Front. Environ. Sci. Eng. 2022, 16(9): 117
https://doi.org/10.1007/s11783-022-1549-0

RESEARCH ARTICLE

Energy neutrality potential of wastewater treatment plants: A novel evaluation framework integrating energy efficiency and recovery

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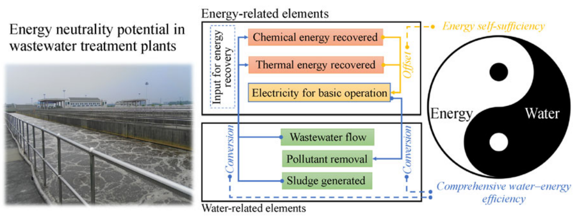
HIGHLIGHTS

- Framework of indicators was established based on energy efficiency and recovery.
- Energy neutrality potential of 970 wastewater treatment plants was evaluated.
- Analysis of characteristics and explanatory factors was carried out.
- Pathways for improving the energy neutrality potential were proposed.

GRAPHIC ABSTRACT



ABSTRACT

Wastewater treatment plants (WWTPs) consume large amounts of energy and emit greenhouse gases to remove pollutants. This study proposes a framework for evaluating the energy neutrality potential (ENP) of WWTPs from an integrated perspective. Operational data of 970 WWTPs in the Yangtze River Economic Belt (YREB) were extracted from the China Urban Drainage Yearbook 2018. The potential chemical and thermal energies were estimated using combined heat and power (CHP) and water source heat pump, respectively. Two key performance indicators (KPIs) were then established: the energy self-sufficiency (ESS) indicator, which reflects the offset degree of energy recovery, and the comprehensive water–energy efficiency (CWEE) indicator, which characterizes the efficiency of water–energy conversion. For the qualitative results, 98 WWTPs became the benchmark (i.e., CWEE = 1.000), while 112 WWTPs were fully self-sufficient (i.e., ESS ⩾ 100%). Subsequently, four types of ENP were classified by setting the median values of the two KPIs as the critical value. The WWTPs with high ENP had high net thermal energy values and relatively loose discharge limits. The explanatory factor analysis of water quantity and quality verified the existence of scale economies. Sufficient carbon source and biodegradability condition were also significant factors. As the CWEE indicator was mostly sensitive to the input of CHP, future optimization shall focus on the moisture and organic content of sludge. This study proposes a novel framework for evaluating the ENP of WWTPs. The results can provide guidance for optimizing the energy efficiency and recovery of WWTPs.

ARTICLE INFO

Article history:
Received 21 October 2021
Revised 2 December 2021
Accepted 15 December 2021
Available online 30 January 2022

Keywords:
Wastewater treatment plants
Energy neutrality potential
Energy efficiency
Energy recovery
Evaluation framework

1 Introduction

Wastewater treatment plants (WWTPs) consume high amounts of energy and emit considerable amounts of greenhouse gases (GHGs) (Wang et al., 2016). Owing to the huge treatment scale and sewer length in China (Huang et al., 2018; Lu et al., 2019), it is crucial to focus on WWTPs to achieve the nationally determined contribution to carbon neutrality in 2060. As the GHG emissions of WWTPs are highly dependent on bioreactors and the input of grid electricity, carbon neutrality is related to the energy neutrality of WWTPs (Maktabifard et al., 2018). Thus, studies on energy neutrality can provide information for developing measures to achieve the carbon neutrality with respect to WWTPs.

The main pathways for decarbonization of WWTPs can be summarized as energy reduction, energy recovery, and energy renewables (Nakkasunchi et al., 2021). To date, some researchers have evaluated WWTPs in terms of the

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three pathways above. For energy reduction, related studies have mainly been conducted to evaluate and improve the energy efficiency of WWTPs. To characterize the efficiency, normalization is the initial method to relate the energy input to the output of pollutant removal, such as the specific energy consumption required to remove a certain load of a given contaminant (Zou et al., 2019). In addition, indicators of another dimension, such as the removal rate of contaminants, can be added to enrich the normalization outcome (Di Fraia et al., 2018). To consider multiple types of pollutants, models of data envelopment analysis have been used to evaluate the energy efficiency of WWTPs from a multidimensional perspective. As a result, indicators of energy efficiency became comprehensive and applicable to large sample sets of WWTPs. The evaluation results of energy efficiency could also be extended to other functions, for example, identifying the internal discrepancies within a certain region (Huang et al., 2021). Regarding energy recovery, recent studies have mostly concentrated on energy self-sufficiency (ESS). The use of biogas from the anaerobic digestion of sludge for digester heating and electricity generation is a feasible and effective way to improve the ESS (Gu et al., 2017). Yan et al. established the Net-Zero Energy model to utilize the chemical energy of excessive sludge to offset operational consumption (Yan et al., 2017; Yan et al., 2020). In addition to the chemical energy, the thermal energy of the WWTPs is promising in China (Hao et al., 2019b). The key parameters to estimate the potential chemical and thermal energy are sludge production and wastewater flow, respectively (Yang et al., 2020). For the energy renewables, the Photovoltaic (PV) has been commonly used to utilize solar energy in previous studies of WWTPs. The key parameter to estimate the potential solar energy is the surface area of the biological reactor in a WWTP (Yang et al., 2020). The input use of PV would further add to the ESS of a WWTP, with the actual effect influenced by the plant scale, presence of anaerobic digestion, and geographical location (Strazzabosco et al., 2019).

