Operational energy performance assessment system of municipal wastewater treatment plants

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ABSTRACT

Based on the statistical analysis of operational energy consumption and its influential factors from data of 599 Chinese WWTPs in 2006, it is noticed that the most influential factors include treatment technology adopted, treated sewage amount, removed pollutants amount, etc. Using the conclusion above, this paper sets up an integrated system of operational energy performance assessment for municipal wastewater treatment plants. Combining with result from on-spot research and model simulation, the calculating method of benchmark value and score of 7 energy efficiency indicators grouped into 3 levels is stated. Applying the assessment system to three plants, its applicability and objectivity are proved and suggestions to improve energy performance are provided.

Key words | benchmarking, energy performance assessment, wastewater treatment

INTRODUCTION

Wastewater treatment is an energy-intensive industry. In America, the water systems and wastewater systems accounted for 3% of the national electricity use (Brian McLean 2009). In China, the wastewater treatment industry consumed 2.81 billion kWh electricity in 2006, taking up only 0.1% of the national electricity consumption, which was largely due to inadequate wastewater treatment in the country. With stricter demands and enforcement of wastewater treatment rules as well a more rapid development of the wastewater treatment industry in China, it is foreseeable that without proper energy management and conservation in wastewater treatment plants (WWTPs), the energy consumption will skyrocket in the future.

According to statistical data from the Ministry of Construction of the People’s Republic of China and the “China Urban Wastewater Treatment Plant Compilation” (Yang 2006), 746 WWTPs with a gross treatment capacity of 56 million m³ have been completed in China by 2006. The average energy consumptions for secondary treatment plants with different treatment technologies are (ranging from the highest to the lowest): 0.340 kWh/m³ for extended aeration systems (13 WWTPs), 0.336 kWh/m³ for sequence batch reactors (SBR, 103 WWTPs), 0.330 kWh/m³ for biomembrane systems (36 WWTPs), 0.302 kWh/m³ for oxidation ditches (170 WWTPs), 0.283 kWh/m³ for anoxic-oxic systems (A/O, 48 WWTPs), 0.269 kWh/m³ for traditional activated sludge systems (36 WWTPs), 0.267 kWh/m³ for Anaerobic-Anoxic-Oxic systems (A/A/O, 87 WWTPs), 0.253 kWh/m³ for land treatment and constructed wetlands (10 WWTPs), and 0.219 kWh/m³ for adsorption-biology systems (17 WWTPs), respectively. The average energy consumption of 559 secondary WWTPs is 0.290 kWh/m³ (2.06 kWh/kgBOD of 450 secondary WWTPs), indicating potential for energy conservation, in comparison to former 0.200 kWh/m³ in America and 0.304 kWh/m³ in Japan (including effluent disinfection and sludge digestions) (Gao 2002), and 0.42 kWh/m³ in Sweden (Lingsten & Lundkvist 2008).

Energy efficiency management and application of energy saving technology are the keys to energy conservation. The energy performance assessment allows WWTPs to evaluate their energy consumption level and track their
energy use, thus it is the prerequisite step for taking efficient energy conservation measures.

Plenty of researches in this field have been sponsored by national and international agencies. Energy Star Programme in America provided a platform for the comparison of different plants’ energy consumption. Benedetti proposed a performance assessment for the integrated urban wastewater system with several original indicators (Benedetti et al. 2007). Lindtner pointed out a statement that standard design load of pollutants had significant impact on cost, based on the investigation of most Austrian sewage plants (Lindtner et al. 2004). Sato summarized the function relationship between plant size reported and cost, as well as compared the cost efficiency of UASB (Up-flow Anaerobic Sludge Bed) and BAF (Biological Aerated Filter) (Sato et al. 2007).

Many countries in the Organization for Economic Cooperation and Development (OECD) performed statistic and assessment on total energy consumption of waste water service (Merkel 2002; OECD 2006). International Water Association (IWA) summarized the indicators evaluating the process of waste water treatment and put forward different energy performance indicators to specifically evaluate certain energy consumption processes, such as energy consumption of influent flow pump unit per sewage volume pumped per pump head (Matos et al. 2003).

