Supplementary information for "Validating and comparing energy estimation methods at water resource recovery facilities"

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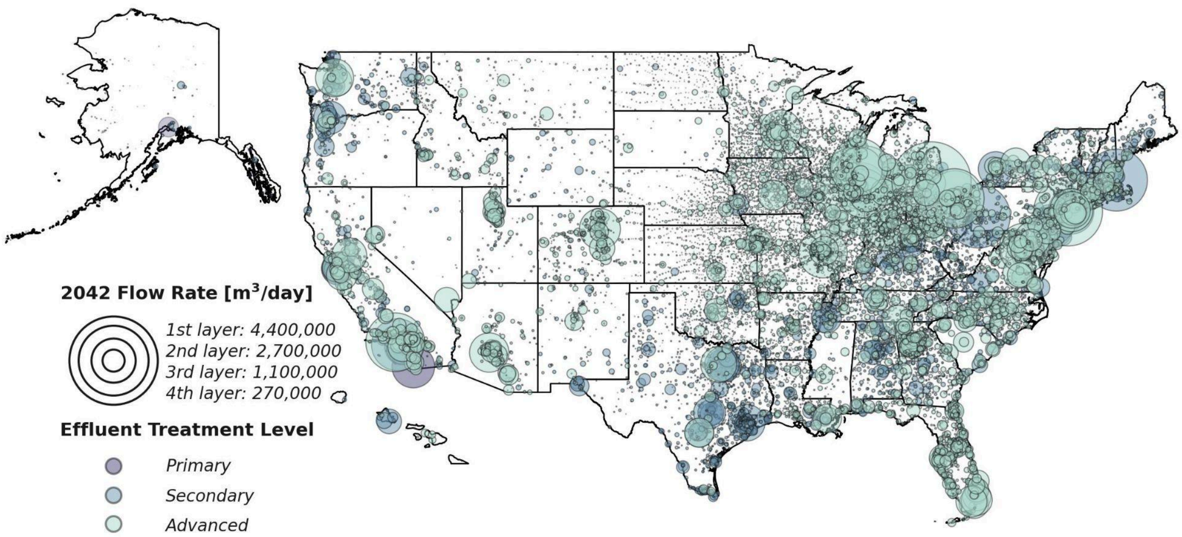

Figure S1: Projected national water resource recovery facility inventory, compiled using location, flow rate, and effluent treatment level data from the Clean Watersheds Needs Survey (CWNS). Note that, because the 2022 CWNS does not distinguish between design and observed flow, the projected annual flow rate shown here is likely an overestimate.