However, existing studies do not combine the pathways for decarbonization. As energy efficiency and ESS are indicators that reflect one aspect of energy neutrality, it is necessary to comprehensively include multiple aspects of the decarbonization pathways. Accordingly, this study aims to integrate more pathways when evaluating a WWTP. To reach this purpose, conversions of the energy-to-water and water-to-energy in WWTPs are considered concurrently. In addition to ESS, another key performance indicator (KPI), defined as the water–energy efficiency (CWEE) indicator, is set up to characterize the efficiency of the bidirectional conversion of water–energy in a WWTP. As a high ESS does not necessarily mean high feedback, especially for economic investment (Liu et al., 2021), this study integrates energy efficiency and energy recovery. With more elements considered, it is necessary to establish a framework and evaluate the energy neutrality potential (ENP) of WWTPs. The results could provide a scientific basis for assessing the energy neutrality of WWTPs, which is a primary aspect of managing carbon emission in wastewater sector. This framework may be useful for other areas and countries.

2 Data and methodology

2.1 Data collection and study area

In this study, the data source was the China Urban Drainage Yearbook 2018 (China Urban Water Association, 2019). Raw data included total electricity consumption (kWh/a), pollutant concentrations of influent and effluent (mg/L), volume of wastewater treated (10^4 m^3/a), and wet sludge production (10^3 kg/a). The designed capacity (10^4 m^3/d) and the main technologies of the samples were collected through the list of municipal wastewater treatment facilities in China (Ministry of Ecology and Environment, 2020). Due to limited data availability, the usage of chemicals and agents was not considered in this study.

The Yangtze River Economic Belt (YREB) was selected as the study area. The YREB consists of two municipalities and nine provinces in China. It is also composed of three subregions according to the geographical location of the Yangtze River: upstream, midstream, and downstream. The population and gross domestic product (GDP) of the YREB both account for more than 40% of the country's total population and GDP, respectively (Pan et al., 2020). Hence, the YREB is a vital area of China's economy and an important support for sustainable development. Nowadays, the ecological protection has been added to development strategies, which is a huge challenge for regional WWTPs. Thus, this study aims to evaluate the ENP of WWTPs with the YREB set as the demonstration to provide national guidance.

To ensure reliability, data screening was performed to refine the raw data. As a result, data from 970 WWTPs in the YREB were used in this study. Most of these WWTPs were designed with a treatment capacity $< 5 \times 10^4$ m^3/d and were mostly equipped with technologies related to activated sludge, such as anaerobic-anoxic-oxic (AAO), anaerobic-oxic (AO), and oxidation ditch (OD). A flow diagram of the data screening process and descriptions of the selected 970 WWTPs were provided in the Supporting Information.

2.2 Evaluating the energy neutrality potential of wastewater treatment plants

2.2.1 Element flows inside wastewater treatment plants

WWTPs are municipal facilities that consume energy to remove pollutants conventionally. Electricity from the grid is converted to work of pumps and reactors. In this aspect, the energy flows into the wastewater. Conceptually, a WWTP should also function with the recycled resources (Qu et al., 2022). The element flows of wastewater, sludge, and energy in a WWTP are seen in Fig. 1(a). Through the multi-direction of the flows, the chemical and thermal energies can also be recovered to offset the operational consumption of a WWTP (Yan et al., 2017; Hao et al., 2019b). Combined heat and power (CHP) and water source heat pump (WSHP) are the common technologies for recovering the chemical and thermal energies of WWTPs, respectively (Hao et al., 2019b).

Based on the flows in Fig. 1(a), a four-step framework was proposed for evaluating the ENP of a WWTP (Fig. 1(b)). The details of each step are provided in following sections.

2.2.2 Definition and calculation on variables

As shown in Fig. 1(b), the step 1 is to define and calculate the initial variables. All variables are summarized from the element flows inside the WWTP and reflect the conversion situation of the water–energy nexus. Energy consumption and pollutant removal are the primary variables that reveal the energy efficiency of the wastewater treatment system. Except for the energy efficiency, the variables of the energy recovery system are also crucial for determining the ENP. The energy consumed and recovered by CHP and WSHP should be included to characterize the ENP. On the one hand, the net energy recovered offsets the energy consumption for basic operation; on the other hand, the energy consumed and recovered could better enrich the conversion relationship between water and energy. The variables are listed in Table 1.

In Table 1, $C_{\text{operation}}$ is the total electricity consumption (kWh/a), which was obtained from the China Urban Drainage Yearbook 2018. The energy consumed and recovered by these technologies should be estimated using appropriate methods. The relevant equations and parameters are detailed in the Supporting Information.

2.2.3 Estimation of two key performance indicators

After defining and calculating all variables, the following two KPIs were estimated using steps 2 and 3 in Fig. 1(b): ESS, which characterizes the offset degree of the recovered energy, and CWEE, which reveals the conversion efficiency of water–energy.

(1) KPI I: Energy self-sufficiency

The ESS (%, labelled as η_{recovery}) of each WWTP, was obtained using a normalization method. The WWTP samples with ESS values of $\geqslant 100\%$ were defined as fully self-sufficient, whereas those with ESS values of $< 100\%$ were defined as non-self-sufficient.

(2) KPI II: Comprehensive water–energy efficiency

The CWEE indicator, denoted as θ, reveals the conversion efficiency of water–energy. In this study, we used slack-based measure model and selected the conditions of the non-oriented type and variable returns to scale. WWTPs with CWEE values equal to 1 were taken as the benchmark sites, while those with CWEE values of < 1 were taken as the normal WWTP samples.

