

Supplementary materials

Section S1 Sample list and distribution of the WWTPs

Table S1 shows the basic information of 20 large-scale (each $\geq 10000 \text{ m}^3/\text{d}$) WWTPs that had been retrofitted from CAS to MBR in eastern and central China.

Table S1 Sample list of the WWTPs

Code	Project	Province	Region	Operating year	Commission year	Treatment process	Effluent standard	Design capacity ($10^3 \text{ m}^3/\text{d}$)	Capacity ($10^3 \text{ m}^3/\text{d}$)
1	BJ1	Beijing	N	2017	2014	A ² O-MBR-DFRO	DB_11	10	10.11
				2014	2012	SBR	DB_11	10	6.72
2	BJ2	Beijing	N	2015	2013	MBR	DB_11	150	170.33
				2015	2004	A ² O	DB_11	400	411.56
3	BJ3	Beijing	N	2014	2013	A ² O + MBR	DB_11	30	25.44
				2013	2003	SBR	DB_11	30	22.68
4	TJ1	Tianjin	N	2016	2016	A ² O + MBR	DB_12	20	16.68
				2015	2009	AAC	GB_1B	10	11.00
5	HB1	Hebei	N	2017	2015	A ² O-MBR	GB_1A	100	74.36
				2014	2004	ABT	GB_2	100	83.90
6	SX1	Shanxi	N	2015	2015	A ² O + MBR	GB_1A	10	5.10
				2014	2009	Others	GB_1A	10	5.03
7	SX2	Shanxi	N	2015	2014	OD + MBR	GB_1A	10	8.41
				2014	2007	OD	GB_1A	10	8.43
8	SX3	Shanxi	N	2017	2016	A ² O + MBR	GB_1B	15	4.90
				2014	2008	A ² O	GB_1B	15	6.56
9	SX4	Shanxi	N	2015	2015	A ² O-MBR	GB_1A	20	6.26
				2014	2010	A ² O	GB_1A	20	7.32
10	LN1	Liaoning	N	2017	2015	A ² O + MBR	GB_1A	200	157.15
				2014	2012	BT	GB_2	200	133.20
11	LN2	Liaoning	N	2017	2016	MBR	GB_1B	15	16.99
				2014	2010	BT	GB_1B	15	12.15
12	JL1	Jilin	N	2014	2014	MBR	GB_1A	150	72.15
				2014	2007	CAS	GB_1B	300	282.60
13	SH1	Shanghai	S	2016	2015	A ² O-MBR	GB_1A	10	15.82
				2014	2009	CAST	GB_2	10	10.80
14	JS1	Jiangsu	S	2015	2014	A ² O-SBR, MBR	GB_1A	40	36.12

				2012	2008	AO-SBR	GB_1A	40	33.72
15	JS2	Jiangsu	S	2016	2015	CAST + A ² O +	GB_1A	75	57.48
						MBR			
16	FJ1	Fujian	S	2012	2006	CAST, A ² O	GB_1A	50	40.80
				2016	2015	MBR			
17	SD1	Shandong	N	2014	2003	A ² O + OD	GB_1B	400	368.80
				2016	2015	A ² O-MBR-RO			
18	HN1	Hunan	S	2013	2008	A ² O	GB_1B	250	228.91
				2015	2014	A ² O + MBR			
19	HN2	Hunan	S	2015	2008	A ² O	GB_1A	100	65.90
				2016	2016	A ² O-MBR			
20	GD1	Guangdong	S	2014	2010	A ² O	GB_1B	12	11.52
				2016	2013	OD + MBR			
				2012	2010	A ² O-OD	GB_1B	50	58.00

Notes: N = North; S = South. A²O = anaerobic anoxic oxic. MBR = membrane bioreactor. DFRO = deep filter reverse osmosis. SBR = sequencing batch reactor activated sludge process. AAC = anoxic anaerobic carousel. ABT = anaerobic biological treatment. OD = oxidation ditch. BT = biological treatment. CAS = conventional activated sludge. CAST = cyclic activated sludge technology. AO = anoxic oxic. RO = reverse osmosis.