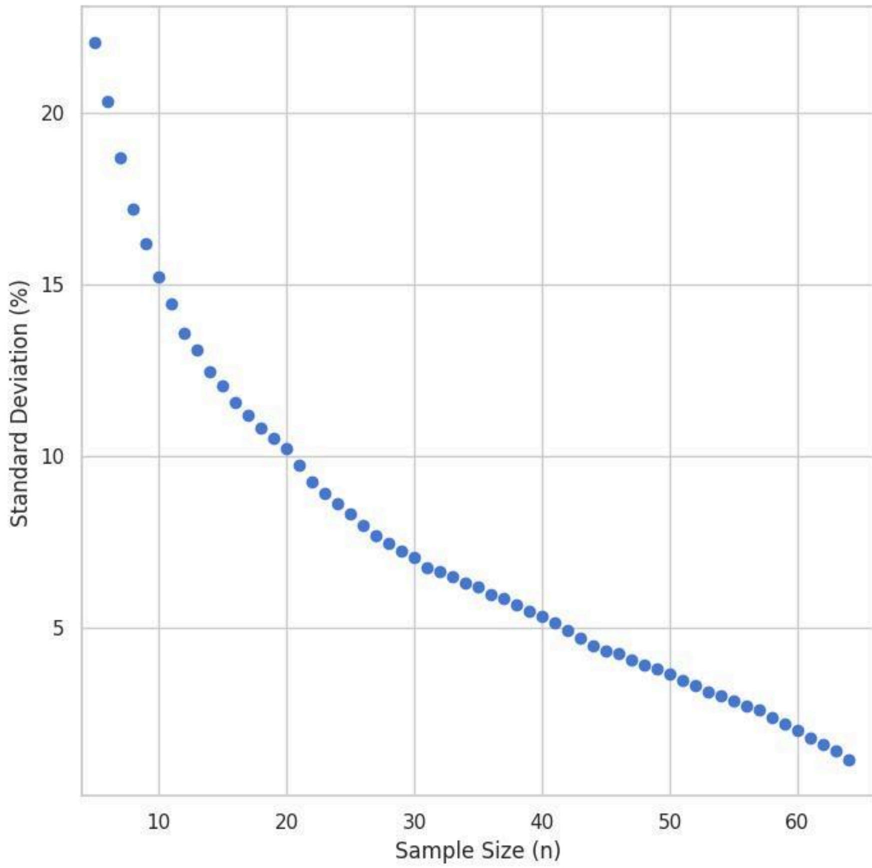

Figure S2: Standard deviation of mean absolute percent error for different samples (n = 5 to 65) of the validation set. As the sample size increases, the standard deviation of error decreases, affirming that the size of the validation set impacts our assessment of error for each estimation method.

Table S1: Summary of existing U.S. water resource recovery facility electricity consumption estimations

Primary authors	**Publication date**	**Scale**	**Electricity consumption [TWh]**
Gingerich and Mauter [1]	2018	National	19.5
Tarallo [2]	2014	National	22.0
Tidwell, Moreland, and Zemlick [3]	2014	Western U.S.	9.00
Pabi *et al* [4]	2013	National	30.2
Stillwell *et al* [5]	2010	National	18.1-23.8

Table S2: Summary of water resource recovery facilities used for estimation method validation

Clean Watersheds Needs Survey ID	Location	Latitude	Longitude	Annual flow rate, 2012 [Mm^3/year]	Effluent treatment level, 2012
36004064002	Albany, NY	42.6	-73.8	31.6	Secondary
48000105001	Amarillo, TX	35.3	-102	16.6	Advanced
02000106001	Anchorage, AK	61.2	-150	41.0	Primary
13000054001	Augusta, GA	33.4	-82.0	42.3	Advanced
06005010002	Bakersfield, CA	35.3	-119	15.6	Secondary
24000001001	Baltimore, MD	39.3	-76.5	215	Advanced
48006001001	Beaumont, TX	30.0	-94.1	47.0	Advanced
30000060001	Billings, MT	45.8	-108	21.8	Secondary
25000128001	Boston, MA	42.4	-71.0	428	Secondary
09000150001	Bridgeport, CT	41.2	-73.2	33.3	Advanced
09000150002	Bridgeport, CT	41.2	-73.2	11.1	Advanced
36009071001	Buffalo, NY	42.9	-78.9	206	Secondary
50000016001	Burlington, VT	44.5	-73.2	6.59	Advanced
37006001002	Charlotte, NC	35.1	-80.9	39.6	Advanced
37006001003	Charlotte, NC	35.2	-80.9	15.9	Advanced
37006001005	Charlotte, NC	35.2	-80.9	18.4	Advanced
37006001008	Charlotte, NC	35.4	-80.9	5.68	Advanced
37006001009	Charlotte, NC	35.3	-80.7	2.25	Advanced
17000721001	Chicago, IL	41.8	-87.8	1,120	Advanced
17000721002	Chicago, IL	42.0	-88.1	12.4	Advanced
17000721005	Chicago, IL	42.0	-88.0	37.3	Advanced
17000721009	Chicago, IL	41.7	-87.6	321	Advanced
39003369002	Cincinnati, OH	39.1	-84.6	209	Secondary
39001666002	Cleveland, OH	41.4	-81.6	235	Advanced
39001666003	Cleveland, OH	41.5	-81.7	48.4	Advanced
08000001001	Colorado Springs, CO	38.8	-105	37.3	Advanced
48004026001	Dallas, TX	32.8	-96.6	171	Advanced
39002093001	Dayton, OH	39.7	-84.2	99.5	Advanced

