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RESEARCH ARTICLE

Techno-economic characteristics of wastewater treatment plants retrofitted from the conventional activated sludge process to the membrane bioreactor process

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HIGHLIGHTS

- Retrofitting from CAS to MBR increased effluent quality and environmental benefits.
- Retrofitting from CAS to MBR increased energy consumption but not operating cost.
- Retrofitting from CAS to MBR increased the net profit and cost efficiency.
- The advantage of MBR is related to the adopted effluent standard.
- The techno-economy of MBR improves with stricter effluent standards.

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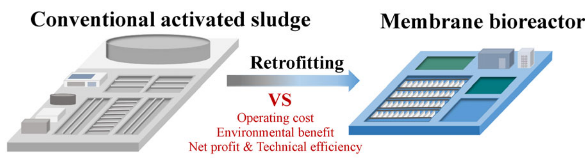
GRAPHIC ABSTRACT



ABSTRACT

While a growing number of wastewater treatment plants (WWTPs) are being retrofitted from the conventional activated sludge (CAS) process to the membrane bioreactor (MBR) process, the debate on the techno-economy of MBR vs. CAS has continued and calls for a thorough assessment based on techno-economic valuation. In this study, we analyzed the operating data of 20 large-scale WWTPs (capacity⩾10000 m^3/d) and compared their techno-economy before and after the retrofitting from CAS to MBR. Through cost-benefit analysis, we evaluated the net profit by subtracting the operating cost from the environmental benefit (estimated by the shadow price of pollutant removal and water reclamation). After the retrofitting, the removal rate of pollutants increased (e.g., from 89.0% to 93.3% on average for NH_3-N), the average energy consumption increased from 0.40 to 0.57 kWh/m^3, but the operating cost did not increase significantly. The average marginal environmental benefit increased remarkably (from 0.47 to 0.66 CNY/g for NH_3-N removal), leading to an increase in the average net profit from 19.4 to 24.4 CNY/m^3. We further scored the technical efficiencies via data envelopment analysis based on non-radial directional distance functions. After the retrofitting, the relative cost efficiency increased from 0.70 to 0.73 (the theoretical maximum is 1), while the relative energy efficiency did not change significantly. The techno-economy is closely related to the effluent standard adopted, particularly when truncating the extra benefit of pollutant removal beyond the standard in economic modeling. The modeling results suggested that MBR is more profitable than CAS given stricter effluent standards.

1 Introduction

To address the water crisis, wastewater must be treated and reclaimed. The membrane bioreactor (MBR), a promising wastewater treatment technology, has been broadly applied because of its small footprint and high effluent quality

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(Huang et al., 2010; Judd, 2016). Many wastewater treatment plants (WWTPs) in China have adopted MBRs to replace the conventional activated sludge (CAS) process to better achieve environmental goals (Xiao et al., 2019). However, retrofitting from CAS to MBR has been controversial due to the high energy consumption and membrane fouling in MBR applications (Hao et al., 2018). Can the advantages of MBR outweigh its weaknesses? Is retrofitting economically reasonable? How about the cost effectiveness of MBR over CAS? It is essential to clarify these issues by comparing the techno-economy of CAS with that of MBR.

The costs of MBR have been calculated in the literature, including capital and operating costs (DeCarolis et al., 2007; Verrecht et al., 2010; Pretel et al., 2015; Yu et al., 2020). The capital cost includes the cost of plant construction (tanks, pipelines, membrane modules and other equipment), pipeline network and non-engineering investment (Xiao et al., 2014). Operating costs cover energy and chemical consumption, sludge disposal and labor costs among others (Verrecht et al., 2010; Iglesias et al., 2017; Xiao et al., 2019). Energy consumption accounts for the largest proportion of operating costs and is a key factor restricting the sustainable development of MBR (Fenu et al., 2010). In particular, the life cycle cost of MBR is also affected by the operating flux, separation performance, initial price and lifespan of the membrane (Lin et al., 2011). Table 1 shows that MBR normally has higher energy consumption (0.4–1.6 kWh/m^3) than that of CAS (0.3–0.8 kWh/m^3) (Iglesias et al., 2017; Krzeminski et al., 2017; Xiao et al., 2019). The operating cost calculated by different studies varies due to the different process flows and geographic locations of WWTPs, but the operating cost of CAS is generally lower than that of MBR. The capital cost of MBR is usually higher than that of CAS but is comparable to that of CAS with added tertiary treatment to achieve similar effluent quality (Brepols et al., 2010).

High costs are often associated with high returns. For example, lowering the effluent pollutant concentration increases the marginal cost of wastewater treatment but results in a higher environmental benefit. Therefore, a justified techno-economic assessment of MBR vs. CAS requires comprehensively considering both economic costs and environmental benefits. One method is to quantify the environmental benefits of wastewater treatment using the

Table 1 Cost comparison between MBRs and CASs

Literature	Cost	Unit	CAS	MBR
Verrecht et al., 2010	Capital cost	USD/(m^3/d)	N.A.	264
	Operating cost	USD/m^3	N.A.	0.10
DeCarolis et al., 2007	Capital cost	USD/(m^3/d)	N.A.	2111–2602
	Operating cost	USD/m^3	N.A.	0.16–0.22
Gabarrón et al., 2014	Operating cost	USD/m^3	N.A.	0.55–0.68 (HF MBR)
				0.42 (FS MBR)
				0.25 (HF hybrid MBR-CAS)
				0.15 (HF dual-stream MBR-IFAS)
				0.27 (FS dual-stream MBR-CAS)
Krzeminski et al., 2017	Energy consumed	kWh/m^3	0.3–0.6	0.4–1.6
Young et al., 2012	Capital cost	USD/(m^3/d)	1955	1849
	Operating cost	USD/m^3	0.09	0.10
Xiao et al., 2014; 2019	Capital cost	USD/(m^3/d)	380	380–800
	Operating cost	USD/m^3	0.11	0.11–0.18
	Energy consumed	kWh/m^3	0.3–0.4	0.45–0.8 ($Q < 50000$ m^3/d)
				0.4–0.6 ($Q \geqslant 50000$ m^3/d)
Iglesias et al., 2017	Capital cost	USD/(m^3/d)	N.A.	2379–3807 ($Q =$ 1000–2000 m^3/d)
				744 ($Q > 10000$ m^3/d)
	Energy cost	USD/m^3	0.05–0.10	0.07–0.13
	Energy consumed	kWh/m^3	0.4–0.8	0.8–1.2
Brepols et al., 2010	Capital cost (life cycle cost)	USD/(m^3/d)	4653	3630
	Operating cost (life cycle cost)	USD/m^3	0.41	0.46

Notes: Exchange rate in April 2021: 1 USD ≈ 0.84 EUR ≈ 6.55 CNY. Q = capacity. CAS = conventional activated sludge. MBR = membrane bioreactor. HF = hollow-fiber. FS = flat-sheet. IFAS = integrated fixed-film activated sludge process. N.A. = not available.

shadow price rather than the market price due to environmental externalities (Färe et al., 2006; Hernández-Sancho et al., 2010; Molinos-Senanteet al., 2010; Molinos-Senante et al., 2011; Gao et al., 2021). The net profit can be obtained by subtracting the costs from the benefits to evaluate the techno-economic feasibility of WWTPs. It was found that the removal of nutrients (e.g., nitrogen and phosphorus) from wastewater contributed the most to environmental benefits, while the contribution of removing suspended particulates was relatively small (Molinos-Senante et al., 2010; Molinos-Senante et al., 2011; Djukic et al., 2016). Environmental benefits were also related to the destination of effluent pollutants. The environmental benefit of removing pollutants in pollutant-sensitive places (e.g., wetlands) was high but that in the sea was low due to the large capacity of dilution and diffusion. Higher environmental benefits could be achieved if the treated wastewater is reused rather than directly discharged (Hernández-Sancho et al., 2010; Djukic et al., 2016). Another method is to measure the input-output efficiency of WWTPs by data envelopment analysis (DEA). The efficiency reflects the coupling relationship between treatment performance and costs in wastewater treatment (Sala-Garrido et al., 2011; Gao et al., 2021). Previous studies evaluated the efficiency of traditional WWTPs and found that this efficiency varied with the plant size, pollutant removal load and aeration condition (Hernández-Sancho and Sala-Garrido, 2009; Hernández-Sancho et al., 2011; Longo et al., 2018).

