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Evaluating the energy neutrality potential of wastewater treatment plants based on comprehensive water-energy efficiency and self-sufficiency rate

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ABSTRACT

Municipal wastewater treatment plants (WWTPs) consume lots of energy and produce large amounts of greenhouse gases (GHGs) to remove pollutants. Nowadays, the concept of energy self-sufficient WWTPs is attracting more attention. This study aims at proposing an evaluation framework for energy neutrality potential of WWTPs from an integrated dimension of water-energy efficiency and energy recovery. To achieve this, operational data of 970 WWTP samples located in Yangtze River Economic Belt (YREB) was extracted from China Urban Drainage Yearbook 2018. The chemical and thermal energy of WWTPs samples were estimated via the technology of combined heat and power (CHP) and water source heat pump (WSHP), respectively. Based on the results of CHP and WSHP, 2 key performance indicators (KPIs) were established to characterize the capability of WWTPs from aspects of basic function and energy recovery, respectively. The first one is comprehensive water-energy efficiency (CWEE) solved by data envelopment analysis (DEA) and the other is energy self-sufficiency rate (ESSR). In terms of the result, 98 samples were determined to be the benchmark, while 112 have potential to achieve the full self-sufficiency level. Moreover, there are 4 types of energy neutrality potential classified with the median of two KPIs set as the critical value. Besides, the explanatory factors were also analyzed, and results show that treatment capacity, influent concentration of chemical oxygen demand (COD), and influent ratio of 5-day biochemical oxygen demand to COD (BOD_5/COD) affect the potential significantly. In addition, the energy neutrality potential of samples in the subregions differs distinctly. This study proposes the evaluation on the potential of WWTPs' energy neutrality with 2 KPIs from both perspective of water-energy efficiency and energy self-sufficiency. The results could provide guidance for other WWTPs under optimization for energy neutrality.

Keywords: wastewater treatment plants, energy neutrality, data envelopment analysis, comprehensive water-energy efficiency, energy self-sufficiency rate, Yangtze River Economic Belt

NONMENCLATURE

Abbreviations	
BOD_5	5-day biochemical oxygen demand
COD	Chemical oxygen demand
CWEE	Comprehensive water-energy efficiency
CHP	Combined heat and power
DEA	Data envelopment analysis
ESSR	Energy self-sufficiency rate
GHG	Greenhouse gas
KPI	Key performance indicator
NDC	Nationally determined contribution
NZE	Net-zero energy
NH_4^+-N	Ammonia nitrogen
SBM	Slacks-based measure
TN	Total nitrogen
VRS	Variable returns to scale
WSHP	Water source heat pump
WWTP	Wastewater treatment plant
YREB	Yangtze River Economic Belt

1. INTRODUCTION

Wastewater treatment plants (WWTPs) are facilities that consume high-intensity energy and emit considerable greenhouse gases (GHGs) [1]. To address the challenges of sustainability, new concept WWTPs are required to ensure water quality, energy recovery and resource recycling at the same time [2]. Nowadays, based on China's nationally determined contribution

(NDC) to achieve carbon neutrality in 2060, decarbonization has been furtherly emphasized on the transition of WWTPs.

So far, the main pathways towards decarbonization for WWTPs can be summarized as '3 Rs' of reduction, recovery and renewables of energy [3]. In specific topics, Gu et al. explored the feasibility of energy self-sufficiency and demonstrated that the usage of biogas from the anaerobic digestion of sludge for digester heating and electricity generation is an effective manner to improve the energy self-sufficiency rate (ESSR) [4]. Yan et al. proposed the net-zero energy (NZE) model to utilize the on-site energy of WWTPs [5]. The results show that chemical and thermal energy of WWTPs have much potential to be recovered. Yang et al. applied the exponential regression to simulate the parameters of energy recovery technologies and found that the incorporation of both the internal and external energy would be better to achieve NZE through technologies of combined heat and power (CHP), water source heat pump (WSHP), and photovoltaic (PV) [6]. Wu et al. elucidated the energy flow in terms of dinitrogen process and pointed out that the combination of organics capture at the early stage and anaerobic ammonia oxidation is a promising approach for WWTPs towards energy neutrality [7]. Besides, Liu et al. revealed the existence of marginal effect in energy recovery scenarios and indicated that, for a certain WWTP, high ESSR does not determine a high economic feedback necessarily [8]. However, the studies above just focused on the self-sufficiency or energy offset. As the primary function of WWTPs is removing pollutant and preventing risks to human health [9], the study on decarbonization should not ignore the energy efficiency [10]. Thus, WWTPs remain to be further evaluated from an integrated perspective with both aspects of water-energy efficiency and self-sufficiency included.