08000070001	Denver, CO	39.8	-105	210	Advanced
26000596001	Detroit, MI	42.3	-83.1	913	Advanced
27000002001	Duluth, MN	46.8	-92.1	53.5	Advanced
48001009001	El Paso, TX	31.8	-106	23.2	Secondary
48001009007	El Paso, TX	31.8	-107	10.2	Advanced
41000045001	Eugene, OR	44.1	-123	53.2	Advanced
08000037001	Fort Collins, CO	40.6	-105	17.4	Advanced
18000225001	Fort Wayne, IN	41.1	-85.1	55.3	Advanced
48004122001	Fort Worth, TX	32.8	-97.1	192	Advanced
37004102003	Greensboro, NC	36.1	-79.7	30.3	Advanced
42001006001	Harrisburg, PA	40.2	-76.9	18.2	Advanced
15000003010	Honolulu, HI	21.3	-158	34.0	Secondary
18000061002	Indianapolis, IN	39.8	-86.2	67.7	Advanced
12000016001	Jacksonville, FL	30.4	-81.6	52.5	Advanced
12000016002	Jacksonville, FL	30.1	-81.6	0.83	Advanced
12000016003	Jacksonville, FL	30.4	-81.5	17.8	Advanced
26000108001	Kalamazoo, MI	42.3	-85.6	38.7	Advanced
32000011001	Las Vegas, NV	36.1	-115	85.7	Advanced
31001425002	Lincoln, NE	40.9	-96.6	9.05	Secondary
05000001001	Little Rock, AR	34.7	-92.2	12.4	Secondary
05000001008	Little Rock, AR	34.7	-92.2	27.9	Secondary
06004010001	Los Angeles, CA	33.9	-118	449	Secondary
06004010002	Los Angeles, CA	33.8	-118	22.8	Advanced
21000025001	Louisville, KY	38.2	-85.8	135	Secondary
21000025011	Louisville, KY	38.1	-85.9	41.1	Secondary
55002781001	Madison, WI	43.0	-89.4	56.7	Advanced
47000940001	Memphis, TN	35.1	-90.1	97.4	Secondary
12000017004	Miami, FL	25.8	-80.2	175	Secondary
27000001003	Minneapolis, MN	44.8	-93.2	25.2	Advanced
27000001012	Minneapolis, MN	44.8	-92.9	2.10	Advanced
27000001026	Minneapolis, MN	44.7	-93.1	4.89	Advanced

47001016001	Nashville, TN	36.2	-86.8	127	Advanced
47001016002	Nashville, TN	36.3	-86.7	24.3	Advanced
47001016006	Nashville, TN	36.2	-86.9	48.3	Advanced
22009071001	New Orleans, LA	30.0	-90.0	127	Secondary
36002001007	New York, NY	40.7	-74.0	82.9	Secondary
36002001008	New York, NY	40.6	-74.1	47.0	Secondary
36002001009	New York, NY	40.6	-73.9	129	Advanced
36002001010	New York, NY	40.6	-74.0	120	Secondary
36002001011	New York, NY	40.7	-74.0	375	Secondary
36002001012	New York, NY	40.8	-74.0	235	Secondary
36002001013	New York, NY	40.6	-74.1	33.2	Secondary
36002001014	New York, NY	40.6	-73.8	29.0	Secondary
51000308001	Norfolk, VA	37.0	-76.4	27.9	Secondary
51000308002	Norfolk, VA	37.1	-76.5	19.3	Advanced
51000308011	Norfolk, VA	36.9	-76.4	23.5	Secondary
51000308012	Norfolk, VA	36.8	-76.0	47.9	Secondary
48004354001	North Texas*	33.1	-96.6	25.7	Advanced
48004354004	North Texas*	33.0	-96.6	29.2	Advanced
48004354009	North Texas*	33.1	-96.6	55.3	Advanced
06002036001	Oakland, CA	37.8	-122	111	Secondary
17000430001	Peoria, IL	40.7	-89.6	37.3	Advanced
42000094001	Philadelphia, PA	40.0	-75.1	272	Secondary
42000094002	Philadelphia, PA	39.9	-75.2	274	Secondary
42000094003	Philadelphia, PA	39.9	-75.2	131	Secondary
04001316001	Phoenix, AZ	33.4	-112	41.5	Advanced
42005016001	Pittsburgh, PA	40.5	-80.0	227	Secondary
44000022001	Providence, RI	41.8	-71.4	65.9	Secondary
49000064001	Provo, UT	40.2	-112	18.7	Advanced
06005009001	Sacramento, CA	38.5	-122	228	Secondary
41000031001	Salem, OR	45.0	-123	41.0	Secondary
48008015004	San Antonio, TX	29.2	-98.4	8.70	Advanced

