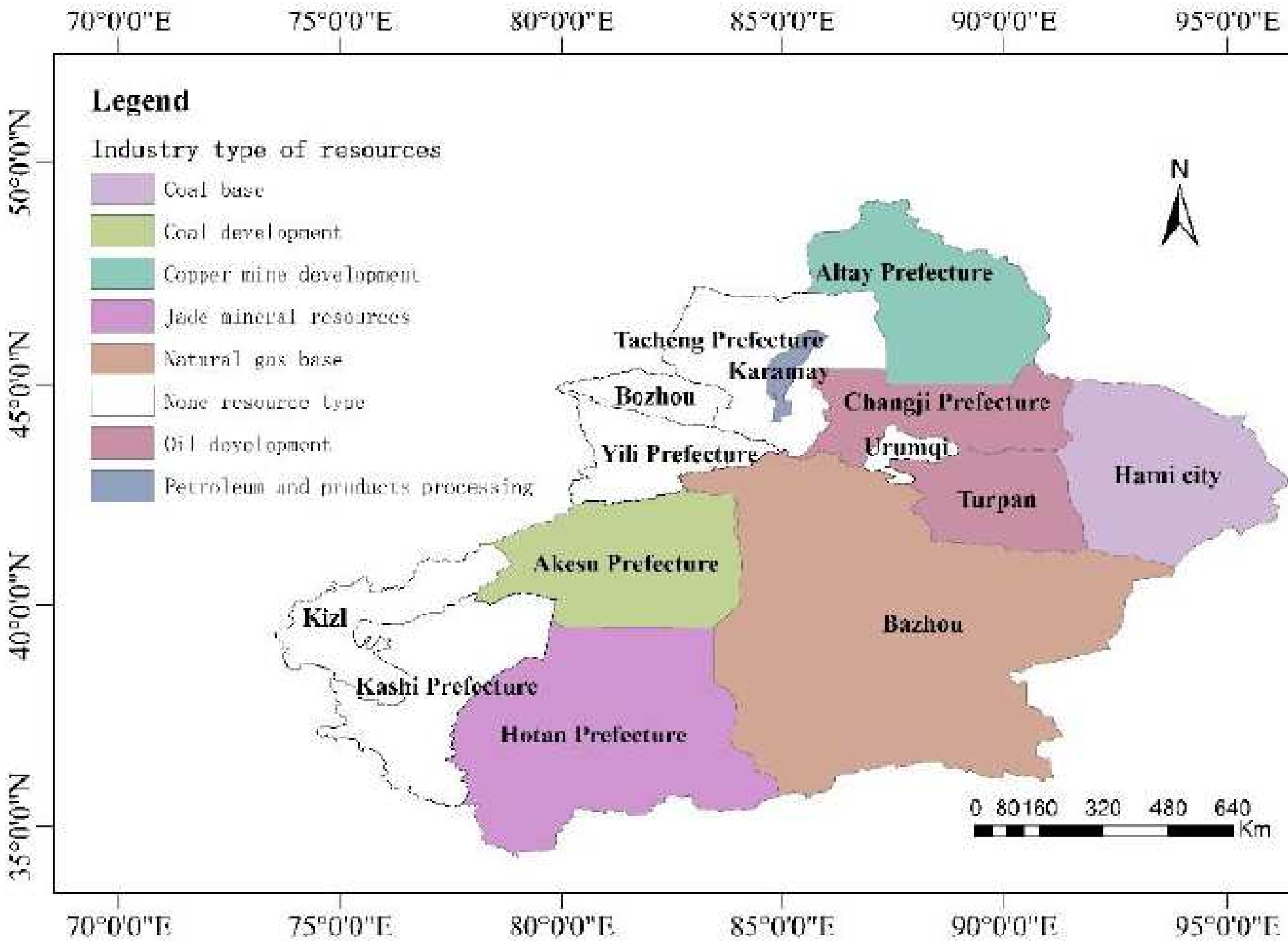

Figure 18

Resource prefecture distribution map of Xinjiang Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.