This study aims at evaluating the energy neutrality potential of WWTPs. 2 key performance indicators (KPIs) are established from both aspects of water-energy efficiency and self-sufficiency to provide solid and integrated evidence. Besides, the study area is Yangtze River Economic Belt (YREB) consisting of 2 municipalities and 9 provinces in China. According to the geographical location of Yangtze River, YREB can also be divided into 3 subregions of the upstream, midstream, and downstream (see Fig. 1). Nowadays, the ecological protection has been added to its development strategies [11], which is also a challenge for the regional WWTPs. As the hugest economic belt in China, the transition of

Fig. 1 The study area of Yangtze River Economic Belt in China.

WWTPs in this region would determine the realization of NDC to some extent. Results might provide scientific basis for energy neutrality and decarbonization of WWTP and demonstration for other regions.

2. METHODOLOG AND DATA

2.1 Establishment of key performance indicators

2.1.1 KPI 1: Comprehensive water-energy efficiency

The first KPI is the comprehensive water-energy efficiency (CWEE), which characterizes the efficiency of WWTPs from 2 aspects. On the one hand, CWEE includes the energy efficiency of WWTPs [12]; on the other, CWEE involves the consumption and generation of energy to quantify the recovery efficiency CHP and WSHP.

Data envelopment analysis (DEA) was applied to evaluate the CWEE of WWTPs. In this study, we used the model of slack-based measure (SBM) [13] with variable returns to scales. Besides, the non-oriented type was selected. The equations could be seen in Liu et al. 2021 [8] and the input and output indicators related are shown in Table 1.

Table 1. Input and output indicators of comprehensive water-energy efficiency.

	Indicators	Label	Unit
Input	Total energy consumption for basic functions	$E_{consume}$	kWh
	Energy consumption by CHP	C_{CHP}	kWh
	Energy consumption by WSHP	C_{WSHP}	kWh
Output	Volume of pollutant removal	$R_{pollutant}$	10^3 kg
	Energy recovered by CHP	E_{CHP}	kWh
	Energy recovered by WSHP	E_{WSHP}	kWh

*$R_{pollutant}$ includes the removal of chemical oxygen demand (COD), 5-day biochemical demand (BOD), TN (total nitrogen), NH_4^+-N (ammonia nitrogen), and TP (total phosphorus).

*C_{CHP}, C_{WSHP}, E_{CHP}, and E_{WSHP} were calculated through equations in Yang et al. 2020 [6].

2.1.2 KPI 2: Energy self-sufficiency rate

The second KPI is ESSR (%), labelled as $\eta_{recovery}$(%), that characterizes the offset degree of WWTPs with internal chemical and thermal energy. The ESSR can be calculated by the equation below:

$$\eta_{recovery}=\frac{N_{CHP}+N_{WSHP}}{E_{consume}}\times 100\% \quad (1)$$

Where, N_{CHP} and N_{WSHP} are the net energy recovery via CHP and WSHP. They can be obtained through the equations below:

$$N_{CHP}=E_{CHP}-C_{CHP} \quad (2)$$

$$N_{WSHP}=E_{WSHP}-C_{WSHP} \quad (3)$$

The C_{CHP}, C_{WSHP}, E_{CHP}, and E_{WSHP} are the same variables in section 2.1.1.

2.2 Classification of energy neutrality potential

With 2 related KPIs calculated, the energy neutrality potential of WWTPs can be classified. The median was selected as the critical value and the details are shown below in Table 2.

Table 2. Classification of energy neutrality potential of wastewater treatment plants.

Level of potential	Classification
High	High CWEE and ESSR
Middle type 1	Low CWEE and high ESSR
Middle type 2	High CWEE and low ESSR
Low	Low CWEE and ESSR

2.3 Data collection

In this study, the data source is China Urban Drainage Yearbook 2018 [14]. Raw data includes total electricity consumption (kWh/y), pollutant concentration in influent and effluent, volume of wastewater treated, and wet sludge production. 970 WWTP samples in YREB were put into use in this research.