2.2.4 Classification of energy neutrality potential

The step 4 in Fig. 1(b) classifies the ENP of a WWTP. After calculating both KPIs, the ENP of each WWTP can be classified. To distinguish the relative differences, the

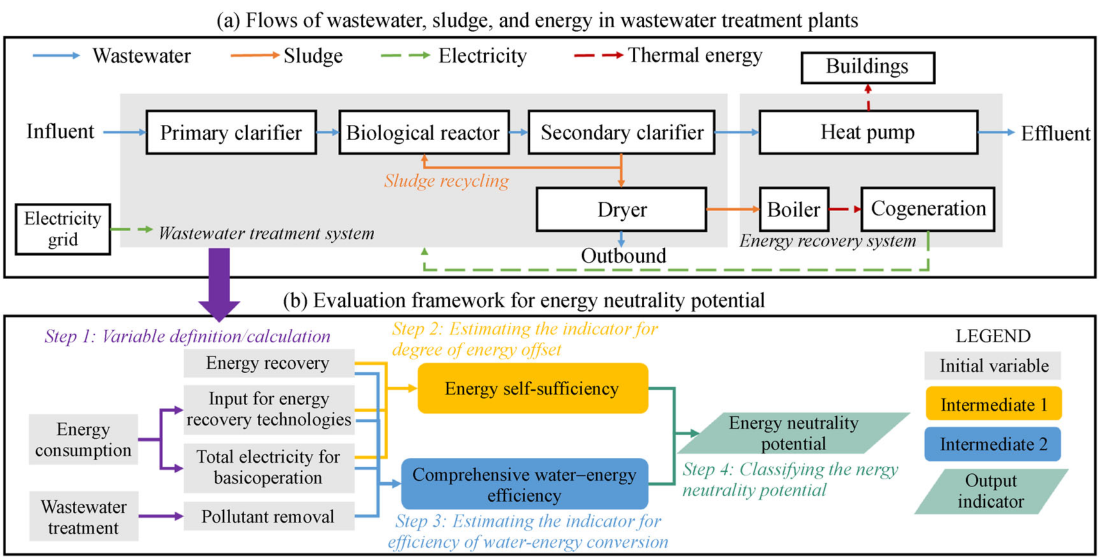

Fig. 1 Evaluation framework for energy neutrality potential based on element flows inside a model wastewater treatment plant.

Table 1 Initial variables of the framework to evaluate the energy neutrality potential of a wastewater treatment plant

Variable	Label	Unit
Total electricity consumption for basic operation	$C_{operation}$	kWh
Energy consumed by combined heat and power	C_{CHP}	kWh
Energy consumed by water source heat pump	C_{WSHP}	kWh
Energy recovered by combined heat and power	E_{CHP}	kWh
Energy recovered by water source heat pump	E_{WSHP}	kWh
Pollutant removal	$R_{pollutant}^{*}$	10^3 kg

Note: *Pollutant removal includes reductions in the concentration of chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD_5), total nitrogen (TN), ammonia nitrogen (NH_4^+-N), and total phosphorus (TP).

median of each KPI was selected as the critical value. In addition, the median divided all selected WWTPs into equivalent clusters to avoid errors in the statistical analysis arising from the sample size. The WWTPs with ESS and CWEE values that were equal to or greater than the median of the ESS and CWEE values were classified as having high ENP, while those with ESS and CWEE below the median ESS and CWEE values were classified as having low ENP. For WWTPs with medium ENP, there were two cluster types (medium I and medium II) based on the characteristics of the two KPIs. The details are listed in Table 2.

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

Cluster of energy neutrality potential	Description
High	Relatively high ESS and CWEE
Medium I	Relatively high ESS but low CWEE
Medium II	Relatively high CWEE but low ESS
Low	Relatively low ESS and CWEE

2.3 Statistical analyses

2.3.1 Kappa index

The Kappa index can be used to assess the consistency of two diagnostic results. Theoretically, the kappa value ranges from –1 to 1, but more often ranges from 0 to 1. Empirically, a kappa index of $\geqslant 0.7$ indicates high consistency, whereas a value of < 0.7 but > 0.4 indicates moderate consistency, and < 0.4 indicates low consistency.

In this study, we used Kappa index to assess the consistency of the qualitative results of the ESS (fully self-sufficient and non-self-sufficient) and CWEE (benchmark and normal) indicators.

2.3.2 Chi^2 test

The Chi^2 test is widely used to make statistical inferences based on the deviation between the actual observed value and the theoretical value, whereby the deviation determines the Chi^2 value. In other words, the larger the Chi^2 value, the greater the deviation.

In this study, we used Chi^2 test to determine whether statistical disparities existed among subregions of the YREB in terms of the proportion of selected WWTPs with different ENP.

2.3.3 Kruskal–Wallis *H* test

The Kruskal–Wallis *H* test is used to verify the statistical significance of the differences among several clusters. In addition, as a non-parametric one-way variance analysis method, it can also diagnose the consistency hypothesis of the overall function distribution and the normality and homoscedasticity assumptions. A p-value of > 0.05 indicates no significant difference among the tested samples, whereas a p-value of < 0.05 indicates a significant difference.

In this study, we set the groups according to different explanatory factors and used Kruskal–Wallis *H* test to diagnose the statistical difference based on the graded clusters of the ENP of the studied WWTPs.