However, the previously reported techno-economic evaluation of WWTPs mostly lacked a systematic comparison between the CAS and MBR processes, especially a strict paired comparison between them in the same WWTP. A loose comparison of CAS and MBR for different WWTPs, which was conducted in most previous studies, might be influenced by external factors (e.g., geographical location, local effluent standard and economic conditions) (Gao et al., 2021). A much stricter comparison can be made between the techno-economic performances before and after retrofitting of the same WWTP, but such a comparison has rarely been reported. Moreover, the previous comparisons were mostly limited to the explicit profit and lacked thorough quantification of the implicit environmental benefit. Without this information, the cost-benefit analysis (CBA) can never be complete, and the technical efficiency evaluation can never be justified.

To address the above issues, we analyzed the techno-economic data of 20 full-scale WWTPs (each $\geqslant$ 10000 m^3/d in China) that had been retrofitted from CAS to MBR. The explicit/implicit cost, benefit and net profit of each WWTP before and after the retrofitting were systematically compared via the CBA using the shadow pricing approach. The energy efficiency (EE) and cost efficiency (CE) of CAS vs. MBR were evaluated using the non-radial distance function (NDDF) in DEA. A sensitivity analysis was performed to assess the reliability of the results. The results would show that MBR was overall more profitable and efficient than CAS. Through modeling, we would also show how the strictness of the adopted effluent standard could influence the techno-economy of CAS vs. MBR.

2 Materials and methods

2.1 Sample data

The sample set consisted of 20 large-scale (each $\geqslant$ 10000 m^3/d) WWTPs that had been retrofitted from CAS to MBR in eastern and central China. Among them, 17 WWTPs were restructured by replacing CAS with MBR; the other 3 WWTPs were expanded with MBR while retaining the original CAS (i.e., operated in parallel with MBR). The basic information and operating data of the 20 WWTPs in both the CAS and MBR periods were obtained from the *China Wastewater Treatment Engineering Network* and *China Urban Drainage Statistical Yearbook* during 2013–2018. The data included the design capacity, treatment capacity, operating cost, energy consumption, pollutant removal and sludge production. Table S1 in Section S1 shows the basic information of the 20 WWTPs before and after the retrofitting.

2.2 Cost-benefit analysis

2.2.1 Net profit calculation

The net profit (NP) can be obtained by CBA to evaluate the techno-economic feasibility (Molinos-Senante et al., 2011). NP is the difference between the benefit (B) and the cost (C), as shown in Eq. (1):

$$\mathrm{NP} = B - C, \tag{1}$$

where C represents the operating cost. The capital cost is not considered here because it is difficult to allocate the share before and after the retrofitting of the WWTP. B includes the environmental benefits of water reclamation and pollutant removal (Hernández-Sancho et al., 2010; Molinos-Senante et al., 2010), which is expressed as Eq. (2):

$$B = B_{\mathrm{r}} + \sum_{j=1}^{J} P_j \cdot \Delta U_j, \tag{2}$$

where B_{r} represents the environmental benefit from reclaiming wastewater (the reclaimed water price in China is 1 CNY/m^3). Because real market pricing for pollutant removal was unknown, the environmental benefit of removing pollutants was evaluated from the shadow price (a model-calculated virtual price rather than the real market price) of the pollutants (Färe et al., 2006; Hernández-Sancho et al., 2010; Molinos-Senante et al., 2010; Molinos-Senante et al., 2011). P_j is the shadow price of the jth pollutant calculated using the direction distance function (DDF) (Färe et al., 1989; Färe et al., 2006; Hernández-Sancho et al., 2010; Molinos-Senante et al., 2010; Molinos-Senante et al., 2011), and ΔU_j is the amount of the jth pollutant that is removed (i.e., influent concentration minus effluent concentration).

2.2.2 Shadow price calculation

A WWTP can be considered as a production unit that converts the inputted cost (**x**) into reclaimed water as the desirable output (**y**) and discharged residual pollutants as the undesirable output (**b**). If we plot the WWTP sample points (each point representing a WWTP) in a vector space coordinated by the input and outputs, then the upper boundary of **y** forms the "production frontier". A sample point sitting on the production frontier attains the largest desirable output given fixed **x** and **b**. The distance from a sample point to the production frontier measures the badness of the production status of the WWTP compared with the optimal level. In this vector space specified by the WWTP sample points, the distribution of profit contours and distance contours (i.e., lines connecting points of equal profit and equal distance) determines the shadow price at each sample point, as illustrated in Fig. 1(a). In the sense of economics, the determination of the shadow price obeys the principle of profit maximization (i.e., the "rational economic man" hypothesis): to maximize the profit of the WWTP at the same technical level (i.e., to attain maximum profit on a distance contour) or, equivalently, to allow the lowest technical level when achieving the same profit (i.e., to allow the farthest distance on a profit contour) (Färe et al., 2006). Therefore, the production frontier and the functions of distance and profit need to be determined to calculate the shadow price.

1) Determine the production frontier

In the diagram of **y** vs. **b** (Fig. 1(a)), the boundary formed by the outermost sample points determines the production frontier (also regarded as the production possibility boundary). All possible combinations of **y** and **b** produced by the input (**x**), including the points within and on the frontier, thus form the production possibility set $P(\mathbf{x})$. The cost (C, CNY/year) is set as the input $\mathbf{x} = (x_1, ..., x_M)^T$ (in this study, $M = 1$). The volume of treated wastewater (m^3/year) is set as the desirable output $\mathbf{y} = (y_1, ..., y_N)^T$ (in this study, $N = 1$). The amount of discharged pollutants (COD and NH_3-N, g/year) is set as the undesirable output $\mathbf{b} = (b_1, ..., b_J)^T$ (in this study, $J = 2$). The waste gas, SS, TP and other pollutants are not considered here due to data limitations.

2) Determine the directional distance and profit functions

Along the ideal direction where **y** increases and **b** decreases, the directional distance is the distance between a WWTP sample and the frontier, which is expressed as Eq. (3):

$$\vec{D}_0(\mathbf{x},\mathbf{y},\mathbf{b};\mathbf{g_y},\mathbf{g_b}) = \max\{\beta : (\mathbf{y} + \beta\mathbf{g_y}, \mathbf{b} - \beta\mathbf{g_b}) \in P(\mathbf{x})\}, \tag{3}$$

where β represents the scale of change along the direction $\mathbf{g} = (\mathbf{g_y}, \mathbf{g_b})$. For simplicity, $(\mathbf{g_y}, \mathbf{g_b}) = (1, -1)$.

