Supporting Information

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

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1 Equations and parameters

1.1 Internal energy I: Chemical energy in sludge

The heat required to increase the temperature is labelled as Q_s. The total energy consumption of combined heat and power (CHP), C_{CHP}, could be obtained through combining Q_s and the heat for drying the sludge solids, Q_w, which is related to the water evaporation under drying, M_w. The detailed equations are seen below:

$$Q_s=(T_2-T_1)\times C_s\times M_{sludge} \qquad \text{Eq.1}$$

$$M_w=\frac{M_{sludge}}{(1-\alpha_1)}-\frac{M_{sludge}}{(1-\alpha_2)} \qquad \text{Eq.2}$$

$$Q_w = \frac{C_w \times M_{sludge} \times \alpha_1}{(1-\alpha_1)} \times (T_2 - T_1) + Q_g \times M_w \quad \text{Eq.3}$$

$$C_{CHP} = \frac{(Q_s + Q_w)}{(1-\eta_1) \times 3600} \quad \text{Eq.4}$$

Where, M_{sludge} is production of excessive sludge,
T_1 is the initial temperature of the drying for sludge, ℃,
T_2 is the temperature under drying, ℃,
C_s is the specific heat capacity of sludge, kJ/(kg·℃),
Q_g is the thermal energy of vapors in potential, kJ/kg,
α_1 is the water content after machinery dehydration,
α_2 is the water content before machinery dehydration,
η_1 is the heat loss rate of sludge dryer.

The energy generation of electricity equivalent, can be estimated by Eq.5:

$$E_{CHP} = Q_{gr} \times M_{sludge} \times (1-\eta_2) \times \eta_3 \times 0.278 \quad \text{Eq.5}$$

Where, Q_{gr} is the heat value of MLSS, MJ/kg,
η_2 is the heat loss rate,
η_3 is the coefficient of CHP.

Thus, the net recovery amount of chemical energy (N_{CHP}, kWh/y) can be achieved via the Eq.6:

$$N_{CHP} = E_{CHP} - C_{CHP} \quad \text{Eq.6}$$

The parameters in detail are seen in Table S1.

Table S1 Parameters for estimation on chemical energy recovered through combined heat and power.

Parameter	Unit	Value	Source
T_1	℃	20	(Yang et al., 2020)
T_2	℃	100	(Yang et al., 2020)
C_s	-	3.62	(Yang et al., 2020)
α_1	%	78	(Yang et al., 2020)
α_2	%	58	(Yang et al., 2020)
C_w	kJ/(kg • ℃)	4.2	(Yang et al., 2020)
Q_g	kJ/kg	2,260	(Yang et al., 2020)
Q_{gr}	MJ/kg	11.9	(Hao et al., 2019)
η_1	%	20	(Hao et al., 2019)
η_2	%	7	(Li et al., 2014)
η_3	%	80	(Li et al., 2014)

1.2 Internal energy II: Thermal energy in wastewater flow

The function of water source heat pump (WSHP) mainly consists of heating and cooling that function in winter and summer, respectively. The estimation on the energy generated through heater and cooler, labelled as P_{heat} (kWh/d) and P_{cool} (kWh/d), can be achieved by Eqs.7 and 8.

Meanwhile, the energy consumption, labelled as C_{heat} (kWh/d) and C_{cool} (kWh/d), can be calculated via Eqs.9 and 10.

$$P_{heat}=\frac{Q\times\Delta t\times COP_h}{0.86\times(COP_h-1)} \tag{Eq.7}$$

$$P_{cool}=\frac{Q\times\Delta t\times COP_c}{0.86\times(COP_c+1)} \tag{Eq.8}$$

$$C_{heat}=\frac{P_{heat}}{COP_h} \tag{Eq.9}$$

$$C_{cool}=\frac{P_{cool}}{COP_c} \tag{Eq.10}$$

Where, Q is daily wastewater flow in average, m^3/d,

Δt is the temperature difference, ℃,

COP_h is heating co-efficient,

COP_c is cooling co-efficient.

Besides, to characterize the energy recovery via WSHP, boiler and air-cooling heat pump are normally used to make the comparison for heater and cooler. Thus, heat and cool equivalent can be calculated by Eqs.11 and 12, respectively. The total energy consumption and generation of WSHP can be estimated via Eqs.13 and 14.

$$E_{heat}=\frac{P_{heat}\times\eta_6\times(1-\eta_7)}{\eta_4\times\eta_5} \tag{Eq.11}$$

$$E_{cool}=\frac{P_{cool}}{COP_a} \tag{Eq.12}$$

$$C_{WSHP}=C_{heat}+C_{cool} \tag{Eq.13}$$

$$E_{WSHP}=E_{heat}+E_{cool} \tag{Eq.14}$$

Where, COP_a is coefficient of air-cooling heat pump,

η_4 is efficiency of boiler,

η_5 is heating efficiency,

η_6 is power generation efficiency,

η_7 is grid loss rate.