Comparatively little research on energy, few researches concerning energy performance assessment has been conducted in China so far and current works have not proposed performance system aiming at energy conservation of WWTPs. As the progressively increasing of world’s attention on energy efficiency, this study sets out to characterize the energy consumption behaviours of WWTPs, to find out the influence factors, and to establish an objective energy performance assessment framework tailored to WWTPs in China, based on a national survey. Due to the large number of WWTPs in China, most of the parameters including treatment technologies, influent quality and plant size are under consideration, so the analysis result is also worthy for reference for other countries.

The countrywide survey was launched in 2006, assisted by the Ministry of Construction of the People’s Republic of China, requiring all practicing WWTPs to report their operation information. A total of 746 WWTPs was investigated and information regarding technologies, influent and effluent qualities, wastewater treated volumes, loads of pollutants entering WWTPs and energy consumptions were collected. All the data were checked before analysis to ensure their reliability. After the data confirmation, energy consumption information (electricity consumption specific to volume of treated wastewater, expressed as kWh/m³) from 559 WWTPs (including 9 primary treatment plants and 529 secondary treatment plants, the rest were not clear) was used in this study. In addition, 10 WWTPs with a representative range of sizes and treatment technologies in China were evaluated on-spot. Treatment technologies, treatment capacity, influent quality, precipitation, temperature, economy factors were taken into account in the selection of the 10 WWTPs to make sure they reflected the current treatment level and energy consumption status in China. The 10 WWTPs, locating in different regions of China (including North China, East China, Mid-China, South China, and Northeast China), used the main treatment technologies applied in China, including oxidation ditch, SBR, A/A/O, and A/O. The treatment capacities of the investigated WWTPs ranged from 10,000 to 600,000 m³/d. The on-spot investigation collected energy consumption information from each operational unit apart from the basic information such as treatment technologies, water qualities, plant scale, which was of importance for determining benchmarks of energy performance indicators discussed below.

FRAMEWORK OF OPERATIONAL ENERGY PERFORMANCE ASSESSMENT

Energy consumption of WWTP was influenced by uncontrollable and inoperative factors, such as historic development of design (Lindtner et al. 2006), treatment technology, influent quality and discharge standard. So this study aims to develop an operational energy performance assessment framework that allows comparison of energy performance among WWTPs with different treatment technologies, design capacities and influent qualities, by establishing a set of energy performance indicators along with a scoring method for each indicator.
The following instructions should be taken into consideration when using the assessment system.

i. Energy consumption in this assessment system means electrical consumption (kWh), which is the most common energy source used in WWTPs.

ii. Only the plants with the ratio of effluent standard compliance above 85% are qualified.

iii. Industrial load does not account beyond 30 percents and does not contain toxic matter.

iv. It is assumed that the diversity of energy consumption is caused by influent quality, and water temperature difference of biochemical treatment process.

Energy performance indicators

The energy performance assessment system contains 7 indicators that can be divided into three levels.

Level 1: comprehensive energy consumption indicators

Energy consumption per volume of wastewater treated ($E_V$) and Energy consumption per total pollutant mass removed ($E_M$) are chosen to represent the comprehensive energy consumption.

Indicator 1: energy consumption per volume of wastewater treated ($E_V$). $E_V$ is the most common indicator for evaluating energy consumption. Considering the fact that it is affected by the treatment technologies and the designed treatment capacity as aforementioned (Yang et al. 2009), when assessing $E_V$ of a specific WWTP, its treatment technology and designed capacity should be involved. Many researchers have concluded that designed capacity has scale effect with operation energy consumption, but get influenced by load rate. Since the most common treatment technologies in China are oxidation ditch (OD), sequencing batch reactor (SBR), and anaerobic aerobic activated sludge treatment (AO), which can provide credible statistical analysis result from large WWTP samples, so only these three technologies are discussed in this paper.

Statistical result of this research indicates that $E_V$ of AO and OD plant is mainly determined by designed capacity, when its load rate is no less than 60% and 70% respectively. A SBR can be composed of groups of tanks, whose number can be adjusted freely by water load. A SBR plant usually has higher automatic level, which can adjust aeration amount and time. So $E_V$ of SBR plant is basically influenced not by load rate but by design capacity. Thus before comparing energy consumption, scale effect should be eliminated. This research performs regression between design capacity ($V_{DC}$) and the mean of $E_V$ under different capacities to get Equation (1). This function calculates average energy consumption level under given capacity, which is adopted in this research as a benchmark (marked as $B_{EV}$).

$$B_{EV} = C_1 \cdot V_{DC}^{C_2} \text{ (kWh/m}^3\text{)}$$ (1)

From Table 1, $R^2$ are quite low, this is because the capacity is not the only influence factor for energy consumption, energy consumption is also influenced by treatment conditions etc. But, according to confidence, the scale effect does exist and this function is practicable.