3 Results and discussion

3.1 Assessment of key performance indicators

3.1.1 Frequency distribution

The initial difference between the ESS and CWEE indicators appeared in the basic statistics. The ESS values of the studied 970 WWTPs ranged from 9.94% to 181.36%, while the CWEE values ranged from 0.123 to 1.000. The median and mean ESS values were 67.26% and 69.33%, respectively, while the median and mean values were 0.544 and 0.576, respectively. Although the mean and median values of each KPI were similar, the ESS had a relatively high standard deviation of 27.09%. The other difference existed in the qualitative results. As shown in Fig. 2, 121 WWTPs were fully self-sufficient (ESS$\geqslant$ 100%), while 98 WWTPs were considered benchmarks (CWEE = 1.000). The intervals with upper bounds of < 0.5 included most of the WWTPs.

The WWTP with ESS of 181.36% is situated in the midstream of YREB. The technology configured in this WWTP was OD in its initial project phase and, after the reconstruction, the technology has been modified to AAO. Nowadays, this WWTP has a designed capacity of 12 $\times$ 10^4 m^3/d. According to the China Urban Drainage Yearbook 2018, this WWTP loaded 5 292 $\times$ 10^4 m^3 of wastewater and consumed 5 179 120 kWh of electricity in 2017, generating 16 733 $\times$ 10^3 kg of wet sludge. Hence,

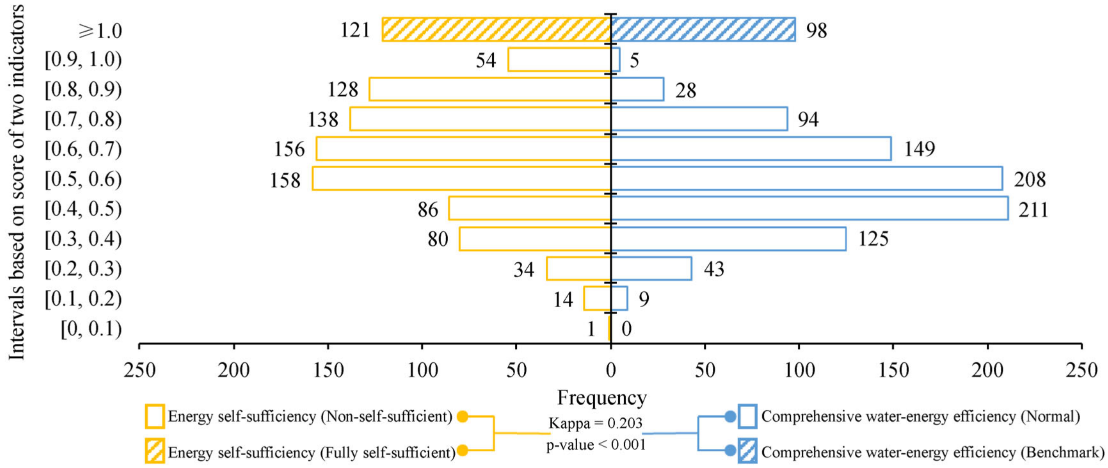

Fig. 2 Frequency of WWTP distribution in intervals of energy self-sufficiency and comprehensive water–energy efficiency.

the specific energy intensity was approximately 0.10 kWh/m^3, which indicates a high energy efficiency. Meanwhile, the recovered chemical and thermal energies were estimated to be 286 130 and 9 106 646 kWh. Thus, the high ESS resulted from the low electricity cost for wastewater treatment and the large amount of energy recovered.

The degree of consistency between the two KPIs was low, with a Kappa index of 0.203. This indicates that the emphasis of ESS and CWEE was different. The intersection of these two KPIs are the energy-related variable; ESS equals the sum of the net energy recovered divided by the total operational energy, while CWEE is a unitless indicator that is composed of several inputs and outputs. The variables for pollutant removal were also included in the CWEE indicator. Thus, the calculated ESS directly reflects the offset degree through chemical and thermal energy recovery in the studied WWTP samples, whereas the calculated CWEE includes the components that characterize the energy efficiency of a certain production procedure. Considering the different calculation methods of the KPIs, the classification results of the ENP of the WWTPs are reasonable to represent the condition from both aspects of energy efficiency and energy recovery.

3.1.2 Comparative analysis on variables

To gain further insight into the determined ESS and CWEE, the statistics of the input and output variables were analyzed. The mean values of the variable were compared using 50% of the sample set as the baseline. The variables were analyzed in terms of both water and energy in WWTPs. The following figure shows the percentage proportion of fully/non-self-sufficient and benchmark/normal WWTPs. The variables for the studied WWTPs differed with respect to the calculated ESS and CWEE.

For ESS, the WWTPs that recovered more energy did not necessarily have more input. The fully self-sufficient WWTPs tended to consume less for operational functions ($C_{\mathrm{operation}}$) and cogeneration (C_{CHP}). The consumption (C_{WSHP}) and production (E_{WSHP}) of the WSHP were the only two variables that exceeded the baseline for the fully self-sufficient WWTPs. Meanwhile, the amount of pollutant removal of fully self-sufficient WWTPs was also less than that of the non-self-sufficient WWTPs (see Fig. 3). As $C_{\mathrm{operation}}$ is the direct outcome of pollutant removal, the fully self-sufficient WWTPs may have had lower inputs in operational functions of the biochemical process. Meanwhile, the high amount of thermal energy recovery offset the total electricity consumption. Thus, the 121 WWTPs that achieved fully self-sufficiency may have done so owing to both water quantity and quality. Less pollutant removal leads to less electricity and the sufficient recovery of thermal energy offsets the electricity consumption.