If the heater and cooler function for four months respectively, the net energy of WSHP (N_{WSHP}, kWh/y) could the estimated through the equation below:

$$N_{WSHP}=120\times(E_{heat}-C_{heat})+123\times(E_{cool}-C_{cool}) \tag{Eq.15}$$

It is worthwhile to notice that in China November, December, January, and February can be considered as the wintertime when the heater functions, while May, June, July, and August are the summertime when the cooler functions.

The parameters in detail are seen in Table S2.

Table S2 Parameters for estimation on thermal energy recovered through water source heat pump.

Parameter	Unit	Value	Source
Δt	℃	3	(Chae and Kang, 2013)
COP_c	-	3.5	(Hepbasli et al., 2014)
COP_h	-	4.5	(Hepbasli et al., 2014)
η_4	%	85	(Hao et al., 2015)
η_5	%	80	(Hao et al., 2015)
η_6	%	33	(Hao et al., 2015)
η_7	%	8	(Hao et al., 2015)
COP_a	-	4.0	(Yang and Wu, 2016)

1.3 Energy self-sufficiency

With the variables of N_{CHP} and N_{WSHP} (kWh) attained, the ESS can be calculated by the equation below:

$$\eta_{recovery}=\frac{N_{CHP}+N_{WSHP}}{C_{operation}}\times 100\% \qquad \text{Eq.16}$$

Where, $C_{operation}$ is the energy consumption for pollutant removal (kWh).

In this study, we define $C_{operation}$ as total electricity consumption for basic operation. Besides, the WWTP samples with ESS value of ≥ 1 are defined as the fully self-sufficient, while the ones with ESS value of < 1 are the non-self-sufficient.

1.4 Comprehensive water-energy efficiency

The CWEE characterizes the efficiency of WWTP samples from two aspects. On the one hand, CWEE includes the energy efficiency of WWTP samples; on the other, CWEE involves the consumption and generation of energy to quantify the recovery efficiency. Data envelopment analysis was applied to evaluate the CWEE. In this study, we used the model of slack-based measure (Tone, 2001). Besides, conditions of the non-oriented type and variable returns to scale were selected. The equation could be seen below:

$$min\ \theta=\frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_{ik}^{-}}{x_{ik}}}{1+\frac{1}{q}\sum_{r=1}^{q}\frac{s_{rk}^{+}}{y_{rk}}}$$

$$s.t.\ X\lambda+s^{-}=x_k$$

$$Y\lambda-s^{+}=y_k \qquad \text{Eq.17}$$

$$e\lambda=1$$

$$\lambda,s^{+},s^{-}\geqslant 0$$

Where, θ is the value of CWEE,

s^-_{ik} is the slack of inputs,
s^+_{rk} is the slack of outputs,
x_{ik} is the inputs,
y_{rk} is the outputs,
λ is a positive coefficient,
e is a unit vector,
k is the sequence of the WWTP sample under evaluation,
j, i, and r represent the order of WWTP, input, and output.

WWTP samples with CWEE value equal to 1 are defined as the benchmarks, while the ones with CWEE value < 1 are the normal WWTP samples. The input and output variables are shown in Table S3.

Table S3 Input and output variables of comprehensive water-energy efficiency.

	Variables	Label	Unit
Input	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
Output	Pollutant removal	$R_{pollutant}{}^*$	10^3 kg
	Energy recovered by combined heat and power	E_{CHP}	kWh
	Energy recovered by water source heat pump	E_{WSHP}	kWh

*Note: $R_{pollutant}$ includes the removal of chemical oxygen demand (COD), 5-day biochemical demand (BOD_5), total nitrogen (TN), ammonia nitrogen (NH_4^+-N), and total phosphorus (TP).

2 Figures and Tables

2.1 Procedure of data screening

This study took a flow diagram to carry out the data screening. After collection of data from the source, we set the criteria to ensure the reliability. First, we deleted the WWTP sample with deficiency in key data types, which includes total electricity consumption (kWh/y), pollutant concentration in influent and effluent (mg/L), volume of wastewater treated (10^4 m^3/y), and wet sludge production (10^3 kg/y). Second, the WWTP samples with inconsistencies in the data sources were also excluded. Third, we used the indicator of energy intensity to check the validity in terms of energy efficiency. The critical value of energy intensity was set as 0.1 kWh/m^3. The WWTP samples that have a lower energy intensity of < 0.1 kWh/m^3 were taken abnormal. The flow chart is displayed as Fig. S1.

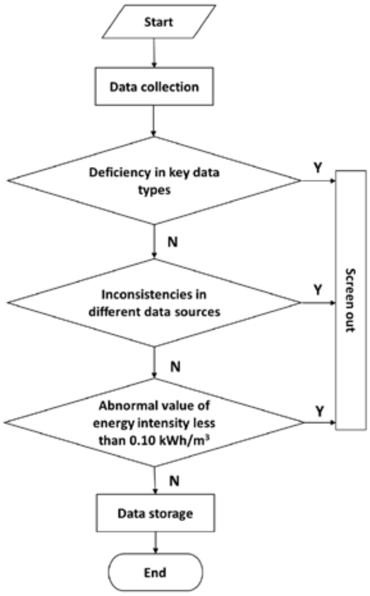

Fig. S1 Flow diagram of data screening.