Section S2 An example of the calculation procedure

Section S2.1 Calculation of shadow price

This example contains 20 decision making units (DMU, in this study DMU = WWTP). Each DMU on (or within) the production frontier includes one input x (total cost, CNY/year), one desirable output y (treated water, m³/year) and two undesirable outputs b_1 – b_2 (emissions of pollutants including COD and NH₃-N, g/year). Given the raw data in Table S2, the calculation results of the DDF model are shown in Tables S3 and S4.

Table S2 Raw data for the shadow price example

DMU	x	y	b_1	b_2
1	3440000	2452800	45622080	1066968
2	105153580	150219400	2403510400	217818130
3	10999800	8278200	245862540	6622560
4	2000000	4015000	65846000	2694065
5	39230000	30623500	1534237350	45629015
6	2350000	1835950	41859660	4406280
7	8150000	3076950	78462225	10277013
8	1226746.302	2392575	78476460	14331524.25

9	10950000	2671800	29122620	4141290
10	27965204.43	48618000	1385613000	106959600
11	2550000	4434750	164972700	21508537.5
12	31231231.4	103149000	6529331700	838601370
13	18670000	3942000	167140800	14427720
14	10010000	12307800	259694580	9353928
15	16830000	14892000	513774000	10275480
16	115700000	134612000	2153792000	169611120
17	29095500	83553600	2799045600	82718064
18	17940000	24053500	269399200	56285190
19	2400000	4204800	138758400	36161280
20	12698300	21170000	565239000	39376200

Table S3 The initial calculation results of the shadow price example

DMU	Score	Dual price (x)	Dual price (y)	Dual price (b1)	Dual price (b2)
1	1.00	-6.43E-08	1.97E-07	0.00E + 00	-2.46E-07
2	0.94	-1.50E-10	3.55E-09	-1.89E-10	-5.66E-10
3	0.86	-1.24E-08	3.81E-08	0.00E + 00	-4.76E-08
4	1.00	-3.20E-08	9.83E-08	0.00E + 00	-1.23E-07
5	0.72	-2.30E-09	7.07E-09	0.00E + 00	-8.82E-09
6	0.75	-8.80E-09	2.08E-07	-1.11E-08	-3.31E-08
7	0.67	-4.47E-09	1.06E-07	-5.62E-09	-1.68E-08
8	0.88	-3.11E-07	2.00E-07	-2.73E-09	0.00E + 00
9	1.00	0.00E + 00	1.89E-07	-9.19E-09	-5.75E-08
10	0.85	-1.67E-08	1.07E-08	-1.47E-10	0.00E + 00
11	0.82	-1.58E-07	1.02E-07	-1.39E-09	0.00E + 00
12	1.00	-1.29E-08	5.16E-09	-1.97E-11	0.00E + 00
13	0.52	0.00E + 00	5.61E-08	-2.72E-09	-1.70E-08
14	0.93	-9.17E-09	2.81E-08	0.00E + 00	-3.51E-08
15	0.92	-7.77E-09	2.39E-08	0.00E + 00	-2.98E-08
16	0.95	-1.76E-10	4.16E-09	-2.21E-10	-6.63E-10
17	1.00	-7.09E-09	5.77E-09	0.00E + 00	-3.33E-09
18	1.00	-9.13E-10	2.16E-08	-1.15E-09	-3.44E-09
19	0.85	-1.66E-07	1.07E-07	-1.46E-09	0.00E + 00
20	0.84	-3.93E-08	2.52E-08	-3.44E-10	0.00E + 00

Table S4 The final calculation result of the shadow price example

DMU	Shadow price (b1)	Shadow price (b2)	Benefit (b1)	Benefit (b2)	Sum_ benefit	NP (CNY/m ³)
1	0.00	-1.25	0.00	40.41	41.41	40.00
2	-0.05	-0.16	24.94	7.47	33.40	32.70