The direction distance function and the profit function are coupled according to the duality of linear programming. Given the price vectors $\mathbf{p_x} = (p_{x1}, ..., p_{xM})$, $\mathbf{p_y} = (p_{y1}, ..., p_{yN})$ and $\mathbf{p_b} = (p_{b1}, ..., p_{bJ})$, the profit function can be expressed as Eq. (4):

$$\pi(\mathbf{p_x},\mathbf{p_y},\mathbf{p_b}) = \mathbf{p_y}\mathbf{y} - \mathbf{p_x}\mathbf{x} - \mathbf{p_b}\mathbf{b}$$

$$\text{s.t. } \vec{D}_0 \geqslant 0, \tag{4}$$

3) Calculate the shadow price

The point with the highest profit at the same technical level (e.g., point A) is obtained when the profit contour is tangent to the distance contour, as shown in Fig. 1(a). The slopes of the distance contour and the profit contour are equal at this point, yielding:

$$\frac{\mathbf{p_b}}{\mathbf{p_y}} = \left(\frac{\partial\vec{D}_0(\mathbf{x},\mathbf{y},\mathbf{b};\mathbf{g})/\partial\mathbf{b}}{\partial\vec{D}_0(\mathbf{x},\mathbf{y},\mathbf{b};\mathbf{g})/\partial\mathbf{y}}\right). \tag{5}$$

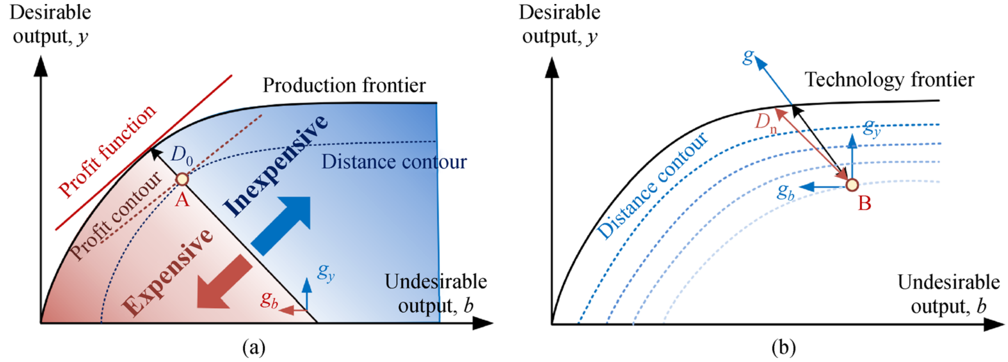

Fig. 1 Schematic diagram for calculating the (a) shadow price and (b) technical efficiency.

Therefore, the shadow price $\mathbf{p_b}$ can be calculated given the price $\mathbf{p_y}$ (i.e., the reclaimed water price in China is 1 CNY/m^3). Equation (5) suggests that $\mathbf{p_b}/\mathbf{p_y}$ is proportional to $(\Delta\mathbf{b}/\Delta\mathbf{y})^{-1}$, i.e., the reciprocal of the effluent concentration, indicating that a lower effluent concentration corresponds to a higher shadow price of pollutant removal, which might be explained by the augmentation of the marginal cost toward more thoroughly purified effluent water. The slope of the profit contour in Fig. 1(a) refers to $\mathbf{p_b}/\mathbf{p_y}$. Taking the 45° line at point A as the dividing line, the farther to the left, the higher the shadow price is, and the farther to the right, the lower the shadow price is. Overall, the shadow price $\mathbf{p_b}$ is defined as the relative marginal cost of pollutant removal, indicating the cost required to further improve the effluent quality. In the reference system constructed from the sample set of WWTPs, the average shadow price would be relatively high if the sample points are concentrated in the "expensive zone" on the left, while it would be relatively low if the sample points are concentrated in the "inexpensive zone" on the right. The procedure and an example of the shadow price calculation are given in Fig. 2 and Tables S2–S4 in Section S2, respectively.

2.3 Technical efficiency calculation

DEA has been employed to evaluate the energy efficiency of power generation industries and the technical efficiency

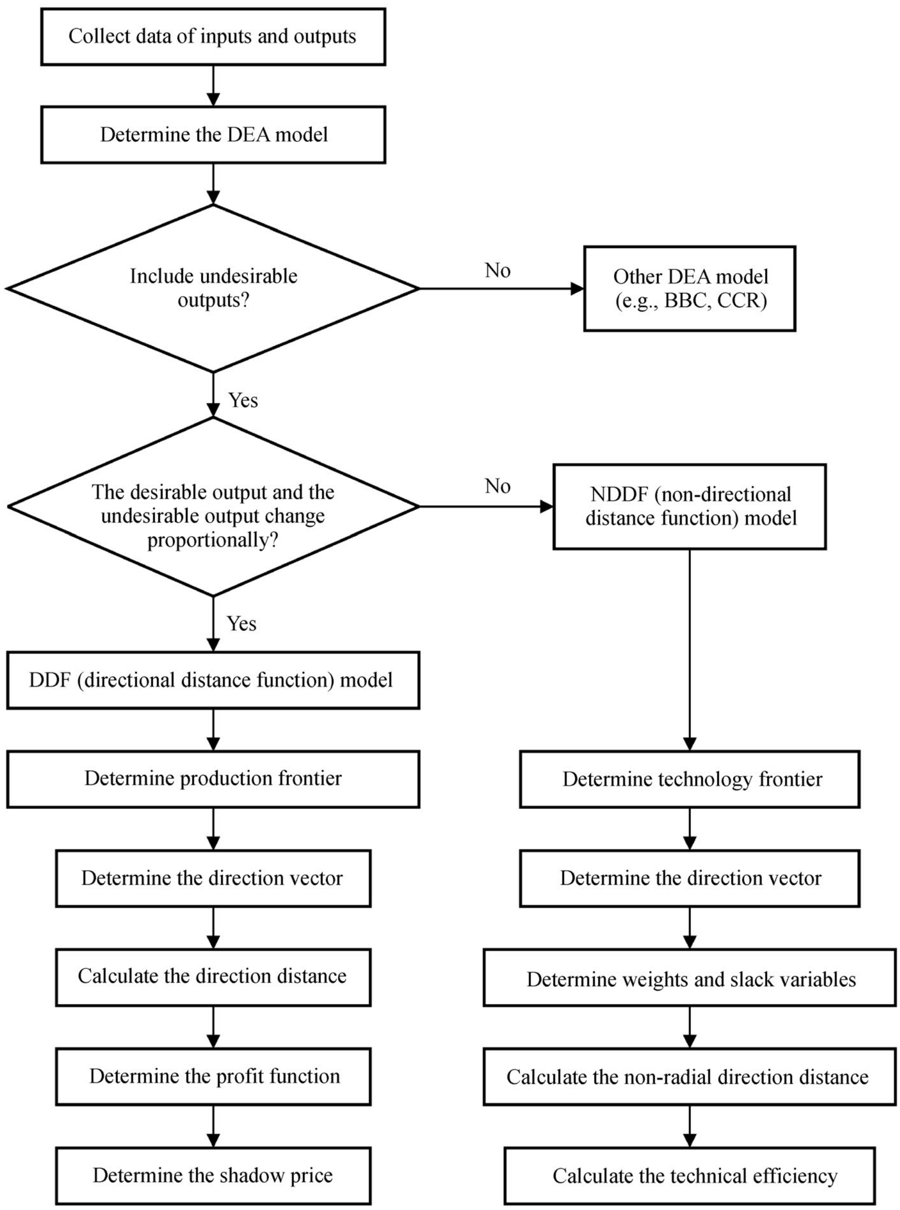

Fig. 2 Procedure for calculating the shadow price and technical efficiency.