3. RESULTS AND DISCUSSION

3.1 Assessment of key performance indicators

3.1.1 KPI 1: Comprehensive water-energy efficiency

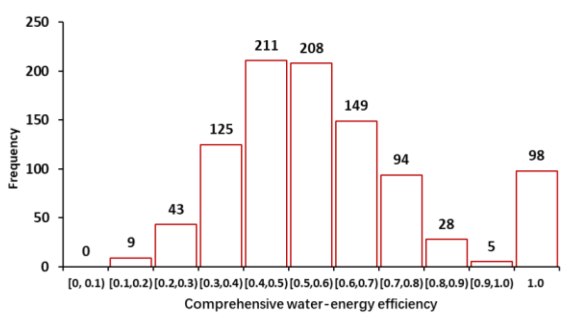

Fig. 2 Frequency of WWTPs distrubution in intervals of comprehensive water-energy efficiency.

As shown in Fig. 2, 98 WWTPs turn out to be benchmarks (CWEE = 1), while the left 872 ones are relative inefficient. Besides, the intervals with upper bounds less than 0.5 contains the most WWTP samples. 125, 211, 208, and 149 WWTP samples distribute in the intervals of [0.3, 0.4), [0.4, 0.5), [0.5, 0.6), and [0.6, 0.7), respectively. This phenomenon indicates that the overall WWTPs samples own a medium CWEE level.

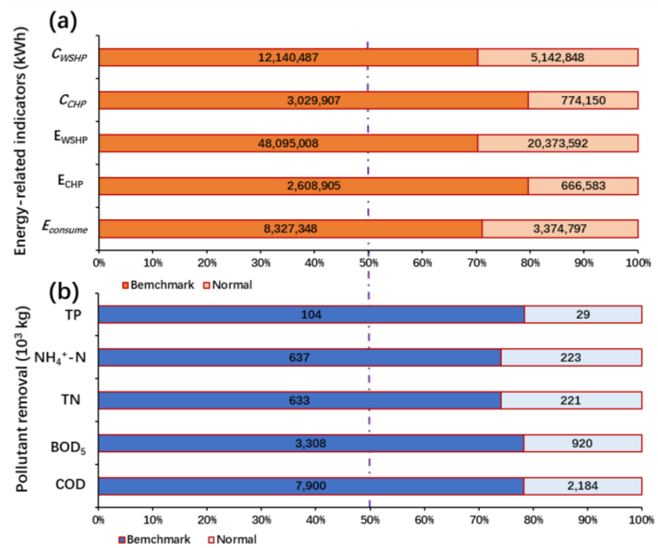

Fig. 3 Comparative analysis on the mean values of the indicators for benchmark and normal WWTPs (a) energy consumption and recovery, (b) water quality improvement by pollutant removal. The inputs are in italics.

To get an insight into the CWEE, the statistics on the input and output indicators were prepared for analysis. The mean value of each indicator is seen in Fig. 3. For the benchmark WWTPs, both input and output indicators are much more than the outputs. Thus, for CWEE, the benchmark WWTPs consume more and generates more at the same time. In this study, CWEE is also influenced by scale economies that is commonly seen in wastewater treatment facilities [15].

3.1.2 KPI 2: Energy self-sufficiency rate

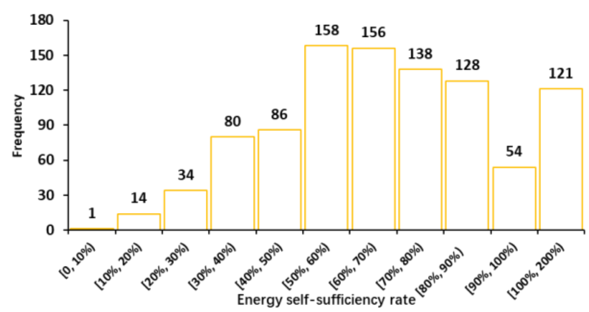

Fig. 4 Frequency of WWTPs distrubution in intervals of energy self-sufficiency rate.

Regarding the ESSR, the mean and median equals to 69.33% and 67.26%, respectively. 121 samples get a full self-sufficiency level (ESSR >= 100%). As shown in Fig. 4, there are 158, 156, 138, and 128 WWTP samples distribute in the intervals of [50%, 60%), [60%, 70%), [70%, 80%), and [80%, 90%). This indicates that the most WWTPs samples own a medium ESSR level.