3	0.00	-1.25	0.00	45.19	46.19	44.87
4	0.00	-1.25	0.00	28.75	29.75	29.25
5	0.00	-1.25	0.00	31.60	32.60	31.32
6	-0.05	-0.16	16.92	4.53	22.44	21.16
7	-0.05	-0.16	19.81	4.70	25.50	22.85
8	-0.01	0.00	4.36	0.00	5.36	4.85
9	-0.05	-0.30	12.09	14.41	27.51	23.41
10	-0.01	0.00	2.48	0.00	3.48	2.90
11	-0.01	0.00	3.45	0.00	4.45	3.88
12	0.00	0.00	1.07	0.00	2.07	1.77
13	-0.05	-0.30	14.79	3.99	19.78	15.04
14	0.00	-1.25	0.00	34.13	35.13	34.32
15	0.00	-1.25	0.00	25.23	26.23	25.10
16	-0.05	-0.16	6.43	2.06	9.50	8.64
17	0.00	-0.58	0.00	24.71	25.71	25.36
18	-0.05	-0.16	12.64	3.18	16.82	16.08
19	-0.01	0.00	1.50	0.00	2.50	1.93
20	-0.01	0.00	2.11	0.00	3.11	2.51

Section S2.2 Calculation of technical efficiency

This example contains 20 decision making units (DMU, in this study DMU = WWTP). Each DMU on (or within) the technology frontier includes one input x (operating cost, CNY/m³), three desirable outputs y_1 – y_3 (respectively treated water (m³/d), COD removal rate and NH₃-N removal rate), and one undesirable output b (sludge production, m³/d). Given the raw data in Table S5, the calculation results of the NDDF model are shown in Table S6.

Table S5 Raw data for the technical efficiency example

DMU	x	y_1	y_2	y_3	b
1	1.40	0.67	0.91	0.99	1099
2	0.70	41.16	0.97	0.97	29128
3	1.33	2.27	0.91	0.98	1393
4	0.50	1.10	0.93	0.97	308
5	1.28	8.39	0.82	0.94	16796
6	1.28	0.50	0.93	0.92	0
7	2.65	0.84	0.94	0.90	311
8	0.51	0.66	0.91	0.85	248
9	4.10	0.73	0.96	0.97	856
10	0.58	13.32	0.86	0.89	799
11	0.58	1.22	0.87	0.78	662

12	0.30	28.26	0.82	0.77	43000
13	4.74	1.08	0.88	0.78	851
14	0.81	3.37	0.93	0.97	1448
15	1.13	4.08	0.90	0.97	16612
16	0.86	36.88	0.88	0.91	10111
17	0.35	22.89	0.93	0.98	18200
18	0.75	6.59	0.96	0.90	2739
19	0.57	1.15	0.77	0.51	370
20	0.60	5.80	0.85	0.86	1299

Table S6 The calculation results of the technical efficiency example

DMU	β^a_x	β_{y1}	β_{y2}	β_{y3}	β_b	D	TE
1	4.36E-01	2.63E + 01	3.10E-01	2.37E-01	6.73E-14	3.12E + 00	0.24
2	2.44E-11	2.11E-11	6.72E-01	7.39E-01	3.74E-12	1.57E-01	0.86
3	2.45E-01	9.24E + 00	6.57E-01	5.81E-01	1.58E-13	1.25E + 00	0.45
4	1.04E-09	2.68E-08	4.80E-10	2.50E-10	2.90E-09	4.37E-09	1.00
5	7.21E-17	2.54E + 00	1.36E + 00	1.09E + 00	8.94E-01	8.52E-01	0.54
6	9.03E-13	9.27E-12	1.29E-12	1.26E-12	8.02E-13	1.88E-12	1.00
7	2.89E-11	6.28E + 00	1.25E + 00	1.33E + 00	5.47E-11	9.84E-01	0.50
8	5.63E-12	5.46E-11	2.19E-12	4.83E-12	2.50E-12	9.56E-12	1.00
9	4.57E-10	2.04E + 01	2.62E + 00	2.57E + 00	2.19E-10	2.84E + 00	0.26
10	2.21E-08	1.16E-10	7.05E-09	7.73E-09	1.10E-09	9.40E-09	1.00
11	3.67E-10	7.48E + 00	3.14E-11	1.31E-01	2.42E-10	8.46E-01	0.54
12	1.19E-10	1.38E-09	3.15E-09	4.20E-09	8.43E-10	1.29E-09	1.00
13	2.43E-12	1.36E + 01	3.47E + 00	4.01E + 00	3.07E-11	2.35E + 00	0.30
14	4.78E-15	4.59E + 00	3.15E-01	2.89E-01	2.20E-01	6.50E-01	0.61
15	6.56E-15	1.13E + 01	4.43E-01	3.87E-01	9.67E-11	1.35E + 00	0.43
16	2.87E-10	1.98E-10	2.42E-08	2.57E-08	1.44E-08	1.05E-08	1.00
17	1.72E-11	2.80E-11	2.18E-11	2.04E-11	5.68E-12	1.54E-11	1.00
18	5.65E-13	1.62E + 00	1.73E-01	2.85E-01	6.22E-01	4.38E-01	0.70
19	8.14E-11	3.29E + 00	1.52E-10	4.95E-01	2.32E-10	4.21E-01	0.70
20	5.41E-02	1.27E + 00	1.30E-11	2.12E-02	3.93E-01	2.92E-01	0.77