of wastewater treatment plants (Zhou et al., 2012; Chang et al., 2013; Mohsin et al., 2021). Technical efficiency is the ratio between the actual output of a decision-making unit (DMU; in this study, DMU = WWTP) and the maximum possible desirable output (**y**), given the same input (**x**) and undesirable output (**b**). If we plot the WWTP sample points in the coordinate system of the input and outputs, the outermost sample points form the "technology frontier" along the direction where **y** increases and **x** and **b** decrease (Fig. 1(b)). The closer the sample to the frontier, the higher the technical efficiency (ranging from 0 to 1) is obtained. The DEA model based on the NDDF was adopted in this study because it can analyze the undesirable output and allow fine-tuning of the distance toward the frontier.

1) Determine the technology frontier

In the vector space of **y** vs. **b**, the technology frontier is shaped by the outermost sample points, as shown in Fig. 1 (b). All points are enveloped on or within the frontier (Zhou et al., 2012; Lin and Du, 2015) and thus form the technology set:

$$T(\mathbf{x}) = \{(\mathbf{x},\mathbf{y},\mathbf{b}) : \mathbf{X\lambda} \leqslant \mathbf{x}, \mathbf{Y\lambda} \geqslant \mathbf{y}, \mathbf{B\lambda} = \mathbf{b}, \mathbf{\lambda} \geqslant 0\}, \quad (6)$$

where $\mathbf{x} = (x_1, ..., x_K)^{\mathrm{T}}$ (in this study, $K = 1$) is the input vector, referring to the energy consumption (kWh/m^3) or operating costs (CNY/m^3). The desirable output $\mathbf{y} = (y_1, ..., y_O)^{\mathrm{T}}$ includes the volume of treated wastewater (m^3/d) and the rate of removing pollutants (such as COD and NH_3-N, %) (in this study, $O = 3$). The excess sludge production (m^3/d) is set as the undesirable output $\mathbf{b} = (b_1, ..., b_Q)^{\mathrm{T}}$ (in this study, $Q = 1$). **X**, **Y** and **B** are the matrices of the input, desirable output and undesirable output, respectively. $\mathbf{\lambda}$ is the intensity vector.

2) Evaluate efficiency based on NDDF-DEA

The non-radial directional distance between a WWTP sample point and the technology frontier can be expressed as:

$$\vec{D}_{\mathrm{n}}(\mathbf{x},\mathbf{y},\mathbf{b};\mathbf{g}) = \sup\left\{\mathbf{w}^{\mathrm{T}}\boldsymbol{\alpha} : ((\mathbf{x},\mathbf{y},\mathbf{b}) + \mathbf{g}\cdot \mathrm{diag}(\boldsymbol{\alpha})) \in T\right\}, \quad (7)$$

where the slack vector $\boldsymbol{\alpha} = (\boldsymbol{\alpha}_{\mathbf{x}}, \boldsymbol{\alpha}_{\mathbf{y}}, \boldsymbol{\alpha}_{\mathbf{b}})^{\mathrm{T}} \geqslant 0$ represents the degree of fine-tuning. The weight vector of the input, desirable output and undesirable output $\mathbf{w} = (\mathbf{w}_{\mathbf{x}}, \mathbf{w}_{\mathbf{y}}, \mathbf{w}_{\mathbf{b}})^{\mathrm{T}}$ is assumed to be unity according to the practice of Lin and Du (2015). The direction vector $\mathbf{g} = (\mathbf{g}_{\mathrm{x}}, \mathbf{g}_{\mathrm{y}}, \mathbf{g}_{\mathrm{b}}) = (-\mathbf{x}, \mathbf{y}, -\mathbf{b})$ represents the changing direction toward higher **y** and lower **x** and **b**, and diag $(\cdot)$ is used to diagonalize the vector $\boldsymbol{\alpha}$. The technical efficiency (TE) can be obtained via the NDDF-DEA model:

$$\vec{D}_{\mathrm{n}} = \max\{\mathbf{w}^{\mathrm{T}}\boldsymbol{\alpha}\}$$

$$\text{s.t.}\quad \mathbf{X\lambda} \leqslant \mathbf{x} - \boldsymbol{\alpha}_{\mathbf{x}}\mathbf{g}_{\mathbf{x}}, \mathbf{Y\lambda} \geqslant \mathbf{y} + \boldsymbol{\alpha}_{\mathbf{y}}\mathbf{g}_{\mathbf{y}},$$

$$\mathbf{B\lambda} = \mathbf{b} - \boldsymbol{\alpha}_{\mathbf{b}}\mathbf{g}_{\mathbf{b}}, \quad \mathbf{\lambda} \geqslant 0, \quad \boldsymbol{\alpha}_{\mathbf{x}}, \boldsymbol{\alpha}_{\mathbf{y}}, \boldsymbol{\alpha}_{\mathbf{b}} \geqslant 0, \quad (8)$$

$$\mathrm{TE} = 1/(\vec{D}_{\mathrm{n}} + 1), \quad (9)$$

where $\vec{D}_{\mathrm{n}}$ reflects the deviation degree of a DMU from the optimal technical level. The procedure and an example of the TE calculation are given in Fig. 2 and Tables S5 & S6 in Section S2, respectively. TE is called the EE, CE or other-cost efficiency (OE) when energy consumption, operating costs or non-energy operating costs are set as the input variable, respectively.

2.4 Software for calculating the shadow price and technical efficiency

The shadow price and technical efficiency were calculated by the output-oriented DEA model in MaxDEA8.4. The statistical analysis, such as the nonparametric one-tailed Wilcoxon signed rank test which evaluates the difference between paired samples, was implemented by IBM SPSS27.

3 Results and discussion

3.1 Energy consumption and operating cost

Figure 3 shows a comparison of the pollutant removal rates, operating costs and energy consumption of the 20 WWTPs before and after the retrofitting from the CAS to the MBR process. The removal rate of pollutants improved significantly after the retrofitting, demonstrating the advantage of MBR in effluent water quality. The removal rate of COD increased from 89.6% to 91.0% ($p < 0.05$), and that of NH_3-N increased from 89.0% to 93.3% ($p < 0.01$). The energy consumption increased from 0.40 to 0.57 kWh/m^3 ($p < 0.01$), while the operating cost did not increase significantly (CAS vs. MBR = 1.25 vs. 1.22 CNY/m^3).