To get an insight into the ESSR, the statistics on the input and output indicators were prepared for analysis. The mean value of each indicator is seen in Fig. 5. For ESSR, the WWTP sample that generates more energy does not consume more necessarily, which is a totally different phenomenon compared to CWEE. The full sufficient WWTPs consume much less operational energy than non-full sufficient ones. Besides, the WWTPs with a full self-sufficiency condition remove less pollutant than non-full sufficient ones.

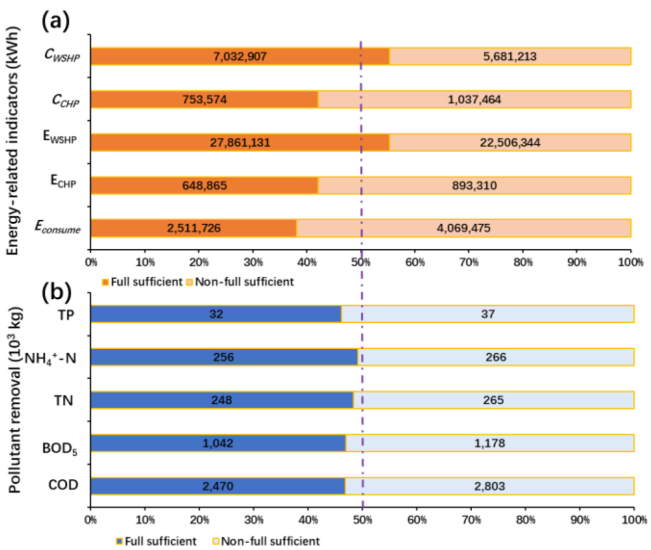

Fig. 5 Comparative analysis on the mean values of the indicators for full- and non-full suffient WWTPs (a) energy consumption and recovery, (b) water quality improvement by pollutant removal. The inputs are in italics.

3.2 *Evaluation on energy neutrality potential*

3.2.1 *Energy neutrality potential classification*

To classify the energy neutrality potential of WWTPs, the median of the two KPIs were set as critical value

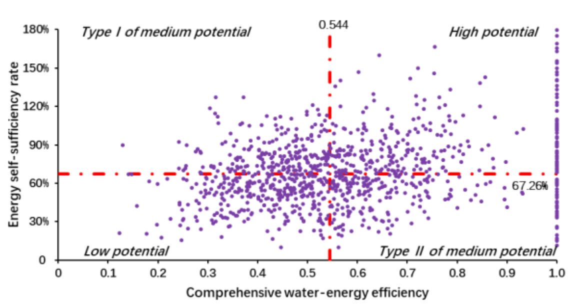

Fig. 6 Classification of energy neutrality potential of 970 wastewater treatment plants samples in Yangtze River Economic Belt.

(0.544 and 67.26% for CWEE and ESSR, respectively). As the determination of two KPIs differs (Kappa = 0.203, p-value < .001), the classification result is objective to represent the potential from both aspects of efficiency and self-sufficiency. The scatterplot of samples is shown in Fig. 6.

3.2.2 Characteristics in terms of water and energy

High potential means the related WWTPs own good performance on both aspects of CWEE and ESSR, while the low represents the poor condition with two KPIs less than an average level. The characteristics of the four potential types are seen in Fig. 7.

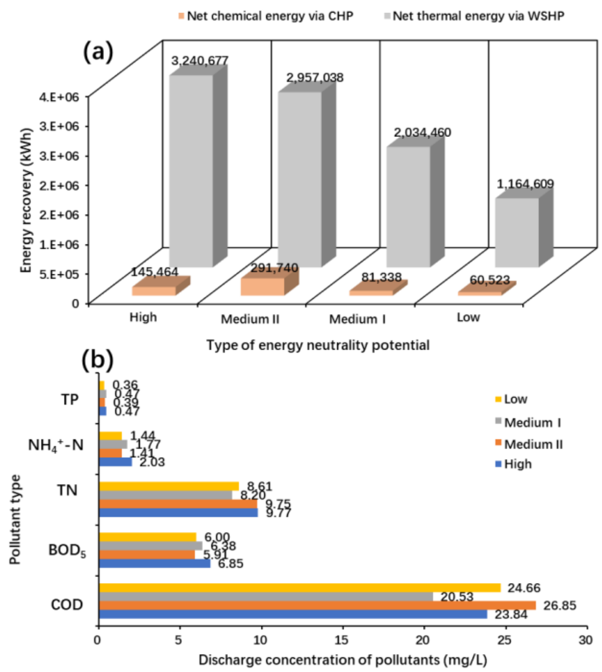

Fig. 7 Characteristics of 4 potential types in terms of water and energy (a) net energy recovery ; (b)discharge concentration of pollutants.

