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The spatial regulation and energy efficiency analysis of wastewater treatment plants in the Beijing-Tianjin-Hebei region

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ABSTRACT

China's wastewater treatment facilities have become increasingly energy-intensive in recent decades. In this study, the relative energy efficiencies of 283 regional wastewater treatment plants in Jing-jin-Ji area (JJJ) were evaluated using a slacks-based measure data envelopment analysis (DEA). Results showed that the efficiencies of 276 wastewater treatment plants have notable improving potential according to the production frontier of DEA. The energy cost of wastewater treatment plants (WWTPs) was quantified for JJJ and analyzed according to the spatial discrepancies. This paper may shed lights on assessment and evaluation of regional wastewater treatment plants considering the energy efficiency.

Keywords: Energy cost, DEA, Energy-water nexus

NONMENCLATURE

Abbreviations	
JJJ	Jing-jin-Ji area
WWTPs	Wastewater treatment plants
DEA	Data envelopment analysis

1. INTRODUCTION

The water security problems such as urban water pollution and excessive sewage discharge have not been fully solved in recent years. Due to the increasing of daily sewage discharge, the demand for advanced wastewater treatment technology is strong, and the energy use intensity of wastewater treatment facilities is increasing continuously [1]. In 2015, China treated 42.88 billion cubic meters of sewage annually, with a sewage treatment rate of 91.90 percent. In 2019, the annual sewage treatment volume increased to 52.59 billion cubic meters, with a sewage treatment rate of 96.81 percent. By the end of 2019, China had 4140 urban wastewater treatment plants. With the rapid development of wastewater treatment plants, China owns the world's largest wastewater treatment industry now [2].

However, with the increase of WWTPs, the increase of wastewater treatment volume leads to an excessive energy consumption. In addition, the Chinese government proposed that China would enhance that its nationally determined contribution and adopt more effective policies and measures to strive for a peak in carbon dioxide emissions by 2030 and achieve carbon neutrality by 2060, at the 75th Session of the United Nations General Assembly on September 22, 2020. It is showed that, with the increasing concern of the government and people on climate issues, energy conservation and energy efficiency had become the principle of common development around the world [3]. In most of the WWTPs, water quality is improved at the expense of significant energy inputs [4]. According to the research, about 20-40% of operating costs can be attributed to energy consumption in traditional WWTP. Therefore, energy optimization of WWTPs is imperative.

Water and energy are closely linked during their production and consumption process [5]. WWTPs are central to water-energy interactions because they consume large amount of energy to remove various pollutants or treat pollutants to acceptable standards for discharge back into the environment or reuse [6]. Yifan et al. quantified the energy consumption of 9 different in southern China with different treatment techniques

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(Oxidation Ditch, Humus Filter, Anaerobic–Anoxic–Oxic, Constructed Rapid Infiltration Technology, 4S-MBR, Membrane Bio-Reactor, Anoxic/Oxic) [7]. Lazarova et al. thought water supply, transportation consumption and wastewater treatment require all forms of energy, while water was one of the most important energy in every stage [8]. Schnoor points out that wastewater treatment through membranes and reverse osmosis as a drinking water supply has a huge energy consumption [9]. To sum up, the water-energy nexus needs to further study.

There are many tools for energy efficiency analysis. Logarithmic mean Divisia index (LMDI), Structural decomposition model (SDA), data envelopment analysis (DEA), multiple criterion decision analysis (MCDA). Ang focused on the LMDI and provided 8 models to analyze industrial electricity consumption. He summarized their origins, decomposition formulas, pros and cons, and laid out guidelines for potential users on model selection [10-11]. Yang et al. used LMDI to analyze the influencing factors of China's carbon emission are discussed according to the actual situation. In 1979, Stanley Zionts published an article about MCDA Which he used to promote and popularize the concept among his business audience. In order to reduce emissions and environmental pollution, Gherghel et al. designed 12 schemes based on the MCDA method [12].