Notes: a) β is the slack variable

Section S3 Sensitivity analysis

Section S3.1 Sensitivity analysis of shadow prices

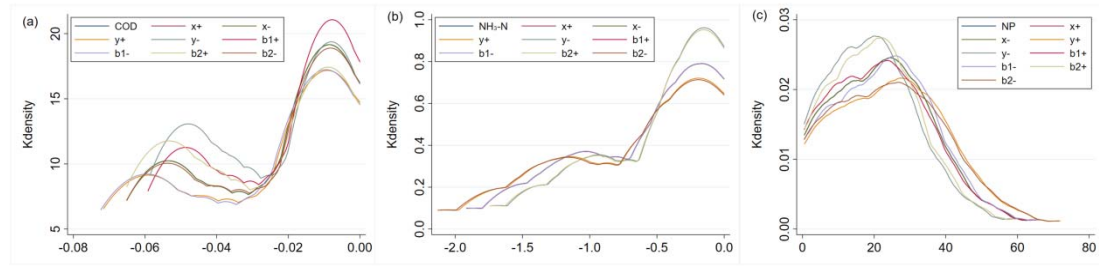


Fig. S1 Sensitivity analysis results of the shadow price of (a) COD and (b) NH₃-N, and (c) the net profit. $x + (-)$ = a 10% increase (decrease) in the input, $y + (-)$ = a 10% increase/decrease in the desirable output, $b_i + (-)$ = a 10% increase/decrease in the i 'th undesirable output

Section S3.2 Sensitivity analysis of efficiency

To test the robustness of the non-radial distance function, we (a) change the assumption of equal weighting of \mathbf{x} , \mathbf{y} and \mathbf{b} into equal weight of inputs and outputs ($\mathbf{x} : \mathbf{y} : \mathbf{b} = 1 : 1 : 1$ into $2 : 1 : 1$), and (b) change the equal weight of the treated water (y_1) and each pollutant's removal rate (y_2 – y_3) into the equal weight of y_1 and the total removal rate of two pollutants ($y_1 : y_2 : y_3 = 1 : 1 : 1$ into $2 : 1 : 1$). The original weight distribution is $x : y_1 : y_2 : y_3 : b = 1/3 : 1/9 : 1/9 : 1/9 : 1/3$, and we get three changes as follows:

- 1) $x : y_1 : y_2 : y_3 : b = 1/2 : 1/12 : 1/12 : 1/12 : 1/4$;
- 2) $x : y_1 : y_2 : y_3 : b = 1/3 : 1/6 : 1/12 : 1/12 : 1/3$;
- 3) $x : y_1 : y_2 : y_3 : b = 1/2 : 1/8 : 1/16 : 1/16 : 1/4$.