As a result, data of 970 WWTP samples in YREB were put into use in this study. The characteristics of the WWTP samples in terms of geographical location, designed capacity, and technical process are seen in the following sections.

2.2 Sample description

For geographical location, the YREB consists of upstream, midstream, and downstream. With regards to designed capacity (10^4 m^3/d), the clusters were determined according to Construction Standard of Urban Wastewater Treatment Project (Ministry of Housing and Urban-Rural Development, 2001). The clusters of 1~5, 5~10, 10~20, 20~50, and 50~100 in unit of 10^4 m^3/d are defined in the standard. In this study, the cluster of 0~1 m^3/d was added to cover all WWTP samples. The technical process of WWTPs could be primarily classified into the activated sludge, membrane technology, and combined technology. Among them, the activated sludge is the most widely used method. It can be further categorized as anaerobic-anoxic-oxic (AAO), anaerobic-oxic (AO), conventional activated sludge (CAS), cycling activated sludge technology (C-Tech), oxidation ditch (OD), sequential bioreactor (SBR), modified sequential bioreactor (MSBR), biological aerated filter (BAF), and others. The statistics of frequency are seen in Fig. S2.

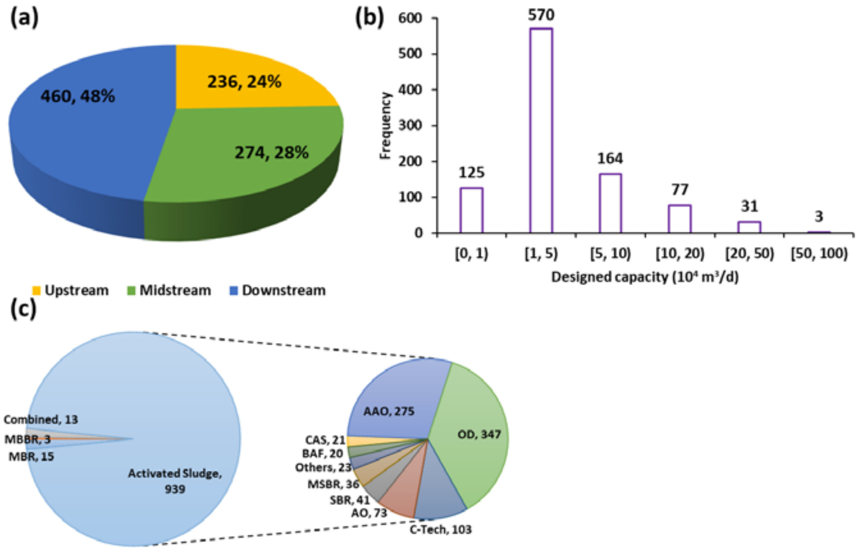

Fig. S2 Details of the 970 wastewater treatment plants in Yangtze River Economic Belt (a) geographical location; (b) designed capacity (10^4 m^3/d); (c) technical process.

As seen in Fig. S2, there are 236, 274, and 460 WWTPs distribute in upstream, midstream, and downstream of YREB. The downstream have the most WWTP samples while the upstream have the least. For designed capacity (10^4 m^3/d), most WWTP samples have a treatment scale between 1 and 5 (10^4 m^3/d). In addition, most WWTPs are configured with technologies of activated sludge. The OD, AAO, and AO are the most commonly seen technology.

2.3 Statistics on key performance indicators

The ESS of the 970 WWTPs ranged from 9.94% to 181.36%, while the CWEE changed between the interval with 0.123 to 1.000 as the lower and upper bounds, respectively. The median value of ESS was 67.26%, while the one of CWEE was 0.544. The summary of basic statistics on ESS and CWEE is seen in Table S4.

Table S4 Statistics on the key performance indicators of 970 wastewater treatment plants.

Key performance indicator	Min-Max	Median	Mean	Std. Dev.
Energy self-sufficiency	9.94%-181.36%	67.26%	69.33%	27.09%
Comprehensive water-energy efficiency	0.123-1.000	0.544	0.576	0.202

2.4 Detailed information of the fully self-sufficient and the benchmark

According to the qualitative analysis of the ESS, the WWTPs could be classified as the fully self-sufficient and the non-full-self-sufficient. For CWEE, the WWTPs could be categoried as the benchmark and the normal. There were 121 WWTPs with ESS value over 100% and 98 WWTPs with CWEE value equal to 1.000. The details of the 121 WWTPs and 98 WWTPs are seen in Table S5 and Table S6, respectively.

Table S5 Details of the 121 wastewater treatment plants with energy self-sufficiency over 100%.