For the CWEE indicator, both the input and output variables of the benchmark WWTPs were considerably higher than the normal ones. All the related variables surpassed the baseline of 50% (see Fig. 3). Thus, for CWEE, the benchmark WWTPs consumed more and generated more at the same time. For normal WWTPs, an output shortfall was observed. Based on this, we inferred that CWEE was also influenced by scale economies, which are commonly associated with wastewater treatment facilities (Hernández-Chover et al., 2018). Thus, for the 98 benchmark WWTPs, the condition of a high CWEE score could be attributed to their relatively large treatment capacities.

3.2 Evaluation on energy neutrality potential

3.2.1 Energy neutrality potential classification

To classify the ENP of the studied WWTPs, the median values of the two KPIs were set as critical values (67.26%

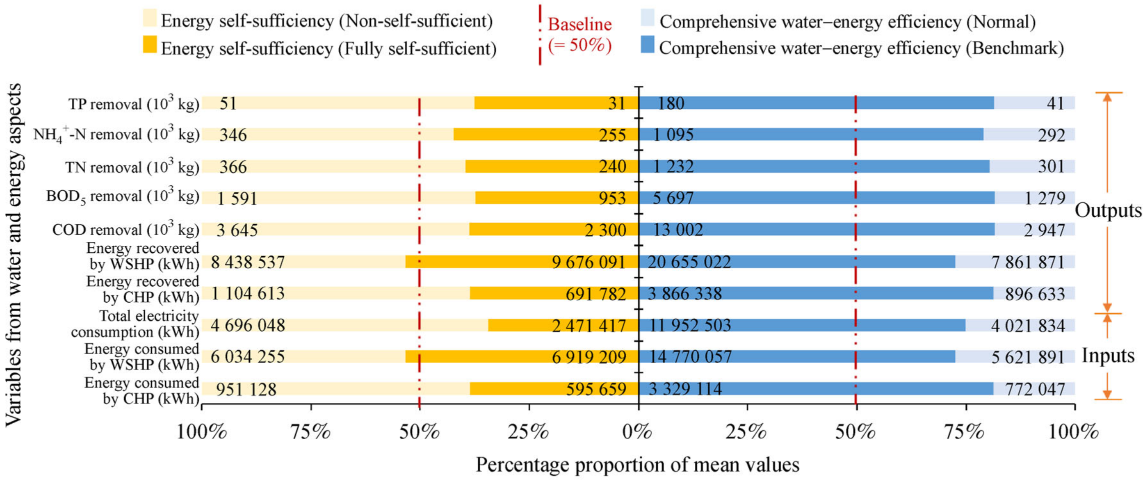

Fig. 3 Comparative analysis of variables for fully/non-self-sufficient and benchmark/normal wastewater treatment plants.

for ESS and 0.544 for CWEE). Although the dimensions of the ESS and CWEE values differ, they shared the intersection of energy recovery and operational energy for pollutant removal. As proved in the previous sections, the classification of ENP based on these KPIs was reasonable. The WWTPs with ESS and CWEE values equal to or exceeding their respective median values were defined as having high ENP. A scatterplot of the studied WWTP samples is shown in Fig. 4.

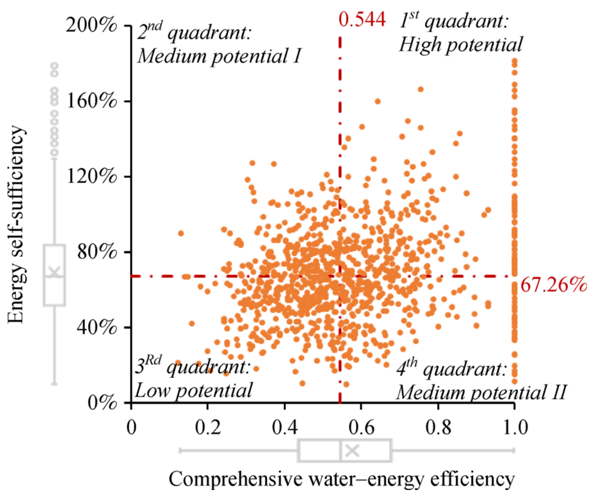

Fig. 4 Classification of the energy neutrality potential of 970 wastewater treatment plants.

The overall distribution trend was very discrete, with many WWTPs scattered in the 2nd and 4th quadrants. Furthermore, many benchmark WWTPs distributed in the bottom-right corner. This result corresponds to the outcome of the Kappa index (see Fig. 2). The WWTPs that plotted near the upper righthand corner had higher ENP. The CWEE values of WWTPs in the upper left part were not high (2nd quadrant, medium potential I), but the ESS values exceeded 67.26% (i.e., the median). Although these WWTPs had a relatively poor water–energy conversion efficiency, the offset degree of energy recovered to the basic operation was high. In contrast, the WWTPs in the 4th quadrant exhibited high CWEE but had a certain deficiency on ESS. Therefore, distinct disparities existed among the WWTPs in each quadrant, representing different ENP. The determined characteristics in terms of region and water–energy features are introduced in the following section.

A list evaluated by several institutions with authority was used for the validation. The list contains the WWTPs given honorary titles for excellent achievements with respect to low carbon and eco-friendliness (Zhao 2021). Among the titled WWTPs, there are two involved in this study, and both were found to have a high ENP. The first is Yixing Urban WWTP in Wuxi, Jiangsu Province (AAO process with a designed capacity of 7.5 × 10^4 m^3/d in 2017) (Ministry of Ecology and Environment, 2020). The WWTP was given an honorary title for plant–network integration. The second is the Taziba WWTP in Mianyang, Sichuan province (AO process with a designed capacity of 20 × 10^4 m^3/d in 2017) (Ministry of Ecology and Environment, 2020). In the list, the Taziba WWTP was classified into the group with an excellent operation of power saving and environmental education. This corresponds well with the high ENP determined in this study. The external validation of these two WWTPs supports the results of the ENP evaluation in this study.