3.2 Shadow price, environmental benefit and net profit

To compare the environmental benefits and net profits of the WWTPs before and after the retrofitting, the shadow prices of pollutants (CNY/g) were estimated via CBA based on the directional distance function (see Section 2.2 for details). Figure 4(a) exhibits the shadow prices of pollutants in the CAS and MBR stages of the WWTPs. NH_3-N had a much higher shadow price than COD, which was consistent with the literature finding (Molinos-Senante et al., 2010). After MBR was adopted, the average shadow price of NH_3-N increased from 0.47 to 0.66 CNY/g, while that of COD changed little, remaining at approximately 0.02 CNY/g. Figures 4(b)–4(e) show the three-dimensional distribution of the WWTP sample points in the vector space specified by the input and desirable/undesirable outputs. Projection of the sample points to the *y-b*

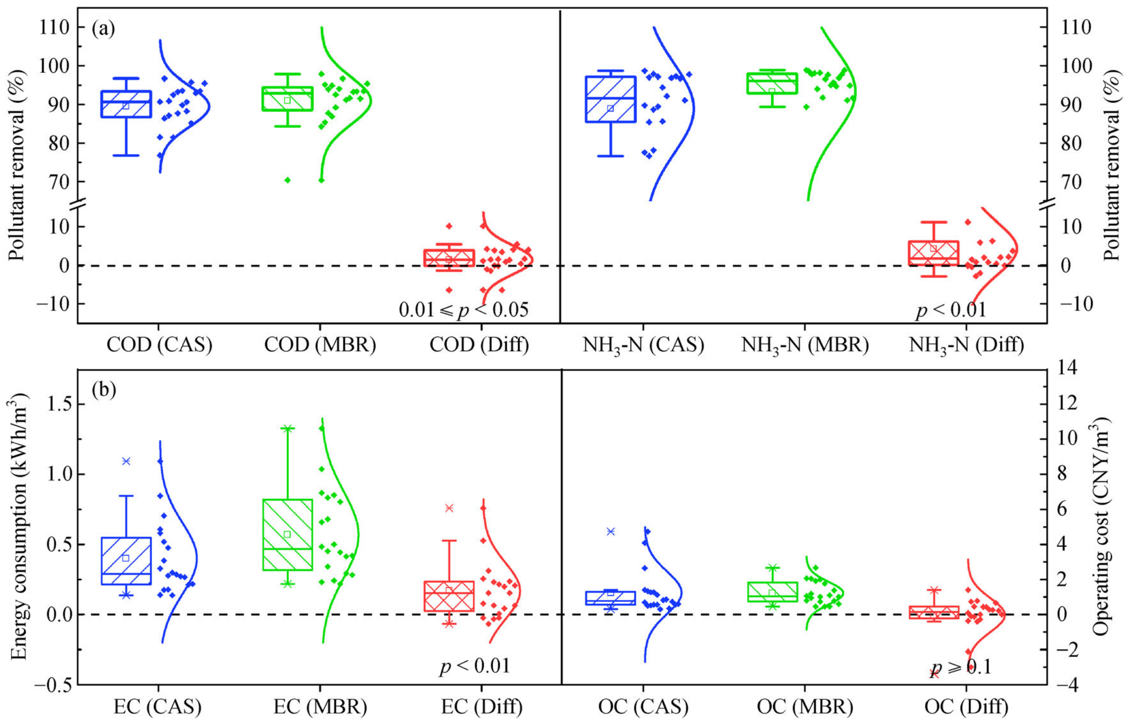

Fig. 3 Comparison of (a) pollutant removal rate, (b) energy consumption (EC) and operating cost (OC) before and after retrofitting from CAS to MBR. Diff represents the difference between MBR and CAS.

plane profiles the production frontier. Compared with the CAS sample points in Figs. 4(b) and 4(c), the MBR sample points in Figs. 4(d) and 4(e) were relatively concentrated in the "expensive zone" mentioned in Fig. 1(a). This observation indicates that MBR had a higher average marginal revenue of pollutant removal than CAS, which might be related to the lower effluent concentration (i.e., better effluent quality) of MBR. Sensitivity analysis indicated that the shadow price changed by only −0.05 to 0.09 CNY/g as the input or output changed by 0–10% (Fig. S1), confirming the robustness of the shadow price calculation. The shadow price represents the possible cost of environmental damage (and hence pollution control) for each pollutant, and thus, the shadow price multiplied by the quantity of removed pollutant indicates the environmental benefit. The total environmental benefit can be obtained by adding the benefits of wastewater reclamation and pollutant removal together, as shown in Eq. (2) (Hernández-Sancho et al., 2010), and is represented by the size of the spheres in Figs. 4(b)–4(e). The average total environmental benefit of the WWTPs increased from 20.6 to 25.6 CNY/m^3 after the retrofitting.

The net profit of each WWTP was obtained by subtracting the operating cost from the total environmental benefit. Figure 5(a) shows that the net profit increased significantly by 26% from 19.4 to 24.4 CNY/m^3 after the retrofitting from CAS to MBR. Since the change in net profit was not significantly related to the passage of time (Table S7), the increase in net profit mainly came from the transformation in technology. MBR would be even more profitable if the potential benefit of land saving (which is difficult to quantify) was taken into account. MBR has much smaller footprint (reported to be 0.5–1.2 m^2/(m^3/d)) than that of CAS with tertiary treatment (1.2–1.6 m^2/(m^3/d)) at a capacity of 10000–50000 m^3/d (Xiao et al., 2019), because membrane modules in MBR replace the secondary sedimentation tank and tertiary treatment facilities (such as clarification and filtration tanks) in CAS. In addition, the environmental benefit can be related to the destination of pollutant discharge and the strictness of the effluent standard (as discussed in Section 3.4). Pollutant-sensitive destinations often have high environmental benefits. The environmental benefit would increase if the effluent quality is sufficient for direct reuse (particularly in the case of MBR). Overall, the retrofitting of WWTPs from CAS to MBR is techno-economically feasible based on the comparison of environmental benefits and net profits.

3.3 Energy efficiency and cost efficiency

The technical efficiency of the WWTPs before and after the retrofitting was calculated using the NDDF in the DEA model according to Section 2.3. It can be evaluated in several ways: 1) EE measures how close the technical level approaches the optimal state determined by energy consumption and treatment performance; 2) CE refers to the closeness toward the optimum according to the total operating cost and treatment performance; and 3) OE