DEA was formally proposed by famous operational research scientist Charnes, Cooper and Rhodes in 1978. The advantage of DEA method is that it does not assume the correlation between input and output indexes. Thus, the evaluation results are objective. The traditional DEA model is linear and cannot measure all slack variables, so it has defects in efficiency evaluation. Slack based model (SBM) is a relatively perfect DEA expansion model, which can meet the needs. Cheng et al. evaluated 681 sewage treatment facilities based on non-radial slack-based data envelopment analysis model to construct an index system. Wang et al. used DEA and SBM models to research the water use efficiency of a regional industrial sector during 2009-2010 in China. Torregrossa et al. used a daily life-cycle analysis (LCA) and DEA analysis in order to monitor the potential deterioration of the eco-efficiency. Zhang and Chen constructed a set of a zero-sum gains (ZSG) two-stage SBM model analyze and evaluate the economic green development efficiency to provide comprehensive efficiency assessment in regions of China [13]. Ayyildiz et al. use stepwise weight assessment ratio analysis (SWARA) method to determine the most appropriate and related parameters, then efficiency scores of WWTPs were calculated using output-oriented DEA models in Turkey [14]. Ramón et al. combined the DEA model with the uncertainty assessments. The model is applicable to a sample of WWTP in Spain [15]. Sala-Garrido et al was evaluated 99 WWTPs in Spanish based-on DEA and technological gap ratios (TGRs) [16]. Bian and Yang focuses on performance analysis for regional urban water use and wastewater decontamination systems based on DEA in China [17]. People research double-bootstrap data envelopment analysis in order to develop a tool for measuring the energy costs of wastewater treatment plants and identifying how they can be reduced. Liu and Yang used DEA to investigates industrial Improving water-use efficiency (WUE) in mainland China. In this study, to unveil the water-energy nexus in wastewater treatment, we used DEA-SBM model to study the energy efficiency of 283 WWTPs in JJJ.

2. METHODS

2.1 Slack-based measure and date envelopment analysis

DEA is a method of operations research and study of economic production boundary. This method is generally used to measure the production efficiency of some decision-making departments. DEA is a linear programming model, expressed as the ratio of output to input. It tried to maximize the efficiency of a service unit by comparing the efficiency of a service unit with the performance of a set of similar units that provide the same service. In addition, DEA can be either input-oriented or output-oriented. In the input-oriented model, DEA quest for how much can the input be reduced proportionately when output level is kept fixed. In the output-oriented model, DEA quest for the maximum proportional increase in production when input level is kept fixed.

In this study, an output-oriented model was chosen to determine the potential for reducing energy. The slack-based measure (SBM) model based on DEA was selected.

If n DMUs (j=1, ⋯ ⋯, n) contain m inputs (i=1, ⋯, j) and p outputs (r=1, ⋯, p), the basic mathematical expression of output-oriented VRS SBM DEA is displayed as following:

Table 1 Statistical characteristics of indicator wastewater treatment plants in Beijing-Tianjin-Hebei region.

	Indicators	Min.	Max.	Mean	Std.dev
Input	Total electricity consumption(kWh)	188,505	155,679,906	8,010,745	16,926,845
Output	COD removal(10^3kg)	29	776	264	136
	BOD_5 removal(10^3kg)	9	454	115	63
	SS removal(10^3kg)	15	1,162	161	109
	TN removal(10^3kg)	5	102	32	15
	TP removal(10^3kg)	0.3	16	4	2

$$\begin{aligned} \max = 1 + \frac{1}{p}\sum\nolimits_{i=1}^{p} \frac{s^+}{x_k} \\ s.t.\, X\lambda \le x_k \\ Y\lambda - s^+ = y_k \\ e\lambda = 1 \\ \lambda, s^+ \ge 0 \end{aligned} \quad (1)$$

The *k* is the sequence number of DMU, λ represents a nonnegative vector, *X* is the input matrix, *Y* represents the output matrix, s^+ stands for the slack variables of the output indicators, *e* is the unit vector, and θ represents the efficiency score and holds $0 < \theta \le 1$. In the outcome of Eq. (1), the θ of an efficient DMUs equals 1, while that of an inefficient DMU is less than 1 but greater than 0. The software used to run the DEA was DEAP 2.1.