3.2.2 Characteristic analysis of different clusters of energy neutrality potential

The characteristic analysis was carried out based on the aspects of region and water–energy conditions. Table 3

Table 3 Number and proportion of wastewater treatment plants with different energy neutrality potential in the subregions

Cluster of energy neutrality potential	Sample number (Proportion rate)			Chi^2 test	
	Upstream	Midstream	Downstream	χ^2	p-value
High	78 (33.1%)	87 (31.8%)	111 (24.1%)	101.601	< 0.001
Medium I	36 (15.3%)	105 (38.3%)	68 (14.8%)		
Medium II	67 (28.4%)	22 (8.0%)	121 (26.3%)		
Low	55 (23.3%)	60 (21.9%)	160 (34.8%)		

represents the number and proportion rate of WWTP samples with different types of ENP in each subregion. The Chi^2 test was used to determine whether there were significant differences among the clusters in terms of proportion. The null hypothesis of the Chi^2 test indicates that the proportion of WWTPs with different types of ENP was the same in the various subregions of the YREB. The statistical results for the sample number and proportion rate are shown in Table 3.

According to the results displayed in Table 3, the p-value of the Chi^2 test was < 0.001, indicating the proportion of WWTPs within each ENP cluster differed significantly between the subregions of the YREB. As demonstrated by current research on YREB, the conditions of population density, economic development level, and water resource endowment may influence the efficiencies of wastewater discharge and treatment (Wang et al., 2020). Meanwhile, the efficiency characterized by the urban sewer length and designed capacity also differed between the subregions of YREB (Pan et al., 2020). Factors relating to population density and the level of economic development can also result in different net-zero energy conditions in WWTPs in China (Xiong et al. 2021). As the economic development and population situation are distinct among the subregions of the YREB, the reasons for the observed differences may include the socio-economy factors that influence the ENP of WWTPs.

As shown in Fig. 5(a), there was a monotonous trend in the net thermal energy via the WSHP. The WWTPs with high ENP exhibited the highest thermal energy recovery, while the cluster with low ENP had the lowest thermal energy recovery. The proportion of chemical energy recovered was much smaller for the WWTPs with high ENP as shown in Fig. 5(a). This result corresponds to the phenomenon of heat over organics (Hao et al., 2019b), which means that there is a much higher potential to recover thermal energy than chemical energy in China.

Regarding the discharge conditions, except for COD, all contaminants were discharged under the least strict conditions in the WWTPs with high ENP, whereby the mean effluent concentration of BOD_5, TN, NH_4^+-N, and TP were 6.85, 9.77, 2.03, and 0.77 mg/L, respectively. Hence, the less strict discharge limits may have contributed to the high ENP of these WWTPs. Enhancing pollutant removal is still the main target of WWTPs, and strict effluent standards are increasingly implemented in WWTPs nationwide (Qu et al., 2019). However, stricter effluent limits tend to have negative effects on WWTPs. For instance, upgrading a WWTP to stricter effluent limits can increase the energy use and carbon footprint (Smith et al., 2019), whereas less strict effluent standards may improve resource recovery performance (Zhang et al., 2020b). Thus, reasonable discharge limits are recommended for WWTPs.

3.3 Analysis of explanatory factors and optimization pathways

3.3.1 Quantity and quality of influent wastewater

The Kruskal–Wallis H test was used to analyze the impacts of different factors on the quantity and quality of influent

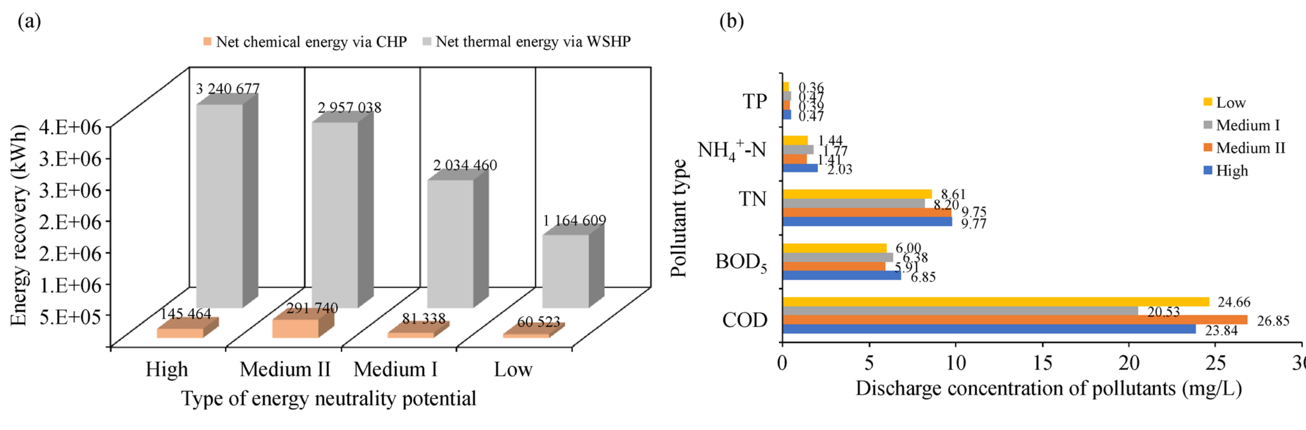

Fig. 5 Characteristics of energy neutrality potential: (a) net energy recovery and (b) discharge condition.

wastewater. The mean rank reflects the value of a factor, whereby the value of a factor increases with an increase in the mean rank. The treatment capacity (10^4 m^3/d) and sludge production (kg/a) are the key factors determining the potential energy recovery. The factors that characterize the influent water quality are the COD concentration (mg/L) and the ratios of BOD_5/COD, COD/TN, and BOD_5/TP. In this section, the ENP types of medium I and II were integrated as one cluster. The results are listed in Table 4.