Order	Province/ Municipality	Geographical location	Technical process	Designed capacity (10^4 m^3/d)	Wet sludge generation (10^3 kg/y)	Treatment capacity (10^3 kg /y)	Total electricity consumption (kWh/y)
1	Jiangsu	Downstream	AAO	[5, 10)	7 707	1 884	3 345 825
2	Jiangsu	Downstream	C-Tech	[5, 10)	4 916	1 861	3 083 080
3	Jiangsu	Downstream	AO	[0, 1)	13.3	36	48 921
4	Jiangsu	Downstream	SBR	[0, 1)	13.2	37	43 467
5	Jiangsu	Downstream	SBR	[0, 1)	15.2	33	40 684
6	Jiangsu	Downstream	CAS	[1, 5)	4 237	1 178	1 621 118
7	Jiangsu	Downstream	AAO	[1, 5)	10 022	1 348	2 089 014
8	Jiangsu	Downstream	AAO	[1, 5)	2 775	1 506	2 530 166
9	Jiangsu	Downstream	AO	[1, 5)	270	188	302 238
10	Jiangsu	Downstream	AAO	[1, 5)	5 950	1 151	2 082 234
11	Zhejiang	Downstream	MSBR	[5, 10)	4 676	701	1 004 321
12	Zhejiang	Downstream	OD	[1, 5)	809	891	934 270
13	Zhejiang	Downstream	AAO	[20, 50)	61 913	5 961	10 370 460
14	Zhejiang	Downstream	AAO	[20, 50)	31 307	7 880	13 209 530
15	Zhejiang	Downstream	AAO	[5, 10)	13 034	2 072	2 980 660
16	Zhejiang	Downstream	AAO	[10, 20)	19 317	5 088	8 546 351
17	Zhejiang	Downstream	AO	[20, 50)	97 456	10 479	18 515 062
18	Zhejiang	Downstream	OD	[1, 5)	1 927	545	665 113
19	Zhejiang	Downstream	CAS	[1, 5)	865	271	414 206
20	Zhejiang	Downstream	AO	[5, 10)	6 342	1 458	2 336 625
21	Anhui	Downstream	AAO	[0, 1)	239	198	305 674
22	Anhui	Downstream	OD	[1, 5)	3 519	1 066	1 685 760
23	Anhui	Downstream	OD	[5, 10)	6 046	1 379	2 177 748

24	Anhui	Downstream	C-Tech	[1, 5)	4 714	1 130	1 966 666
25	Anhui	Downstream	AAO	[1, 5)	4 970	1 794	2 975 358
26	Anhui	Downstream	AAO	[10, 20)	9 422	5 397	7 858 496
27	Anhui	Downstream	AAO	[1, 5)	3 980	845	1 502 146
28	Anhui	Downstream	OD	[1, 5)	1 080	680	1 109 772
29	Anhui	Downstream	AAO	[1, 5)	714	768	1 322 111
30	Anhui	Downstream	AAO	[1, 5)	5 479	1 050	1 813 579
31	Anhui	Downstream	C-Tech	[10, 20)	13 680	4 043	5 922 750
32	Anhui	Downstream	AO	[1, 5)	7 286	1 136	1 861 160
33	Anhui	Downstream	OD	[1, 5)	1 434	530	661 383
34	Anhui	Downstream	OD	[1, 5)	1 129	1 243	1 902 456
35	Jiangxi	Midstream	AAO	[20, 50)	24 784	4 762	8 589 420
36	Jiangxi	Midstream	OD	[10, 20)	4 583	2 920	4 279 940
37	Jiangxi	Midstream	OD	[1, 5)	1 769	561	973 865
38	Jiangxi	Midstream	OD	[1, 5)	3 301	641	1 123 557
39	Jiangxi	Midstream	OD	[1, 5)	434	567	836 849
40	Hubei	Midstream	AAO	[10, 20)	13 398	3 620	5 772 864
41	Hubei	Midstream	AAO	[1, 5)	4 528	1 410	2 424 540
42	Hubei	Midstream	Others	[0, 1)	342	313	495 715
43	Hubei	Midstream	AAO	[10, 20)	13 949	4 570	6 508 639
44	Hubei	Midstream	C-Tech	[1, 5)	124	621	993 224
45	Hubei	Midstream	C-Tech	[1, 5)	636	1 304	1 604 286
46	Hubei	Midstream	C-Tech	[1, 5)	297	615	863 277
47	Hubei	Midstream	AAO	[5, 10)	5 181	1 770	2 416 850
48	Hubei	Midstream	AAO	[1, 5)	2 933	1 169	2 051 928
49	Hubei	Midstream	OD	[1, 5)	3 847	1 215	1 934 248