From function (1) and Table 1, according to $C_2$, the changing speed of $E_V$ ranging from high to low is SBR > OD > AO. And under the same capacity, $E_V$ ranging from high to low is SBR > OD > AO when capacity is less than $4 \times 10^4 \text{m}^3$, while SBR > AO > OD when capacity is no less than $4 \times 10^4 \text{m}^3$, for example: substituting $V_{DC} = 3 \times 10^4 \text{m}^3$ to function (1) with parameters in Table 1, $B_{EV}$ for OD, SBR, AO are 0.295, 0.356, 0.299, SBR > AO > OD. So only in consideration of energy consumption, a plant with small capacity fits for adopting AO technology, and the one

<table>
<thead>
<tr>
<th>Treatment technology</th>
<th>$C_1$ (kWh/m$^3$)</th>
<th>$C_2$</th>
<th>$R^2$</th>
<th>Confidence</th>
<th>Samples</th>
<th>$V_{DC}$ (10$^4$ m$^3$)</th>
<th>Load rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD</td>
<td>0.411</td>
<td>-0.207</td>
<td>0.4407</td>
<td>99.99%</td>
<td>74</td>
<td>[0.5, 33]</td>
<td>$\geq$ 70%</td>
</tr>
<tr>
<td>SBR</td>
<td>0.497</td>
<td>-0.208</td>
<td>0.3306</td>
<td>99.99%</td>
<td>97</td>
<td>[0.1, 30]</td>
<td>Any value</td>
</tr>
<tr>
<td>AO</td>
<td>0.375</td>
<td>-0.137</td>
<td>0.5661</td>
<td>99.99%</td>
<td>107</td>
<td>[0.15, 100]</td>
<td>$\geq$ 60%</td>
</tr>
</tbody>
</table>
with large capacity fits for adopting OD technology, while SBR is fit for plants with large variety of influent load.

**Indicator 2: energy consumption per total pollutant mass removed (EM).** From the value of $R^2$ in Table 1, it is shown that capacity can only partly explain the changing of $E_V$. And from the principle of wastewater treatment, it is known that removal of pollutants is another major element influencing energy consumption. It is the main function of a WWTP; energy consumption is closely linked to the influent and effluent concentrations for pollutants, or loads of pollutants entering WWTPs. However, it is neither practical nor necessary to calculate the energy consumed for removal of each pollutant (e.g. nitrogen, phosphate, heavy metals) since there are numerous kinds of pollutants in wastewater. Thus the energy consumption is weighted on the total pollutant mass removed. The total pollutant mass is an equivalent mass, obtained by summing the pollutant masses removed, each multiplied by an assigned weight (Vanrolleghem et al. 1996; Benedetti et al. 2007). The formula for calculating removed masses of total pollutant (TOP) in our study is as follows:

$$TOP = (COD + 2BOD + 2SS + 20TN + 100TP) \cdot V_{WT}, \quad (kg)$$

where COD and BOD are chemical and biological oxygen demands, SS is suspended solid concentration, TN is total nitrogen concentration, TP is total phosphorus concentration, $V_{WT}$ is the wastewater treated volume. The values of COD, BOD, SS, TN and TP are their concentration difference within influent and effluent.

The value of $E_M$ is therefore calculated by dividing the energy consumption by the corresponding amount of total pollutant mass removed. In this sense, $E_M$ stands for the energy consumption for removing a unit of pollutant, which normalizes the energy consumption efficiency of a WWTP, regardless of the water quality of its influent or effluent. We calculate the mean $E_M$ of three technologies SBR, OD and AO, as the benchmark of $E_M$ (marked as $B_{EM}$) (Table 2).