Table 4 shows that the treatment capacity, sludge production, influent COD concentration, and influent BOD_5/COD ratio significantly affected the ENP (p-value < 0.001), whereas the influent COD/TN and Influent BOD_5/TP ratios did not significantly affect the ENP (p-value > 0.05). Regarding the mean rank, the WWTPs with high ENP generally had relatively high treatment capacities, amounts of sludge production, influent COD concentrations, and influent BOD_5/COD ratios. These results imply that the probability of a WWTP having a high ENP increases with increases in the values of the factors above.

The treatment capacity and amount of sludge production reflect the scale of a WWTP. The treatment capacity determines the amount of wastewater flow used to estimate the thermal energy. As the WWTPs with higher thermal energy values tended to have better performance both in terms of ESS and CWEE (Fig. 3), the treatment capacity was taken as the initial factor influencing most the ENP. This result indicates the effect of scale economies on ENP and corresponds to the findings in Fig. 3. For sludge production, this factor determines the chemical energy of a WWTP. As it is the outcome of the biochemical process, the value of this factor may depend considerably on the removal of contaminants with an oxygen-demand. Thus, there exists some internal correlation between sludge production and the factors of water quality that affect biochemical treatment. For water quality factors, the influent COD is the carbon source of wastewater. As reported in a related study, the COD concentration has a significant effect on potential of energy neutrality and energy positivity at the plant-level (Sarpong et al., 2020). The influent BOD_5/COD ratio is a factor of biodegradability, and a higher value is helpful for increasing the efficiency of pollutant removal (Zhang et al., 2020a). In addition, the influent COD/TN and BOD_5/TP ratios reflect the feasibility of using biotechnology to remove nitrogen and phosphorus (Zou et al., 2019). A low COD/TN ratio may indicate the need for an additional carbon source to attain a high TN removal efficiency (Quan et al., 2018). However, in the present study, the features of these two parameters did not significantly impact the ENP. The effects of the influent COD/TN and BOD_5/TP ratios may only be evident when the conditions of scale, carbon source, and biodegradability are similar for WWTPs.

3.3.2 Optimization pathway analysis

The pathway towards optimizing the ENP of WWTPs shall consider ESS and CWEE. According to the relevant equations, ESS greatly depends on the operational energy consumption and total energy recovery. The CWEE indicator arises from the linear programming of the input and output variables. The input variables involve three types of energy consumption, while the output variables consist of energy recovery and pollutant removal. In terms of performance improvement, it is evident that a lower operational energy consumption and higher energy recovery would optimize ESS. However, the relationship between the variable and CWEE was not that obvious. Thus, a sensitivity analysis was conducted by excluding certain variable from the CWEE calculation. The fitting line was used to compare the baseline values ($y = x$). The smaller the slope of the fitted line, the greater the sensitivity of the CWEE value to the variable excluded. The results are presented in Fig. 6.

Regardless of the excluded variable, a descending tendency was evident, which was the same as that reported in a previous study that applied this method (Liu et al., 2021). According to Figs. 6(a) and 6(b), the fitted lines deviated significantly from the original baseline. The most sensitive variables were the amounts of energy consumed and recovered by CHP, deviating by 0.7532 ($R^2 = 0.8945$) and 0.9050 ($R^2 = 0.9914$), respectively. Regarding WSHP, the fitted lines were very closed to the baseline with slopes of 0.9919 and 0.9633 for the amounts of energy consumed and recovered, respectively (Figs. 6(c) and 6(d)). Thus,

Table 4 Analysis of explanatory factors with different types of energy neutrality potential

Explanatory factor	Mean rank in each cluster			Kruskal–Wallis H test	
	Low	Medium	High	χ^2	p-value
Treatment capacity (10^4 m^3/d)	351.01	510.76	581.15	98.956	< 0.001
Sludge production (kg/a)	393.53	516.31	530.37	41.780	< 0.001
Influent COD concentration (mg/L)	420.12	491.18	542.01	26.382	< 0.001
Influent BOD_5/COD	430.65	491.69	530.75	17.949	< 0.001
Influent COD/TN	486.05	504.51	456.09	4.973	0.083
Influent BOD_5/TP	488.36	479.35	491.98	0.378	0.828