50	Hubei	Midstream	MBR	[1, 5)	333	428	679 691
51	Hubei	Midstream	AAO	[5, 10)	6 666	1 618	2 559 559
52	Hubei	Midstream	AAO	[1, 5)	3 720	1 201	2 049 130
53	Hubei	Midstream	AAO	[1, 5)	502	621	1 056 284
54	Hubei	Midstream	MBR	[1, 5)	224	587	676 000
55	Hubei	Midstream	C-Tech	[1, 5)	800	585	803 436
56	Hubei	Midstream	C-Tech	[1, 5)	2 430	1 796	1 922 714
57	Hubei	Midstream	OD	[1, 5)	169	729	943 075
58	Hubei	Midstream	SBR	[1, 5)	2 779	1 175	1 244 603
59	Hubei	Midstream	OD	[5, 10)	4 295	1 590	2 664 070
60	Hubei	Midstream	C-Tech	[1, 5)	2 331	511	870 525
61	Hubei	Midstream	OD	[1, 5)	3 766	1 595	2 541 620
62	Hubei	Midstream	OD	[10, 20)	11 327	3 238	4 327 065
63	Hubei	Midstream	OD	[1, 5)	508	569	617 745
64	Hubei	Midstream	OD	[1, 5)	1 334	614	1 016 728
65	Hunan	Midstream	MSBR	[20, 50)	32 544	7 605	10 027 536
66	Hunan	Midstream	AAO	[1, 5)	4 986	1 776	2 796 244
67	Hunan	Midstream	OD	[5, 10)	12 834	2 626	4 634 540
68	Hunan	Midstream	C-Tech	[1, 5)	484	279	383 812
69	Hunan	Midstream	OD	[1, 5)	1 994	1 001	1 535 898
70	Hunan	Midstream	AAO	[20, 50)	14 504	5 763	9 534 250
71	Hunan	Midstream	AAO	[5, 10)	1 006	2 693	3 316 159
72	Hunan	Midstream	OD	[1, 5)	3 350	1 522	2 214 802
73	Hunan	Midstream	OD	[1, 5)	4 662	1 047	1 794 940
74	Hunan	Midstream	C-Tech	[1, 5)	866	964	1 415 199
75	Hunan	Midstream	OD	[1, 5)	1 186	824	961 167

76	Hunan	Midstream	SBR	[5, 10)	3 230	1 085	1 737 200
77	Hunan	Midstream	OD	[10, 20)	5 414	4 986	7 446 832
78	Hunan	Midstream	OD	[5, 10)	887	1 937	3 195 780
79	Hunan	Midstream	OD	[1, 5)	1 274	1 001	1 705 397
80	Hunan	Midstream	OD	[1, 5)	2 736	824	997 340
81	Hunan	Midstream	OD	[1, 5)	1 242	781	1 089 937
82	Hunan	Midstream	OD	[10, 20)	19 453	3 638	6 250 216
83	Hunan	Midstream	OD	[10, 20)	16 733	5 292	5 179 120
84	Hunan	Midstream	AAO	[1, 5)	440	453	737 552
85	Hunan	Midstream	AAO	[1, 5)	112	248	420 112
86	Hunan	Midstream	AAO	[10, 20)	16 237	3 677	4 296 233
87	Hunan	Midstream	OD	[1, 5)	3 606	1 240	2 132 160
88	Hunan	Midstream	CAS	[1, 5)	1 233	887	1 305 164
89	Hunan	Midstream	C-Tech	[1, 5)	496	333	414 336
90	Hunan	Midstream	C-Tech	[1, 5)	900	508	871 245
91	Hunan	Midstream	Others	[10, 20)	3 042	5 166	7 397 803
92	Hunan	Midstream	SBR	[1, 5)	5 975	1 257	1 584 031
93	Hunan	Midstream	AAO	[1, 5)	103	697	1 170 384
94	Hunan	Midstream	OD	[1, 5)	652	336	568 057
95	Chongqing	Upstream	OD	[5, 10)	18 577	1 720	3 234 763
96	Sichuan	Upstream	MSBR	[1, 5)	2 517	838	1 450 839
97	Sichuan	Upstream	Combined	[1, 5)	3 545	727	1 273 320
98	Sichuan	Upstream	OD	[1, 5)	4 767	1 461	2 561 418
99	Sichuan	Upstream	OD	[10, 20)	4 276	2 013	3 412 760
100	Sichuan	Upstream	AO	[20, 50)	27 526	6 911	11 762 760
101	Sichuan	Upstream	MSBR	[5, 10)	6 800	1 846	2 738 973