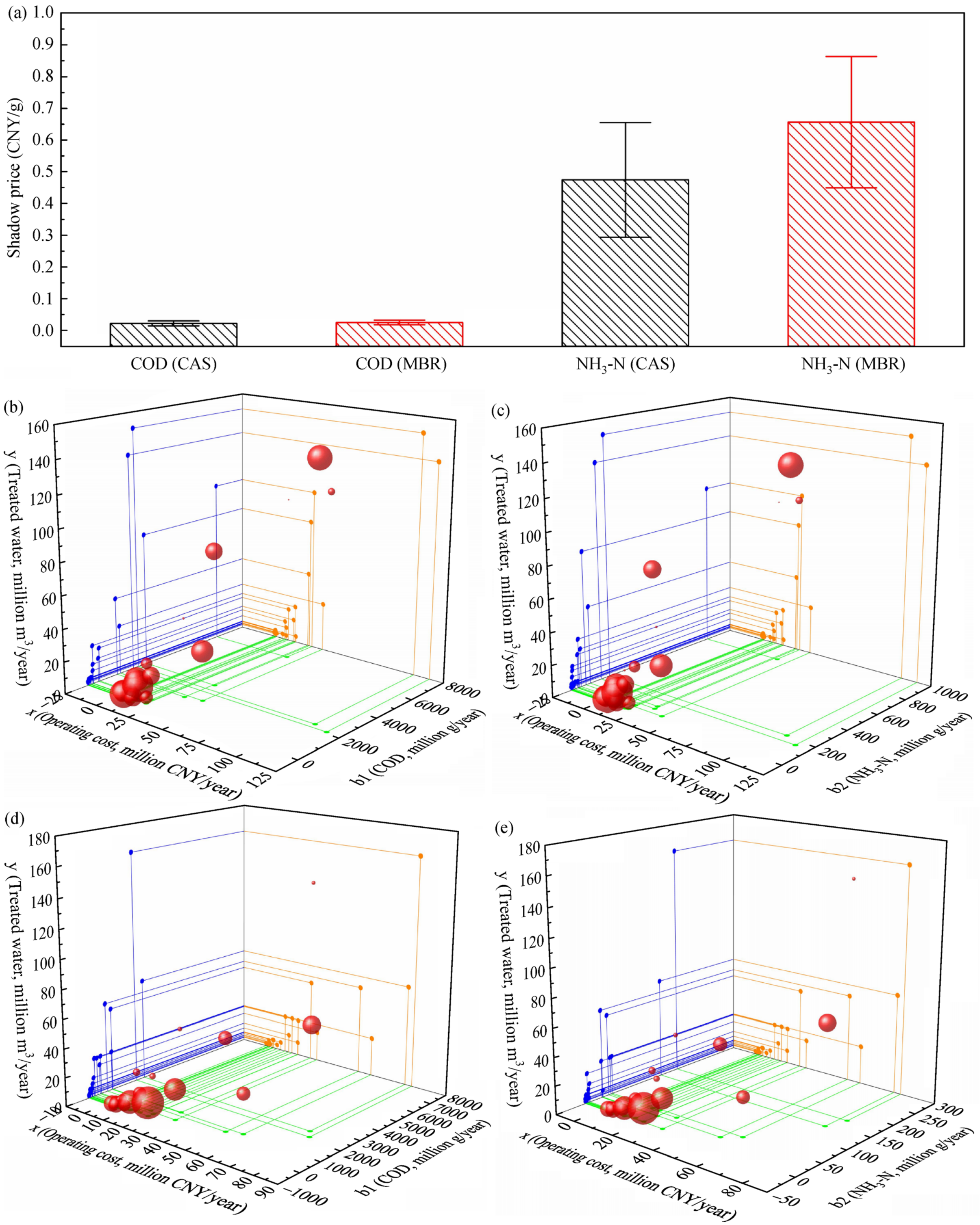

Fig. 4 Distribution of (a) shadow prices specific to each pollutant; (b–e) total environmental benefits: the CAS sample points in the vector space formed by the input and output specific to (b) COD and (c) NH_3-N, and the MBR sample points in the vector space formed by the input and output specific to (d) COD and (e) NH_3-N. The volume of the scatter points represents the size of the environmental benefit.

represents to the closeness according to the partial operating cost (excluding energy consumption) and treatment performance.

Figures 5(b)–5(d) shows the distributions of these technical efficiencies. The average EE, CE and OE of CAS were 0.72, 0.70 and 0.70, respectively, and those of

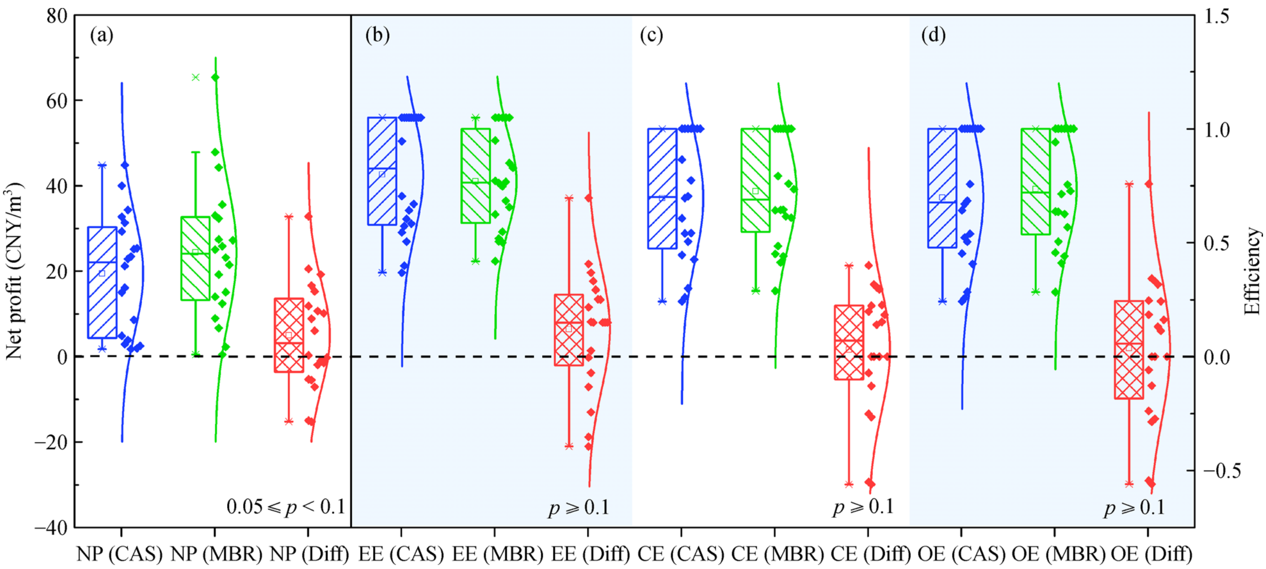

Fig. 5 Distribution of (a) net profit (NP), (b) energy efficiency (EE), (c) cost efficiency (CE) and (d) other-cost efficiency (OE, other-cost = operating costs minus energy consumption) before and after the retrofitting from CAS to MBR. Diff represents the difference between the MBR and CAS processes.

MBR were 0.69, 0.73 and 0.73, respectively. The CE and OE appeared to be improved after the retrofitting from CAS to MBR but with insufficient statistical significance (p>0.1). Note that the technology frontier of MBR somewhat shifted from that of CAS, which might influence the TE values. Nonetheless, the different average efficiencies revealed the essential difference in the distribution of the WWTP sample points in the technology space (sketched in Fig. 1(b)) before and after the retrofitting. In the CAS stage, the WWTPs were distributed dispersedly with large CE and OE differences among the samples; while in the MBR stage, the WWTPs were more concentrated near the technology frontier. This observation indicates that the MBR technology was more robustly approaching its currently optimal state in terms of the CE and OE over a variety of WWTPs. For MBR, the average OE (0.73) was higher than the average EE (0.69), indicating that the sample points were more concentrated near the technology frontier in the OE space than in the EE space. This result suggests that MBR had relatively accurate control over operating costs such as the chemical consumption and labor expenditure but loose control over energy consumption. Taking the technology frontier as a benchmark, much room still exists for many of the MBR-retrofitted WWTPs to improve their EE by applying energy-saving strategies such as buffering the inlet water flow and optimizing the aeration for biological reactions and membrane scouring (Gabarrón et al., 2014). Sensitivity analysis showed that a reasonable fluctuation of the input, outputs and their weights had little impact on the efficiency evaluation (Fig. S2), indicating the robustness of the results. In addition, correlation analysis showed that the different operating time of MBR and CAS were negligible in influencing the TE (Table S7).