### Level 2: unit energy consumption indicators

Evaluating energy performance of each main operational unit (energy consumed due to aeration, to wastewater pumping, and to sludge treatment) allows a WWTP to track its energy use and recognize the space for improvement in each unit and therefore to prioritize areas of intervention in a decision-making context. Three unit energy consumption indicators are adopted in our energy performance assessment framework, namely energy consumption of influent pumping unit per sewage volume pumped per pump head, energy consumption of aeration per volume of wastewater treated, and energy consumption of sludge processing unit per sludge mass treated.

**Indicator 3: energy consumption of influent pumping unit per volume of wastewater pumped per pump head ($E_P$).** $E_P$ expresses the energy used for wastewater lifting. Wastewater lifting is usually done by pumping in WWTPs; therefore, pumps are the main energy consuming facilities in this operational unit. Considering that the energy consumption of wastewater pumping is closely related to the amount of wastewater treated and the height of wastewater elevated, $E_P$ is chosen to evaluate the energy consumption efficiency of the wastewater elevation unit.

**Indicator 4: energy consumption of aeration per volume of wastewater treated ($E_A$).** $E_A$ represents the energy consumed by the bio-chemical treatment technology, such as oxidation ditch, SBR, A/A/O, etc. Bio-chemical treatment is the most prevalent secondary treatment method applied in China, in which the aerator, pumps for reflow and sludge discharge, and water decanter for effluent are the main energy consuming machineries. Energy consumed by aerator accounts for 50% ~ 70% of the total energy consumption. The energy consumption of this unit is connected to the inflow water quality, the efficiency of biological reaction, the efficiency of aerator, etc., wherein the energy consumed by biological reaction can be calculated theoretically and simulated by software such as West and BioWin. Biowin is used for calculating the energy consumed in the bio-chemical treatment technology, since no practical data

<table>
<thead>
<tr>
<th>Treatment technology</th>
<th>$B_{EM}$ (kWh/kg)</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD</td>
<td>0.258</td>
<td>112</td>
</tr>
<tr>
<td>SBR</td>
<td>0.282</td>
<td>69</td>
</tr>
<tr>
<td>AO</td>
<td>0.159</td>
<td>84</td>
</tr>
</tbody>
</table>
are available due to lack of monitoring of the energy consumption of the aeration unit in China’s WWTPs.

Firstly, three typical WWTPs, all with a designed capacity of 10,000 m³/d, using oxidation ditch, SBR, and A/A/O as treatment technologies respectively, are set up according to the requirement of the European Cooperation in the Field of Scientific and Technical Research and “Urban Sewage Treatment Project Construction Standards” (The Ministry of Construction of the People’s Republic of China 2001). These simulative WWTPs are used as models for calculating $E_A$ benchmark in the corresponding types of WWTPs.

Secondly, typical inflow water qualities are inputted into BioWin to calculate the volume of air needed under those conditions for each type of WWTP, respectively. The intense of aeration is adjusted accordingly to make sure the qualities of effluent meet criteria of the first grade B of the discharge standard of pollutants for municipal wastewater treatment plant of China (shown in Table 3). For selection of typical inflow water qualities, i.e. COD, BOD, and concentrations of TN, NH$_3$-N, TP, SS, the required influent information input in BioWin, the influent water qualities in China are analyzed based on data from 173 WWTPs. It is found that CODs are closely correlated to BODs ($\text{BOD}_5 = 0.47 \text{ COD}$, $R^2 = 0.949$) and, that NH$_3$-N concentrations are correlated to TN concentrations (NH$_3$-N = 0.75 TN, $R^2 = 0.929$). In addition, since within a normal range, concentration of SS of the influent has little effect on the efficiency of biological treatment technology, it is set to be 200 mg/L (the national average) for all influents in the simulation. Therefore, only variation of COD, TN, and TP in the influents is considered in the simulation, while BOD and NH$_3$-N concentrations are calculated according to the regression functions obtained. Furthermore, the COD profile, the TN concentration profile in a given COD, and the TP concentration profile in a given COD and a given TN concentration are found to follow the normal distribution. Moreover, TN and TP’s distribution and plants’ amount with a single COD are taken into consideration, in order to choose several values of TN and TP or their combination. Finally, a list of 51 most typical inflow wastewater qualities is determined as inputs of BioWin (shown in Table 4), where every influent quality scenario is simulated under three different temperature conditions (15°C, 20°C, 25°C).