102	Sichuan	Upstream	C-Tech	[1, 5)	8 110	1 077	1 791 675
103	Guizhou	Upstream	OD	[0, 1)	777	260	256 680
104	Guizhou	Upstream	OD	[1, 5)	2 236	509	631 239
105	Guizhou	Upstream	OD	[0, 1)	205	297	379 214
106	Guizhou	Upstream	SBR	[1, 5)	501	154	156 355
107	Yunnan	Upstream	C-Tech	[0, 1)	761	250	434 397
108	Yunnan	Upstream	C-Tech	[1, 5)	2 348	591	766 009
109	Yunnan	Upstream	C-Tech	[1, 5)	2 193	733	1 226 400
110	Yunnan	Upstream	SBR	[5, 10)	7 724	1 451	2 591 148
111	Yunnan	Upstream	C-Tech	[1, 5)	785	220	373 930
112	Yunnan	Upstream	SBR	[1, 5)	3 401	637	1 051 861
113	Yunnan	Upstream	C-Tech	[0, 1)	679	150	254 680
114	Yunnan	Upstream	C-Tech	[1, 5)	2 165	535	810 391
115	Yunnan	Upstream	C-Tech	[5, 10)	909	779	1 327 071
116	Yunnan	Upstream	SBR	[5, 10)	3 072	1 170	1 899 735
117	Yunnan	Upstream	SBR	[0, 1)	929	195	347 607
118	Yunnan	Upstream	C-Tech	[1, 5)	1 964	352	527 193
119	Yunnan	Upstream	C-Tech	[1, 5)	1 184	249	388 049
120	Yunnan	Upstream	CAS	[5, 10)	9 345	2 017	2 339 140
121	Yunnan	Upstream	OD	[1, 5)	2 905	705	747 914

Table S6 Details of 98 wastewater treatment plants with comprehensive water-energy efficiency of 1.000.

Order	Province/ Municipality	Geographical location	Technical process	Designed capacity (10^4 m^3/d)	Wet sludge generation (10^3 kg/y)	Treatment capacity (10^3 kg /y)	Total electricity consumption (kWh/y)
1	Shanghai	Downstream	OD	[5, 10)	6 033	1 459	3 819 640
2	Shanghai	Downstream	AAO	[20, 50)	33 000	5 700	12 829 140
3	Shanghai	Downstream	Others	[1, 5)	4 381	512	2 129 570
4	Jiangsu	Downstream	AAO	[50, 100)	72 555	24 034	55 831 356
5	Jiangsu	Downstream	CAS	[20, 50)	42 035	11 668	24 332 051
6	Jiangsu	Downstream	AAO	[1, 5)	4 244	460	2 536 000
7	Jiangsu	Downstream	AAO	[5, 10)	8 866	1 353	12 639 132
8	Jiangsu	Downstream	AAO	[5, 10)	16 212	1 451	3 948 268
9	Jiangsu	Downstream	C-Tech	[5, 10)	4 916	1 861	3 083 080
10	Jiangsu	Downstream	AO	[0, 1)	13.3	36	48 921
11	Jiangsu	Downstream	AO	[0, 1)	5.3	24	84 961
12	Jiangsu	Downstream	SBR	[0, 1)	13.2	37	43 467
13	Jiangsu	Downstream	SBR	[0, 1)	15.2	33	40 684
14	Jiangsu	Downstream	AO	[0, 1)	36.2	7	17 342
15	Jiangsu	Downstream	AAO	[1, 5)	1 223	586	2 033 694
16	Jiangsu	Downstream	CAS	[1, 5)	4 237	1 178	1 621 118
17	Jiangsu	Downstream	BAF	[1, 5)	2 351	404	1 936 985
18	Jiangsu	Downstream	AAO	[1, 5)	2 775	1 506	2 530 166
19	Jiangsu	Downstream	Others	[1, 5)	673	773	7 922 114
20	Jiangsu	Downstream	AAO	[1, 5)	17 733	344	1 066 926
21	Jiangsu	Downstream	AO	[1, 5)	270	188	302 238
22	Jiangsu	Downstream	Others	[0, 1)	37.4	24	70 508
23	Jiangsu	Downstream	OD	[1, 5)	1 060	1 005	2 543 862

24	Zhejiang	Downstream	AAO	[50, 100)	202 882	23 470	78 836 081
25	Zhejiang	Downstream	CAS	[20, 50)	110 822	3 602	32 079 000
26	Zhejiang	Downstream	CAS	[10, 20)	151 706	2 716	17 913 340
27	Zhejiang	Downstream	CAS	[10, 20)	61 324	1 302	12 670 490
28	Zhejiang	Downstream	OD	[1, 5)	809	891	934 270
29	Zhejiang	Downstream	AAO	[20, 50)	61 913	5 961	10 370 460
30	Zhejiang	Downstream	MBR	[5, 10)	10 813	1 770	3 645 145
31	Zhejiang	Downstream	BAF	[1, 5)	11 477	1 055	2 107 850
32	Zhejiang	Downstream	Others	[0, 1)	148	202	822 567
33	Zhejiang	Downstream	AAO	[10, 20)	19 317	5 088	8 546 351
34	Zhejiang	Downstream	AO	[20, 50)	97 456	10 479	18 515 062
35	Zhejiang	Downstream	AO	[20, 50)	120 805	11 160	50 062 094
36	Zhejiang	Downstream	C-Tech	[10, 20)	20 412	2 940	12 052 608
37	Zhejiang	Downstream	Others	[1, 5)	2 654	627	1 861 470
38	Zhejiang	Downstream	AO	[50, 100)	786 448	21 469	138 869 383
39	Zhejiang	Downstream	AAO	[1, 5)	5 793	868	13 986 800
40	Zhejiang	Downstream	C-Tech	[5, 10)	9 904	1 714	4 197 340
41	Zhejiang	Downstream	AAO	[10, 20)	39 512	6 094	26 224 950
42	Zhejiang	Downstream	OD	[5, 10)	15 024	1 814	5 799 342
43	Anhui	Downstream	AAO	[20, 50)	23 630	6 864	19 792 800
44	Hubei	Midstream	SBR	[0, 1)	9.2	20	103 945
45	Hubei	Midstream	AO	[0, 1)	3.85	19	43 974
46	Hubei	Midstream	AAO	[20, 50)	87 869	11 061	22 629 076
47	Hubei	Midstream	C-Tech	[1, 5)	636	1 304	1 604 286
48	Hubei	Midstream	C-Tech	[1, 5)	297	615	863 277
49	Hubei	Midstream	MBR	[1, 5)	224	587	676 000