3.4 Impact of the effluent standard on the comparison between CAS and MBR

The CBA principle and the above results indicate that the environmental benefit increases as the effluent quality is elevated toward pure water. However, it is not realistic for WWTPs to treat wastewater into pure water. Wastewater treatment is often aimed at meeting the effluent standard for discharge or reuse rather than pursuing complete purification. From a more practical point of view, the extra environmental benefit beyond the effluent standard could be temporarily neglected. Following this assumption, the recalculated net profit and technical efficiency are shown in Fig. 6. The retrofitting from CAS to MBR was often prompted by the upgrading of the effluent standard, as shown in Tables 2 and S1. For example, a WWTP in Hunan Province adopted the conventional anaerobic-anoxic-aerobic (A^2O) with secondary sedimentation to meet the national GB_1B standard before its retrofitting and then used the A^2O-MBR technology to satisfy the stricter national GB_1A standard (Table 2). After the retrofitting from CAS to MBR, 9 of the 20 WWTPs were adapted to stricter effluent standards. Considering the different effluent standards, the recalculation of the net profit and technical efficiency was conducted under three scenarios. First, old and new effluent standards were adopted before and after the retrofitting, respectively, which was the actual case. Figure 6(a) shows that the recalculated net profit (NP1) of MBR was significantly higher than that of CAS. The recalculated average technical efficiencies (EE1, CE1 and OE1) also improved after the retrofitting but were not statistically significant (p>0.1). Second, both CAS and MBR were assumed to adopt the old effluent standard. Figure 6(b) shows that

Table 2 Effluent standards in China

Effluent standard			BOD_5 (mg/L)	COD (mg/L)	NH_3-N (mg/L)	Purpose of effluent
Scope	Code	Abbreviation				
National	GB 18918-2002	GB_1A	10	50	5	Discharge
National	GB 18918-2002	GB_1B	20	60	8	Discharge
National	GB 18918-2002	GB_2	30	100	25	Discharge
National	GB/T 18921-2019	–	6	–	3	Scenic environmental reuse
National	GB/T 18920-2002	–	10	–	10	Urban miscellaneous reuse
National	GB/T 19923-2005	–	10	60	10	Industrial reuse
National	GB 20922-2007	–	40	100	–	Reuse for irrigation
Local	DB 11/307-2005B	–	15	50	5	Discharge
Local	DB 11/890-2012A (new WWTP)	DB_11	4	20	1	Discharge
Local	DB 11/890-2012A (existing WWTP)	–	10	50	5	Discharge
Local	DB 11/890-2012B (new WWTP)	–	6	30	1.5	Discharge
Local	DB 11/890-2012B (existing WWTP)	–	20	60	8	Discharge
Local	DB 12/599-2015A	DB_12	6	30	1.5	Discharge

Notes: DB_11 is for Beijing, and DB_12 is for Tianjin.

there was no significant difference in the recalculated net profit (NP2) and technical efficiencies (EE2, CE2 and OE2) before and after the retrofitting. Third, both CAS and MBR were assumed to adopt the new effluent standard. Figure 6(c) shows that the recalculated net profit (NP3) and technical efficiencies (EE3, CE3 and OE3) increased on average after the retrofitting but were statistically insignificant ($p>0.1$). The above results show that under new effluent standards, the net profit and efficiencies of both CAS and MBR improved (comparing Fig. 6(c) with Fig. 6 (b)) and that the average difference between the two technologies also increased slightly (though not statistically significantly). When CAS and MBR adopted old and new standards, respectively, the difference between them in terms of the techno-economy was even larger, especially in terms of the net profit. Overall, the techno-economy of MBR, while not prominent under the old standard, can be better fulfilled under the stricter new standard.

The significance of the techno-economic advantage of MBR over CAS, specific to different effluent standards, was further simulated via statistical modeling. Given a sample size of 20, the Wilcoxon T statistic approximately obeys the normal distribution when the Wilcoxon signed rank test is applied to test the difference between paired samples. The Z statistic can then be constructed to calculate the significance level of the difference. Figure 7 depicts the approximate normal probability density distribution of the techno-economic difference before and after the retrofitting under different standards (the strictness of the standards follows the order GB_2 < GB_1B < GB_1A < DB_11). The area under the curve represents the probability. The area to the right of the dotted line is 0.1, corresponding to the one-tailed significance criterion of 0.1 (i.e., p value of 0.1). If the Z statistic is located to the right of the dotted line, the techno-economy of the WWTP increases significantly after adopting the MBR technology at the significance level of 0.1 (i.e., $p < 0.1$). The significance improves as the position of the Z statistic moves further to the right. Figure 7(a) shows that MBR had a significantly larger recalculated net profit than that of CAS, and the significance increased with the strictness of the effluent standards. Figure 7(b) shows that there was no significant difference in the recalculated EE before and after the retrofitting given any of the standards. Figures 7(c) and 7(d) show that MBR had larger recalculated efficiencies (CE and OE) than those of CAS, and the significance decreased with the strictness of the effluent standards. This result thus suggests that the MBR plants were always concentrated near the technology frontier under different standards in the technology space (Fig. 1(b)), while the CAS plants were distributed more dispersedly, with larger efficiency differences among the samples as the standard became looser, which widened the efficiency gap compared to MBR. The results indicate that MBR is more profitable than CAS under the pressure of strict standards, while there is room for MBR to improve its advantage in terms of technical efficiencies.

4 Conclusions

This study assessed the techno-economy of 20 WWTPs before and after retrofitting from CAS to MBR. The statistics of the operating performance showed that the