Thirdly, for each type of WWTP, an equation is generated by the regression of volume of air needed ($G_S$) on corresponding inflow water qualities (COD, BOD, NH$_3$-N, TN, TP, and SS):

$$G_S = 2.4(a\text{COD}^m + b\text{TN}^n + c\text{TP})\exp[k(20 - T)], \quad (3)$$

where $G_S$ is the air demand volume per $10^4$ m$^3$ of wastewater, COD is the chemical oxygen demand, TN is the total

<table>
<thead>
<tr>
<th>No.</th>
<th>COD (mg/L)</th>
<th>TN (mg/L)</th>
<th>TP (mg/L)</th>
<th>No.</th>
<th>COD (mg/L)</th>
<th>TN (mg/L)</th>
<th>TP (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130</td>
<td>20.5</td>
<td>2.4</td>
<td>12</td>
<td>300</td>
<td>38.9</td>
<td>4.1</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>21.9</td>
<td>2.7</td>
<td>13</td>
<td>300</td>
<td>38.9</td>
<td>4.7</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>25.9</td>
<td>2.4</td>
<td>14</td>
<td>300</td>
<td>38.9</td>
<td>5.6</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>25.9</td>
<td>2.7</td>
<td>15</td>
<td>300</td>
<td>47.4</td>
<td>4.1</td>
</tr>
<tr>
<td>5</td>
<td>200</td>
<td>25.9</td>
<td>3.2</td>
<td>16</td>
<td>300</td>
<td>55.8</td>
<td>4.1</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td>25.9</td>
<td>3.7</td>
<td>17</td>
<td>400</td>
<td>32.0</td>
<td>5.5</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>31.6</td>
<td>2.7</td>
<td>18</td>
<td>400</td>
<td>43.8</td>
<td>5.5</td>
</tr>
<tr>
<td>8</td>
<td>300</td>
<td>24.0</td>
<td>4.1</td>
<td>19</td>
<td>400</td>
<td>51.9</td>
<td>3.7</td>
</tr>
<tr>
<td>9</td>
<td>300</td>
<td>32.9</td>
<td>4.1</td>
<td>20</td>
<td>400</td>
<td>51.9</td>
<td>4.8</td>
</tr>
<tr>
<td>10</td>
<td>300</td>
<td>38.9</td>
<td>2.8</td>
<td>21</td>
<td>400</td>
<td>51.9</td>
<td>5.5</td>
</tr>
<tr>
<td>11</td>
<td>300</td>
<td>38.9</td>
<td>3.6</td>
<td>22</td>
<td>400</td>
<td>51.9</td>
<td>7.4</td>
</tr>
</tbody>
</table>
where $1.43 \text{ (kg/m}^3\text{)}$ is the density of oxygen, 21% is the ratio of air needed into energy consumption by the aeration machinery ($E_A$), and the values of them are listed in Table 5.

Another equation is obtained by converting the volume of air into energy consumption by the aeration machinery ($E_A$):

$$E_A = 1.43 \times 21.0\% \times G_S / \eta_E \times (\text{kWh}/10^4 \text{m}^3)$$  \hspace{1cm} (4)

where $1.43 \text{ (kg/m}^3\text{)}$ is the density of oxygen, 21% is the ratio of oxygen in air, and $\eta_E \text{ (kg/kWh)}$ is the efficiency of the aeration machinery. Or Equation (4) when replacing $G_S$ with Equation (3):

$$E_A = 1.43 \times 21.0\% \times 2.4 \times 10^{-4} \times (a \text{COD}^m + b \text{TN}^n + c \text{TP}) \times \exp[k(20-T)]/\eta_E \times (\text{kWh}/\text{m}^3)$$  \hspace{1cm} (5)

Since the regression of these equations has taken the influence of inflow wastewater qualities into account, these equations can be utilized in the calculation of $E_A$ benchmark for any WWTP applying oxidation ditch, SBR, or A/A/O as treatment technology (marking benchmark value as $B_{EA}$).

**Indicator 5: energy consumption of sludge processing unit per sludge mass treated ($E_S$)**. $E_S$ indicates energy consumed in disposal of the sludge produced by a WWTP, typically, including energy used for mixing, sludge dewatering and chemical treatment (e.g. chemical dosing pump). Since the total energy consumption of sludge processing in a WWTP is dependent on the amount of sludge produced, the energy consumption of sludge processing unit is weighted on a sludge mass treated basis.