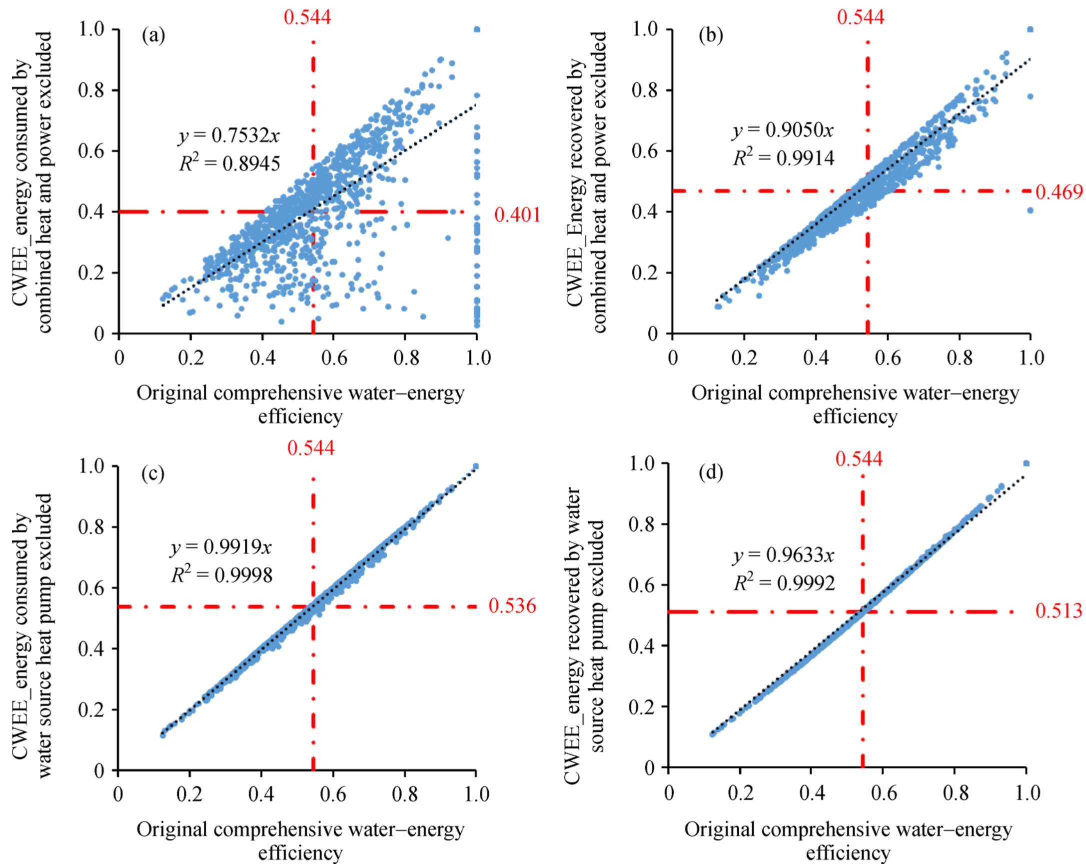

Fig. 6 Sensitivity analysis on variables of energy consumed and recovered.

CWEE was highly sensitive to CHP, while it was less sensitive to the WSHP, indicating that CWEE should be optimized based on the polish of CHP, especially for reducing the input. This is particularly true for WWTPs with ENP categorized as medium I (i.e., a high ESS but low CWEE).

In this study, the water content (%) was a crucial parameter reflecting the properties of excessive sludge. The water content can refer to that after mechanical dewatering or after drying. The water content after mechanical dewatering determines the energy consumption before combustion. The traditional sludge belt filter press can reduce the sludge water content by approximately 80% (Yang et al., 2020). Under these circumstances, further steps of the dryer should reduce the water content for self-sustaining combustion (Hao et al., 2019a). The water content after drying determines the energy requirements for combustion. In addition, the organic content is also important. Empirically, the amount of energy generated through incineration increases with an increase in the organic content of the excessive sludge (Wu et al., 2021). For anaerobic digestion, improvements in the efficiency of anaerobic digestion and substrate allocation between catabolism and anabolism were also recommended (Yan et al., 2020). From the perspective of wastewater treatment, it is promising to combine COD capture and anaerobic ammonium oxidation to convert carbon compounds into high-value organic materials. Moreover, upgrading effluent standards usually results in an increased energy input and a higher carbon footprint (Smith et al., 2019). Hence, moderate discharge limits should be implemented to avoid the latent factors that burden energy neutrality.

Under the framework for evaluating ENP in this study, optimization pathways should concentrate both on the energy recovery system and the wastewater treatment system. Detailed strategies for optimizing energy neutrality should be investigated and formulated for specific WWTPs, such as reducing the water content of excessive sludge, making use of organic matters, and determining the most suitable discharge limits.

4 Conclusions

This study established a novel framework for evaluating the ENP of 970 WWTPs in the YREB. Two KPIs, ESS and CWEE, were evaluated, and the median values were set as the critical values. The results showed that these KPIs characterized energy recovery differently. For ESS, fully self-sufficient WWTPs consumed less energy and removed less pollutants, whereas scale economies affected CWEE. The studied WWTPs with high ENP had higher thermal energy recoveries and relatively loose discharge limit. In addition, an analysis of explanatory factors demonstrated that the treatment capacity, amount of sludge production, influent COD concentration, and influent BOD_5/COD ratios significantly affected the ENP. Optimization methods should focus on reducing the input of CHP. To achieve this, it is crucial to emphasize organic storage and the reduction on the water content of the sludge. The selected discharge limits for wastewater treatment should consider the ENP. The evaluation framework proposed in this study could also be applied to WWTPs in other regions. The results provide guidance for managing WWTPs to optimize energy neutrality both in China and abroad.

Acknowledgements This work was supported by the Foundation of Key Laboratory of Yangtze River Water Environment, Ministry of Education (Tongji University), China (No. YRWEF 202007). The research was partially supported by the Science and Technology Commission of Shanghai Municipality Foundation (Nos. 17DZ1202100 and 21230712200). We are also grateful to editors and the anonymous reviewers for their efforts and insightful suggestions.

Electronic Supplementary Material Supplementary material is available in the online version of this article at https://doi.org/10.1007/s11783-022-1549-0 and is accessible for authorized users.

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