2.2 Water energy intensity

In this paper, we use this indicator to compare water-energy efficiency between different WWTPs. We can easily compare the energy consumption of regional sewage treatment. The specific formula is as follows:

$$\rho = \frac{u}{w} \quad (2)$$

The p is the water energy intensity, u represents electricity consumption of one WWPTs, w is the total treated water of one WWPTs. In order to highlight regional efficiency differences, we need to study Beijing, Tianjin and Henan respectively.

$$\rho_t = \frac{u_t}{w_t} \quad (3)$$

The t means study area (t=Beijing, Tianjin, Hebei). The p_t is the water energy intensity of area t, u_t represents total electricity consumption of WWTPs in area t. The w_t means the total treated water of area.

3. DATA SOURCES AND CASE STUDY

3.1 Data sources

The WWTPs data comes from urban Drainage Yearbook published by China Urban Water Association. From this book, we get data on the total electricity consumption (kWh), and annual mean concentration (mg/L) of COD, BOD_5, SS, TN and TP. In addition, data of design capacity ($10^4m^3/d$) and process type were extracted from the List of Chinese urban sewage treatment facilities released by The Ministry of Ecology and Environment. In order to achieve the purpose of the study, we carried out a comprehensive quality check on all data. Therefore, 283 valid samples of Beijing-Tianjin-Hebei region wastewater treatment plants were used in this study. Descriptive statistics of variables were showned in Table 1.

3.2 Case study

The JJJ is China's capital economic circle, which includes Beijing, Tianjin and Hebei province (Baoding, Langfang, Tangshan, Shijiazhuang, Handan, Qinhuangdao, Zhangjiakou, Chengde, Cangzhou, Xingtai, Hengshui, Dingzhou, Xinji) and the land area is 218,000 square kilometers. The largest and most dynamic region in northern China, JJJ has attracted more and more attention from China and even the whole world. But JJJ region is one of the most densely populated and severely polluted areas in China. The severe situation of water resource environment has captured high attention of the Chinese government.

For the JJJ, Beijing and Tianjin each has 43 wastewater treatment plants. Hebei has the most WWTPs, accounting for 69.61 percent of the entire JJJ (Fig 1). In addition, WWTPs are typical facilities which water and energy are highly interconnected and generate significant levels of carbon emissions that contribute to climate change. Optimization of WWTPs needs to be studied to meet the needs of regional development and carbon neutrality. Under this background, goals of energy-saving and emission-

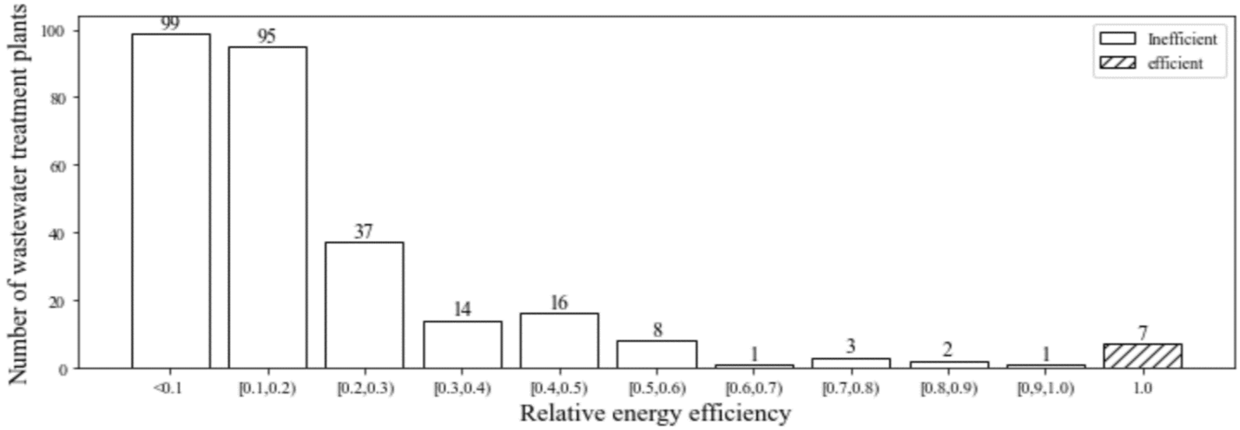

Fig 1 Distribution of wastewater treatment plants at intervals based on relative energy efficiency

reducing have been attached to the regions at national and global levels.