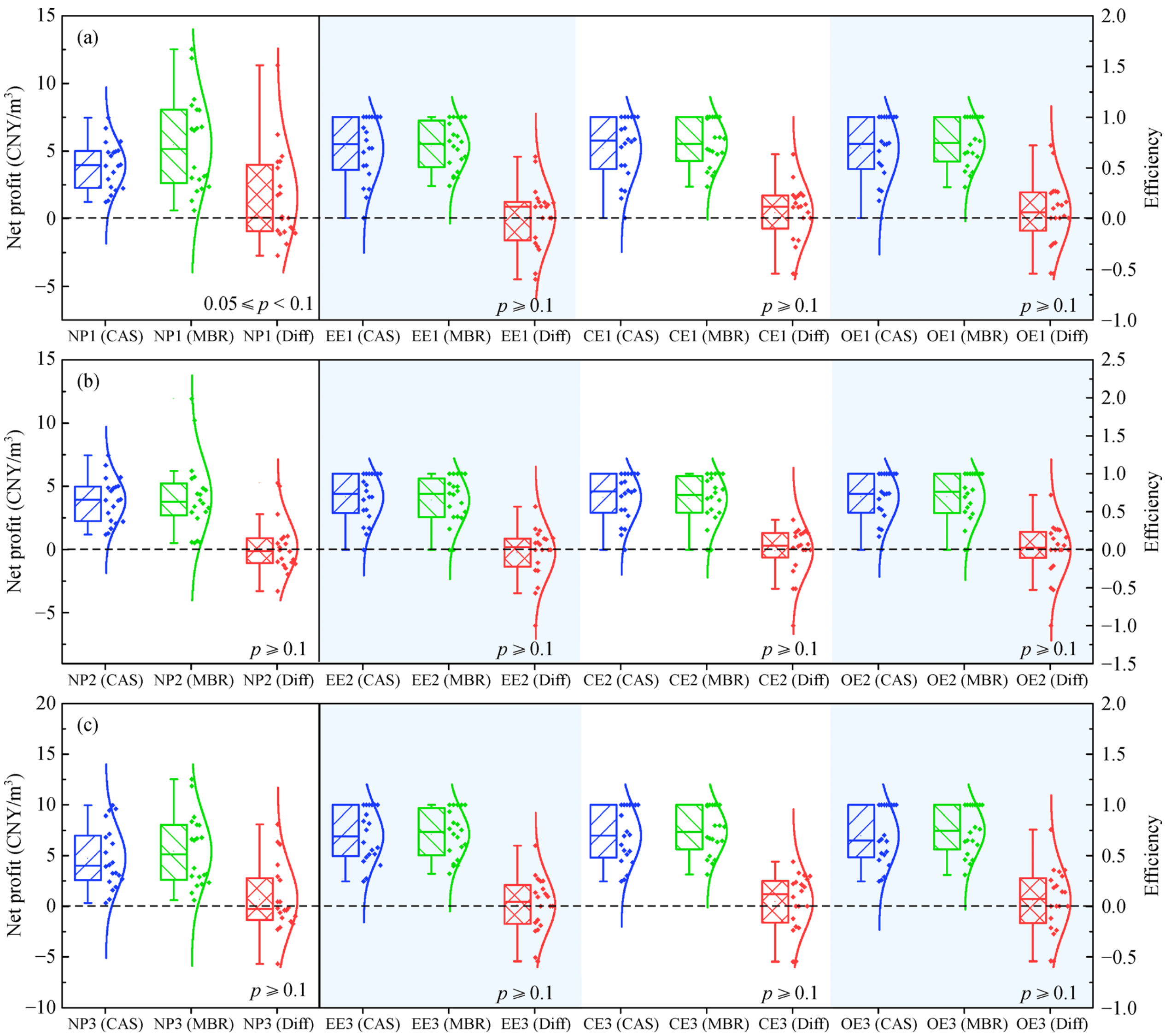

Fig. 6 Distribution of net profit (NP), energy efficiency (EE), cost efficiency (CE) and other-cost efficiency (OE, other-cost = operating costs minus energy consumption) before and after the retrofitting from CAS to MBR under (a) the first scenario (CAS: old effluent standards, MBR: new effluent standards), (b) the second scenario (old effluent standards) and (c) the third scenario (new effluent standards). Diff represents the difference between MBR and CAS.

effluent quality improved significantly, accompanied by an increase in energy consumption from 0.40 to 0.57 kWh/m^3, and there was no significant change in operating costs after the retrofitting.

Cost-benefit analysis based on shadow pricing demonstrated that the average marginal revenue of pollutant removal increased after the retrofitting and that NH_3-N removal made the largest contribution to the marginal benefit. The net profit of MBR was 24.4 CNY/m^3, higher than that of CAS (19.4 CNY/m^3), indicating the techno-economic feasibility of the retrofitting. The net profit of MBR would be even higher if the potential benefits of land saving were taken into account. The results of the NDDF-DEA model showed that after the retrofitting, the average energy efficiency was basically unchanged, while the average cost efficiency improved slightly by approximately 0.03, suggesting that MBR was comparable to CAS in terms of the technical efficiencies.

Statistical modeling further showed that the difference between MBR and CAS in terms of the net profit increased with the upgrading of the effluent standard, indicating the profitability of MBR under the pressure of stringent standards. The difference in technical efficiencies was less sensitive to the strictness of the adopted effluent standard.

Overall, the retrofitting of WWTPs from CAS to MBR has techno-economic advantages. MBR is more profitable in cases of strict effluent standards and pollutant-sensitive destinations, which could highlight the marginal benefit of removing pollutants. Although the performance of MBR is

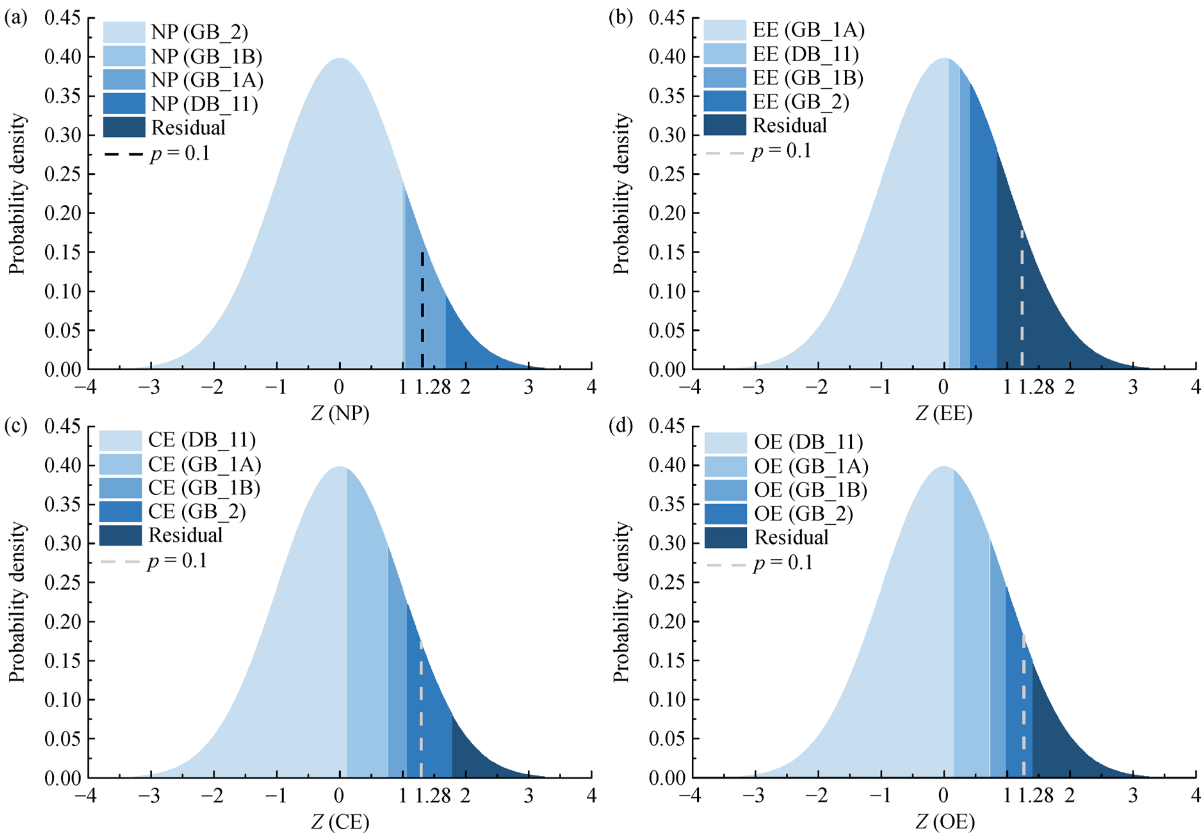

Fig. 7 The probability density curve of the difference before and after the retrofitting from CAS to MBR in terms of (a) net profit (NP), (b) energy efficiency (EE), (c) cost efficiency (CE) and (d) other-cost efficiency (OE, other-cost = operating costs minus energy consumption).

comparable to that of CAS in terms of the energy and cost efficiencies, there is much room for further reducing the energy consumption of MBR by, e.g., optimizing the aeration facilities and conditions.

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