50	Hubei	Midstream	C-Tech	[1, 5)	2 430	1 796	1 922 714
51	Hubei	Midstream	AO	[1, 5)	186	555	1 261 540
52	Hubei	Midstream	OD	[1, 5)	169	729	943 075
53	Hunan	Midstream	MSBR	[20, 50)	32 544	7 605	10 027 536
54	Hunan	Midstream	AAO	[20, 50)	60 170	11 616	29 354 135
55	Hunan	Midstream	OD	[10, 20)	10 429	4 967	9 856 490
56	Hunan	Midstream	AAO	[10, 20)	13 110	6 402	14 609 924
57	Hunan	Midstream	AAO	[5, 10)	1 006	2 693	3 316 159
58	Hunan	Midstream	OD	[5, 10)	703	1 836	6 154 570
59	Hunan	Midstream	OD	[1, 5)	3 650	1 083	2 125 567
60	Hunan	Midstream	OD	[10, 20)	5 414	4 986	7 446 832
61	Hunan	Midstream	OD	[5, 10)	887	1 937	3 195 780
62	Hunan	Midstream	Others	[1, 5)	72.2	182	520 226
63	Hunan	Midstream	OD	[1, 5)	406	364	657 000
64	Hunan	Midstream	OD	[10, 20)	16 733	5 292	5 179 120
65	Hunan	Midstream	OD	[1, 5)	372	1 063	1 846 607
66	Hunan	Midstream	AAO	[10, 20)	16 237	3 677	4 296 233
67	Hunan	Midstream	Others	[10, 20)	3 042	5 166	7 397 803
68	Hunan	Midstream	AAO	[1, 5)	103	697	1 170 384
69	Hunan	Midstream	AAO	[1, 5)	67.3	255	487 002
70	Chongqing	Upstream	CAS	[1, 5)	26 713	1 229	4 075 420
71	Chongqing	Upstream	C-Tech	[0, 1)	2 591	294	1 444 389
72	Chongqing	Upstream	OD	[5, 10)	18 577	1 720	3 234 763
73	Chongqing	Upstream	AAO	[1, 5)	4 702	776	3 129 880
74	Chongqing	Upstream	SBR	[1, 5)	9 621	1 325	4 021 147
75	Chongqing	Upstream	C-Tech	[5, 10)	7 745	1 231	3 047 953

76	Chongqing	Upstream	MBR	[0, 1)	78.6	44	490 185
77	Chongqing	Upstream	OD	[1, 5)	9 407	964	2 369 172
78	Sichuan	Upstream	OD	[10, 20)	4 276	2 013	3 412 760
79	Sichuan	Upstream	AO	[5, 10)	1 954	2 356	4 438 760
80	Sichuan	Upstream	C-Tech	[1, 5)	79	136	1 555 748
81	Sichuan	Upstream	C-Tech	[5, 10)	5 740	1 908	4 033 200
82	Sichuan	Upstream	C-Tech	[0, 1)	39	137	513 558
83	Sichuan	Upstream	OD	[1, 5)	22.1	172	415 500
84	Guizhou	Upstream	Others	[1, 5)	825	912	2 000 363
85	Guizhou	Upstream	OD	[0, 1)	777	260	256 680
86	Guizhou	Upstream	OD	[1, 5)	2 236	509	631 239
87	Guizhou	Upstream	SBR	[1, 5)	501	154	156 355
88	Guizhou	Upstream	OD	[0, 1)	239	86	179 879
89	Yunnan	Upstream	C-Tech	[1, 5)	2 115	308	617 170
90	Yunnan	Upstream	AAO	[20, 50)	12 591	5 147	14 483 630
91	Yunnan	Upstream	AAO	[10, 20)	51 890	8 598	17 468 028
92	Yunnan	Upstream	C-Tech	[0, 1)	760	229	540 265
93	Yunnan	Upstream	SBR	[1, 5)	3 401	637	1 051 861
94	Yunnan	Upstream	SBR	[0, 1)	13.7	9	45 454
95	Yunnan	Upstream	C-Tech	[0, 1)	931	194	429 019
96	Yunnan	Upstream	CAS	[5, 10)	9 345	2 017	2 339 140
97	Yunnan	Upstream	OD	[1, 5)	2 905	705	747 914
98	Yunnan	Upstream	C-Tech	[0, 1)	419	171	562 800

2.5 Analysis on the explanatory factor of technical process

The results of Chi^2 test indicate the difference among WWTPs configured with different technical processes. During the analysis on the technical process, the clusters were sorted in an ascending order according to the proportion percentage of the WWTPs with high ENP.