4. RESULTS AND DISCUSSION

4.1 Efficiency evaluation of WWTPs in the Jing-Jin-Ji area

The REE of an efficient WWTPs equals showed that of an inefficient WWTP was less than 1 but greater than 0. All the plants are within the efficiency score range, indicating that only 2.47% of the WWTPs were relatively efficient (REE). As the mean REE was 0.202 and there were 88 WWTPs at the intervals of which the upper bound was less than 0.202, 31.1% of WWTPs were lower than the average level. Beijing had 19 WWTPs with above-average REE score, and it was 24 WWTPs below average REE score. There were 13 WWTPs above average level and 31 WWTPs below average level. Hebei has the largest number of WWTPs in the region, with 63 above average and 133 below average.

After the data screening statistics, we found the REE of most WWTPs is at (0,0.2) which accounts for 68.55% of the total wastewater treatment plants. we can easily find that most WWTPs were inefficient (There were 194 WWTPs with a REE of less than 0.2). This means that the overall WWTPs energy efficiency of the JJJ is low. Furthermore, there were less WWTPs at the interval of [0.6,1), it means that there was a large gap between efficient and inefficient WWTPs.

4.2 Water energy intensity

According to the picture, the larger the green dot in the picture, the greater the amount of energy required per unit of sewage treatment. we can clearly find that the total sewage discharge of Hebei is about the same as that of Beijing, but the energy shortage is twice as high.