**Level 5: energy recovery indicators**

Energy recovery from residual sludge is a key to energy conservation and thus is a promising energy recovering unit for WWTPs in China. So energy recovery indicators are introduced into the energy performance assessment framework to stimulate WWTPs to invest in the residual sludge processing and energy recovery facilities and to try their best to improve the efficiencies of sludge digestion and energy recovery. Since the main energy recovered is in the form of natural gas from the sludge digestion process and electricity or heat generated by the natural gas, volume of biogas retrieved (produced by sludge digestion) per sludge mass treated ($G_R$) and electronic energy retrieved per energy consumption ($E_R$) are adopted as indicators for energy recovery from residual sludge.

**Indicator 6: volume of biogas retrieved (produced by sludge digestion) per sludge mass treated ($G_R$)**. $G_R$ is chosen to evaluate the natural gas production efficiency in a WWTP. Similar to $E_S$, $G_R$ is affected by the amount of residual sludge; hence it is weighted on a sludge mass treated basis.

**Indicator 7: electrical energy retrieved per energy consumption ($E_R$)**. $E_R$ is used to assess the efficiency of electrical energy recovery, which actually covers the efficiency of natural gas production efficiency and the efficiency of converting the natural gas recovered into electrical energy. $E_R$ is calculated as the ratio of electrical energy recovered to the electrical energy consumed, thus it eliminates the influence of treatment capacity of a WWTP.

### Scoring method for each energy performance indicator

As introduced above, 3 tiers with 7 indicators are adopted in this energy performance assessment framework (Table 6). In the following section, the scoring methods for each indicator and for the energy performance index (EPI) are discussed.

1. **Scoring method of indicators**

   For $E_V$, $E_M$, $E_P$, $E_A$, and $E_S$, as indicator value ($D$) is smaller the WWTP performances better on energy consumption, and $D$ is bigger than benchmark ($B_D$). To be easy to understand, 0 ~ 100 rating system is used, and indicator ($S_D$) is simply calculated by dividing $B_D$ by the $D$ to keep $S_D$ between 0 ~ 100, that is:

$$S_D = \frac{B_D}{D} \times 100$$  \hspace{1cm} (6)
Table 6  | Energy performance indicators and their scoring methods

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Denotation</th>
<th>Implication</th>
<th>Benchmark</th>
<th>Unit</th>
<th>Scoring method</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_V$</td>
<td>$E_M$</td>
<td>$E_P$</td>
<td>$E_A$</td>
<td>$G_R$</td>
<td>$E_R$</td>
</tr>
<tr>
<td></td>
<td>Energy consumption per volume of wastewater treated</td>
<td>Energy consumption per total pollutant mass removed</td>
<td>Energy consumption of influent flow pump unit per volume of wastewater pumped per pump head</td>
<td>Energy consumption of aeration per volume of wastewater treated</td>
<td>Energy consumption of sludge processing unit per sludge mass treated</td>
</tr>
<tr>
<td></td>
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<td></td>
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</table>

According to Equation (5).‡ The lowest value according to the national survey.† According to Table 2.

$S_D = \frac{D}{B_D} \times 100$  

Benchmarks of $G_R$ and $E_R$, as $D$ is bigger the WWTP performances better, and to keep $S_D$ between 0 $\sim$ 100, $S_D$ is calculated by dividing $D$ by the $B_D$, that is: 

And for $G_R$ and $E_R$, as $D$ is bigger the WWTP performances better, and to keep $S_D$ between 0 $\sim$ 100, $S_D$ is calculated by dividing $D$ by the $B_D$, that is: 

Benchmarks of $G_R$ and $E_R$ are determined to be 5.5 m³/kg (Gaobeidian WWTP), and 27% (Shameng WWTP), respectively, representing the highest level in China.