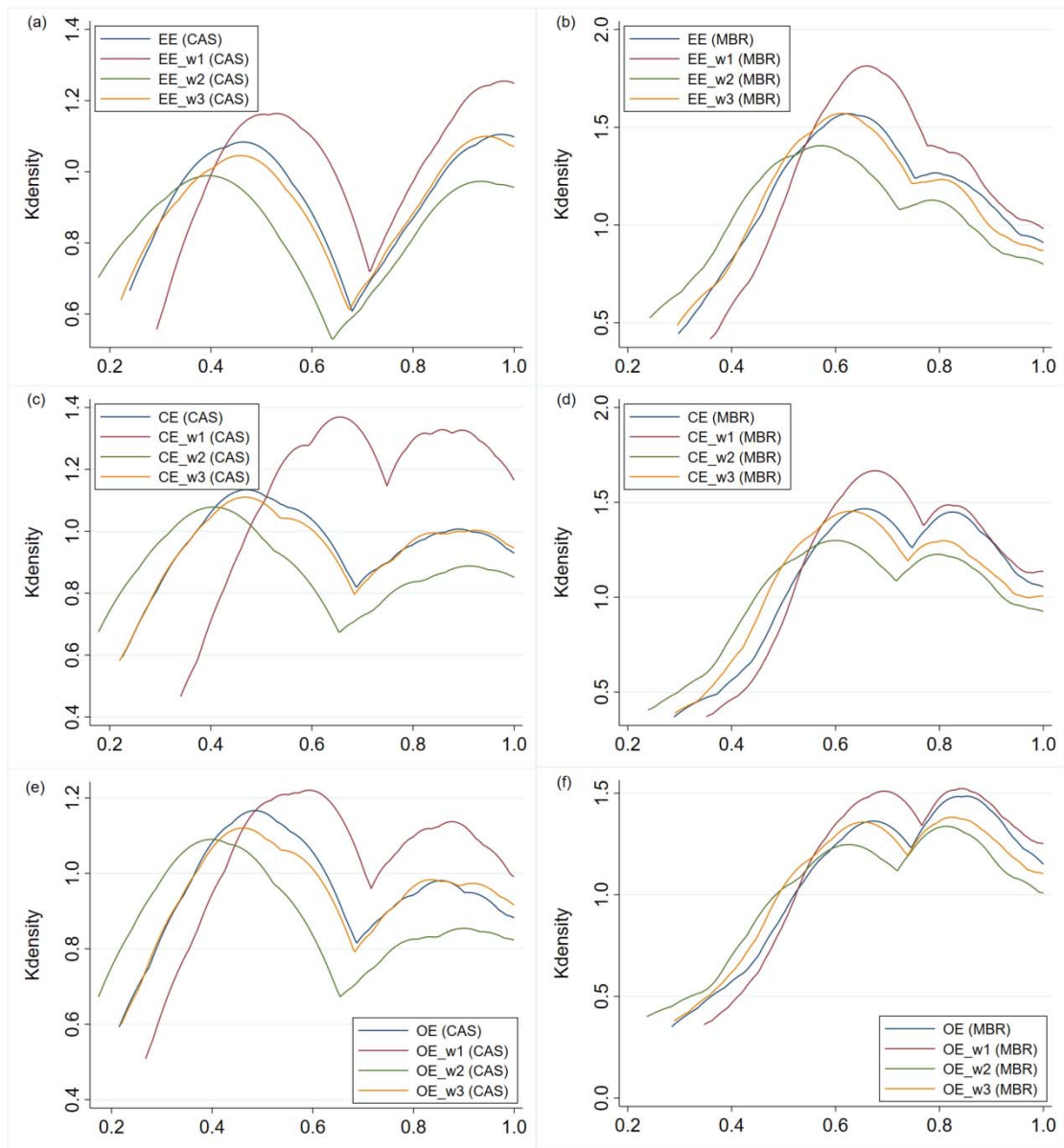


Fig. S2 Sensitivity analysis of technical efficiencies. EE, CE and OE are the original value of energy efficiency, cost efficiency and other-cost efficiency, respectively. w1, w2 and w3 refer to three changes in weight

Section S4 Correlation analysis

Table S7 The correlation analysis of the techno-economy difference and the operating year difference between MBR and CAS

Difference	Δ Year	
	Spearman correlation coefficient	p value
Δ NP	0.058	0.807
Δ EE	0.069	0.772
Δ CE	0.023	0.922
Δ OE	-0.050	0.835