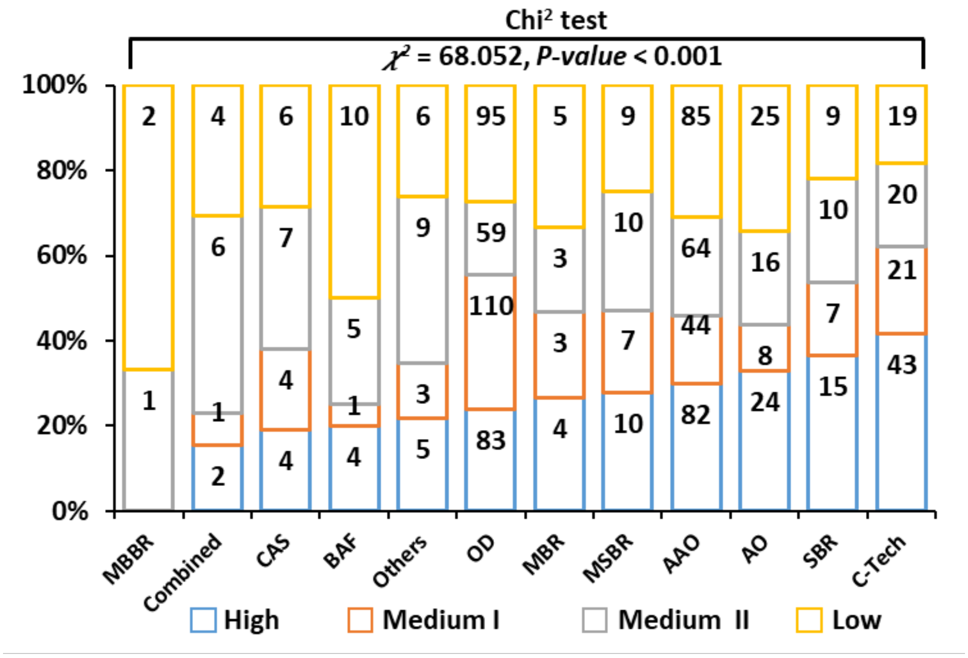

Fig. S3 Sample numbers of wastewater treatment plants with energy neutrality potential in terms of technical process.

As seen in Fig. S3, the proportion of high ENP in C-Tech was the greatest, while no WWTP with MBBR had the high ENP. The WWTPs configured with the technologies related to activated sludge had higher proportion percentage of high ENP overall. However, MBR is the only membrane-based process that ranked before OD, BAF, and CAS.

References

Chae K J, Kang J (2013). Estimating the energy independence of a municipal wastewater treatment plant incorporating green energy resources. Energy Conversion and Management, 75: 664-672

Hao X, Chen Q, Li J, Jiang H (2019). The ultimate approach to handle excess sludge: incineration and drying. China Water & Wastewater, 35(4): 35-42 (in Chinese)

Hao X, Liu R, Huang X (2015). Evaluation of the potential for operating carbon neutral WWTPs in China. Water Research, 87: 424-431

Hepbasli A, Biyik E, Ekren O, Gunerhan H, Araz M (2014). A key review of wastewater source heat pump (WWSHP) systems. Energy Conversion and Management, 88: 700-722

Li S, Li Y, Lu Q, Zhu J, Yao Y, Bao S (2014). Integrated drying and incineration of wet sewage sludge in combined bubbling and circulating fluidized bed units. Waste Management, 34(12): 2561-2566

Ministry of Housing and Urban-Rural Development (2001). Construction Standard of Urban Wastewater Treatment Project. Beijing: Ministry of Housing and Urban-Rural Development of the People's Republic of China (in Chinese)

Tone K (2001). A slacks-based measure of efficiency in data envelopment analysis. European Journal of Operational Research, 130(3): 498-509

Yang X E, Wu S (2016). Application Analysis of Sew age-Source Heat Pump in Tangshan. Journal of Building Energy Efficiency, 44(11): 34-36 (in Chinese)

Yang X, Wei J, Ye G, Zhao Y, Li Z, Qiu G, Li F, Wei C (2020). The correlations among wastewater internal energy, energy consumption and energy recovery/production potentials in wastewater treatment plant: An assessment of the energy balance. Science of the Total Environment, 714: 136655