As seen in Fig. 7, the high potential WWTPs have higher thermal energy recovery, while their discharge concentration of pollutants is less strict. The high proportion of thermal energy recovery determines the high degree of ESSR, while less strict discharge condition benefits the CWEE.

3.3 *Analysis of explanatory factors*

3.3.1 Operational condition and influent characteristics

Kruskal Wallis test was applied to analyze the impact from the factors of treatment capacity, water quality in influent. The results are seen in Table 3.

Table 3. Mean rank of explanatory factors with different type of energy neutrality potential.

Explanatory factor	Type of potential	Kruskal Wallis test		
		Mean rank	χ^2	p-value
Treatment capacity (10^7 kg/d)	High	567.12	78.210	< .001
	Medium	510.59		
	Low	364.83		
Influent COD concentration (mg/L)	High	542.01	25.948	< .001
	Medium	490.53		
	Low	420.87		
Influent BOD_5/COD	High	530.75	17.909	< .001
	Medium	491.56		
	Low	430.63		
Influent COD/TN	High	456.09	4.872	.088
	Medium	503.96		
	Low	486.83		

As displayed in Table 3, treatment capacity, influent COD concentration, and influent BOD_5/COD own significant impact on the energy neutrality potential (p-value < .001). In terms of the mean rank, the larger the value is, the more probability that the WWTP would get a higher level of energy neutrality potential.

The treatment capacity represents the scale of WWTPs. As the effect of scale economies exists [15], the greater treatment capacity boosts the CWEE and furtherly facilities the energy neutrality potential as a result. Besides, the influent COD concentration represents the carbon source of the wastewater and the COD strength have significant on potential of energy neutrality and energy-positive at plant-level [16]. In addition, BOD_5/COD is a parameter for biodegradability and a higher value would be helpful to get a better efficiency level for pollutant removal [17].

3.3.2 Disparities among the subregions

The energy neutrality potential of WWTP samples in subregions of YREB differ distinctly with p-value of Chi^2 test less than .001 (see Table 4).

Table 4. Proportion of different potential types among the subregions of Yangtze River Economic Belt.

Location (-stream)	Type of Potential	Number (Proportion rate)	Chi^2 test	
			χ^2	P-value
Up	High	78 (33.05%)	20.456	< .001
	Medium	103 (43.64%)		
	Low	55 (23.31%)		
Mid	High	87 (31.75%)		
	Medium	128 (46.72%)		
	Low	59 (21.53%)		
Down	High	111 (24.13%)		
	Medium	189 (41.09%)		
	Low	160 (34.78%)		

With reference to explanatory factors analysis in section 3.2.1, the disparities may be caused by different operational conditions of WWTPs. Besides, there is a certain gap in water use efficiency among the eastern, central and western China [18]. As YREB is an area spanning across the East, Middle and West China (See Fig. 1), the difference in the water use efficiency would also be one of the influencing factors. Meanwhile, according to other researches in YREB, the conditions of population density, economic development level, and water resources endowment [19], and the efficiency characterized by indicators of urban sewer length, designed capacity in total, and volume of water treated [20] are proved to be different within the study area. Thus, the reasons may include factors in a wide range of socio-economy that influence the NZE of WWTPs [21].

4. CONCLUSIONS

This study evaluated the energy neutrality potential of WWTP in YREB. Two KPIs, CWEE and ESSR, were established and the median were set as critical value to classify the types of potential.

Results show that CWEE and ESSR characterize the energy recovery differently. In terms of CWEE, the effect of scale economies exists. For ESSR, WWTPs of full self-sufficiency consume less energy and remove less pollutants. Meanwhile, the features of WWTPs with high potential of energy neutrality turn out to be high heat recovery and less strict discharge level. Besides, analysis of explanatory factors demonstrates that the conditions of treatment capacity, influent COD concentration, and influent BOD_5/COD have great influence on the energy neutrality potential. In addition, the disparities exist among the subregions. The results will provide guidance for other WWTPs under optimization for energy neutrality home and abroad.

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