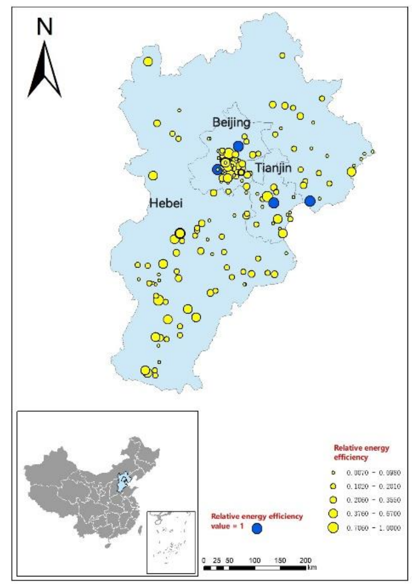

Fig 2 Relative energy efficiency of JJJ

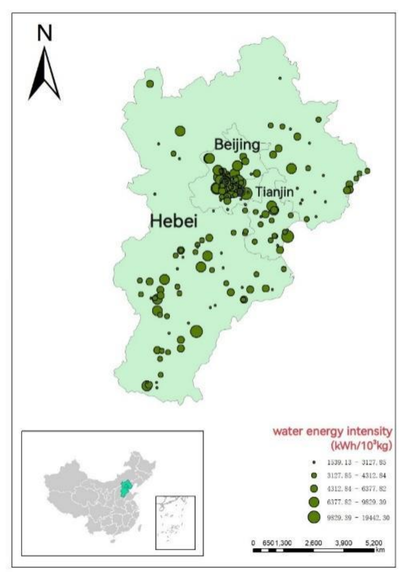

Fig 3 Water energy intensity of JJJ

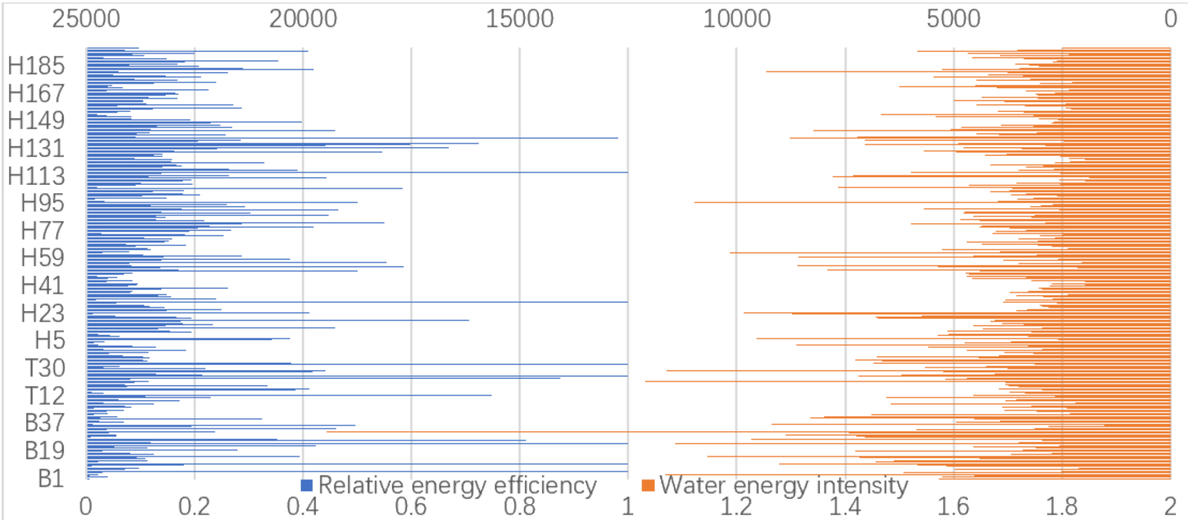

Fig 5 Diagram of relative energy efficiency versus water energy intensity

4.3 Discussion

According to the efficiency chart made by DEA model (Fig 2), we can find that WWTPs are mainly distributed around Beijing and there are 3 WWTPs with an efficiency of 1. Tianjin had 2 highly effective WWTPs. Hebei's WWTPs were scattered, it was also having 2 highly effective WWTPs. In water energy intensity picture (Fig 3), the higher the dot, the more energy it consumes. For better analysis, we compare energy intensity regionally.

Table 2 Regional water and electricity situation

	Wastewater processing (10^3kg)	electricity consumption (kWh)	Average relative efficiency
Beijing	168744.87	935192973	0.2028
Tianjin	103592.54	349457890	0.2090
Hebei	245482.1	982389934	0.2005

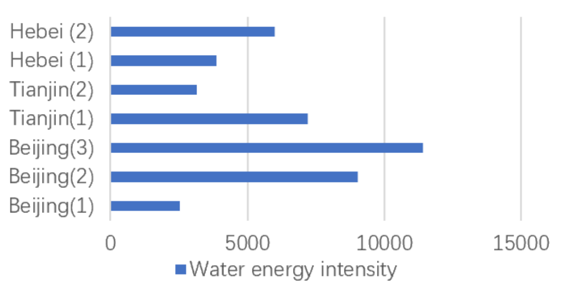

Fig 4 Regional water energy intensity comparison

In the table 2, Hebei is the province with the most water treatment capacity and the province with the most electricity consumption in JJJ. Tianjin has the lowest electricity consumption and sewage treatment capacity in JJJ. But according to the regional average relative efficiency, Tianjin had the highest average REE score. Hebei and Beijing consume similar amounts of electricity, but Beijing treated far less sewage. It was show that the efficiency of Hebei WWTPs was obviously lower than Beijing's and Tianjin's from the regional relative efficiency average.

Overall, water energy intensity seemed to be consistent with DEA evaluation. Through the introduction, we knew that the efficiency obtained by DEA model was objective, but the treatment capacity of different pollutants in WWTPs was not the same. We compared WWTPs with an efficiency score of 1 in more detail (Fig 4).

The picture (Fig 5) provides a comparison of the water energy intensity and relative energy efficiency of 283 wastewater treatment plants. The B1-B43 represent WWTPs of Beijing, the T1-T43 means WWTPs of Tianjin and the H1-H197 represent WWTPs of Hebei. We can easily see that in most cases the relative energy efficiency is high, and the water intensity is low, but sometimes it is different, so that We cannot judge the removal efficiency of WWTPs by relative energy efficiency alone.

5. CONCLUSIONS

This study evaluated the relative energy efficiency of wastewater treatment plants in the JJJ using a slacks-based measure data envelopment analysis model, in which we choose total electricity consumption as input and choose COD, BOD_5, SS, TN and TP as output. The Results of water energy intensity demonstrated that directly evaluation of the efficiency, water energy intensity, is biased. For example, the T25 of REE which value equal 1 was higher than T24 of REE, but T24 of water energy intensity was higher than T25. The study of wastewater treatment plant efficiency needs to be comprehensively evaluated.

From the production and technology perspective, we found that 7 plants owned the highest energy efficiency, and the wastewater treatment technology included anaerobic anaerobic (AAO), anaerobic (AO), oxidation ditch (OD), Sequencing batch Reactor (SBR) and circulating activated sludge technology (C-TECH). The results of this study will guide further analysis and the theories established in this study can be used for reference in other fields.

6. ACKNOWLEDGEMENTS

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