(2) Comprehensive score of unit energy consumption indicators ($S_{EU}$) 

Since $S_{EP}$, $S_{EA}$, and $S_{ES}$ are scores of the three main energy consuming processes, they should be combined to afford a general score for evaluating the unit energy consumption. Therefore, $S_{EP}$, $S_{EA}$, and $S_{ES}$ are assigned a specific weight based on contributions of $E_P$, $E_A$, and $E_S$ in the gross energy consumption, and the general score of unit energy consumption indicators ($S_{EU}$) is calculated by summing $S_{EP}$, $S_{EA}$, and $S_{ES}$, each multiplied by the assigned weight. Based on data of the 10 on-spot investigated WWTPs, the average ratios of energy consumptions for the wastewater elevation (pumping), aeration, sludge processing, and the rest energy use are 26.2%, 64.8%, 6.9%, and 2.1%, respectively. Thus the weight for $S_{EP}$, $S_{EA}$, and $S_{ES}$ are determined to be 0.26, 0.65, and 0.07, respectively. The comprehensive score of unit energy consumption indicators ($S_{EU}$) is calculated by the following equation: 

$S_{EU} = 0.26S_{EP} + 0.65S_{EA} + 0.07S_{ES}$

Energy Performance Index (EPI) 

Energy performance index is used to comprehensively express the energy performance of a WWTP. It combines the energy consumption efficiency of the entire WWTP ($E_V$, $E_M$), energy consumption efficiency of the three operational units ($E_P$, $E_A$, $E_S$), and the efficiency of energy recovery ($G_R$, $E_R$). Since the contribution of these three types of efficiencies is equally considered, the EPI is determined as the average of their scores. Including all the functions above, the EPI is: 

$EPI = \frac{S_{EU} + S_{EM} + S_{EP} + S_{EA} + S_{ES}}{5}$

Interpretation of Scores 

Values of $E_V$ and $E_M$ can be easily calculated and therefore can be applied countrywide with little regard to information availability, since only information
concerning the gross electricity use and the treatment loads are needed in the calculation. Hence, they are adopted to evaluate the energy use of the entire WWTP, and benchmarks of $E_V$ and $E_M$ are set to be the corresponding national average. Based on the countrywide survey, about 40% of WWTPs get a full score, meaning that they perform better than or equally to the national average. Those with scores less than 85 should take measures to improve their energy performance.

$E_P$, $E_A$, and $E_S$ are used to assess energy consumption efficiency of each operation unit in a WWTP. Their benchmarks are determined based on the highest level in China ($E_P$, $E_S$), or theoretical simulation ($E_A$), because only a few WWTPs in China measure unit energy consumption currently. Nevertheless, evaluation of unit energy consumption helps WWTPs to highlight units of poor or good performance and to identify units requiring energy conservation or units with energy saving potential. Getting a score of 85 or above indicates that the WWTP performs well in the corresponding unit, while getting a score of 60 or below alerts the WWTP to improve its energy use even when its scores of $E_V$ and $E_M$ are higher than 85.

In order to promote the implementation of the sludge digestion process in China, $G_R$ and $E_R$ are brought into the energy performance assessment framework for evaluating the energy recovery efficiency. Given that the highest energy recovery levels are set as their benchmarks, getting a score no less than 60 will meet the basic requirement of energy recovery.

EPI indicates the general energy performance of a WWTP, and the higher EPI means the better performance. WWTPs with scores higher than 85 are excellent, those with scores between 70 to 85 have room for energy conservation, those with scores between 60 to 70 have larger space for energy consumption efficiency improvement, and those with scores below 60 should take appropriate measures to increase their energy use efficiency.

### RESULTS AND DISCUSSIONS

In this section, the system’s assessing results from practical data of WWTPs are mainly discussed. Integrated assessment is performed on three WWTPs’ performance circumstance in 2006. Table 7 lists basic information of WWTPs in case study. Corresponding calculation results are shown in Table 8. CASS is short for Cyclic Activated Sludge System, and MSBR is for Multiple Sequencing Batch Reactor (Combined A/A/O with SBR).

Because none of the plants has adopted the process of sludge digestion and power generation from biogas, $G_R$ and $E_R$ are not relevant here. The results are shown in Table 9. The blanks in Table 9 mean data missing due to the limit of research condition. Generally speaking, the existing data of every plant are able to support calculation and assessment. So this assessment system is feasible in practice.

Plant MSBR performs better on pumping and sludge treating, yet the pollutants load and efficiency of biochemical unit are low, leading to the plant’s lack of the removing ability. So enhancing the aeration efficiency of

<table>
<thead>
<tr>
<th>Treatment process</th>
<th>Province (city)</th>
<th>Design capacity ($10^4$ m$^3$/d)</th>
<th>Treatment capacity ($10^4$ m$^3$/d)</th>
<th>$\bar{t}$ (°C)</th>
<th>COD (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASS</td>
<td>Anhui</td>
<td>5.5</td>
<td>4.4</td>
<td>16.6</td>
<td>152</td>
</tr>
<tr>
<td>MSBR</td>
<td>Guangdong</td>
<td>12</td>
<td>5.2</td>
<td>22.8</td>
<td>228</td>
</tr>
<tr>
<td>A/A/O</td>
<td>Beijing</td>
<td>60</td>
<td>53.0</td>
<td>13.5</td>
<td>489</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment process</th>
<th>BOD (mg/L)</th>
<th>SS (mg/L)</th>
<th>NH$_2$N (mg/L)</th>
<th>TN (mg/L)</th>
<th>TP (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASS</td>
<td>52.3</td>
<td>3.3</td>
<td>98.0</td>
<td>10.7</td>
<td>19.5</td>
</tr>
<tr>
<td>MSBR</td>
<td>115</td>
<td>1.9</td>
<td>190</td>
<td>7.2</td>
<td>16.4</td>
</tr>
<tr>
<td>A/A/O</td>
<td>241</td>
<td>11.0</td>
<td>303</td>
<td>13.9</td>
<td>47.0</td>
</tr>
</tbody>
</table>

Table 7 | Basic information of WWTPs in case study
biochemical unit and removing efficiency of pollutants will indeed effectively improve the assessment result. \( E_V \) of plant A/A/O’s is in need of improving, including the energy efficiency of pumping unit and biochemical unit. Based on the score of EPI, the rank of energy saving reconstruction is A/A/O, MSBR and CASS.

From the basic information, it is noticed that both the plant CASS and MSBR have the problem of low water loading rate and pollutants load, which influences the energy efficiency of pollutants removing. Thus the plants also have the problem of designing and construction of corresponding pipe network, so the radical improvement of energy performance requires the cooperation with municipal department on collecting and transporting sewage. Comparing with plant MSBR’s simplified DO control, although having the same problem of over-aeration, plant A/A/O adopts the united control of aeration amount and DO, which distinctively improves the efficiency.

As a whole, every plant has a potential of energy saving, especially in aeration. Aeration efficiency is the foremost improving target, which can be managed through enhancing the automatic control strategy, increasing supervision and adding more control parameters to realize more subtle control. Moreover, huge fluctuation of water amount and low water load are also universal problems for plants. Through adding transducers to pumping and aeration equipments, flexibly adjusting equipment power and keeping effective operation, the performance could be improved remarkably.

Through the case study above, the process of assessment is introduced and the sample is provided. It is proved that the energy consumption assessment system is applicable and helpful for plants to recognize energy saving potential and pressure in order to take actions. What is more, EPI score helps for providing ranks to identify the state of a plant and to perform energy saving.

**CONCLUSIONS**

Through the statistical analysis of municipal WWTPs’ data in 2006, it was summarized as follows: current average electrical energy consumption of Chinese secondary treatment WWTPs was 0.290 kWh/m³, which meant a comparative large gap in comparison with developed countries. Based on the data in 2006, the treatment technology adopted, treated sewage amount and removed pollutants amount played a significant role in energy consumption of sewage treatment.

This paper based on the statistical conclusions above, integrated with current researches to propose an energy performance assessment system, exhibiting the operation characters of WWTPs. This system includes 7 indicators with algorithm or value of benchmark, performing integrative assessment from three aspects, comprehensive energy consumption, unit energy consumption, and energy recovery.

The system assessed three major units, including pumping, aeration and pollutants treatment, as well as the consumption of recycling energy in sludge digestion. For aeration unit, through model simulation and calculation, theoretical consumption of aeration was provided. Finally the integrated energy efficiency was put forward by EPI. Moreover, the system of EPI was adopted to assessing performance of WWTPs in case study. It was proved that this system was applicable and helpful for WWTPs’ recognizing problems and improving energy performance.
In fact, this research mainly discussed the assessment on electrical consumption, and did not take sludge treatment chemicals and phosphorus removal chemicals into consideration. Besides, the assessment simply evaluated common units of secondary treatment plants with OD, AO and SBR treatment technologies. Primary treatment plants and advanced units (like filter and disinfection) should be further discussed to complete the system and improve its applicability.

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REFERENCES