06002041001	San Jose, CA	37.4	-122	198	Advanced
53000776002	Seattle, WA	47.7	-122	152	Secondary
53001220001	Spokane, WA	47.7	-117	60.8	Advanced
29001023001	St. Louis, MO	38.7	-90.2	153	Secondary
29001023002	St. Louis, MO	38.5	-90.3	158	Secondary
29001023003	St. Louis, MO	38.8	-90.3	38.1	Secondary
29001023004	St. Louis, MO	38.8	-90.5	37.0	Secondary
36007136001	Syracuse, NY	43.0	-76.2	98.3	Advanced
36007136005	Syracuse, NY	43.2	-76.2	7.71	Advanced
36007136007	Syracuse, NY	43.2	-76.2	3.70	Advanced
53001280001	Tacoma, WA	47.2	-122	82.9	Secondary
53001280003	Tacoma, WA	47.3	-122	6.22	Secondary
39008260001	Toledo, OH	41.7	-83.5	117	Advanced
04001903001	Tucson, AZ	32.3	-111	38.0	Advanced
04001904001	Tucson, AZ	32.3	-111	53.3	Advanced
20000193001	Wichita, KS	37.6	-97.3	56.1	Advanced
20000193002	Wichita, KS	37.6	-97.5	0.83	Advanced

*Cities served by North Texas Municipal Water District (24 communities north and east of Dallas, including Plano, Allen, Rockwall, and Frisco).

Table S3: Summary of cities excluded from the validation set

Location	**Sufficient data in Chini and Stillwell [6]?**	**Sufficient data in Clean Watersheds Needs Survey (CWNS) [7, 13, 14]?**
Albuquerque, NM	No; utility did not report both energy use and flow rate	No; insufficient unit process data*
Alexandria, VA	Yes	No; insufficient unit process data*
Austin, TX	Yes	No; insufficient unit process data*
Birmingham, AL	No; utility did not report both energy use and flow rate	Yes

Boise, ID	No; utility did not report any electricity use	Yes
Charleston, SC	Yes	No; South Carolina did not report any data to CWNS in 2012
Charleston, WV	No; utility did not report any electricity use	Yes
Cheyenne, WY	No; utility did not report both energy use and flow rate	No; insufficient unit process data*
Columbia, SC	Yes	No; South Carolina did not report any data to CWNS in 2012
Columbus, OH	Yes	No; insufficient unit process data*
Corpus Christi, TX	No; utility did not report both energy use and flow rate	Yes
Des Moines, IA	No; utility did not report both energy use and flow rate	Yes
Fargo, ND	No; utility did not report electricity use	Yes
Fresno, CA	No; utility did not report both energy use and flow rate	Yes
Greenville, SC	Yes	No; South Carolina did not report any data to CWNS in 2012
Houston, TX	No; utility did not report both energy use and flow rate	Yes
Jackson, MS	No; utility did not report both energy use and flow rate	Yes
Kansas City, MO	No; flagged as unreliable by Chini and Stillwell [6]	Yes
Knoxville, TN	No; utility did not report both energy use and flow rate	Yes
Lake Charles, LA	No; utility did not report both energy use and flow rate	Yes
Lubbock, TX	No; utility did not report both	Yes

	energy use and flow rate	
Madison, WI	Yes	No; insufficient unit process data*
Manchester, NH	No; utility did not report natural gas use	Yes
Milwaukee, WI	Yes	No; insufficient unit process data*
Newark, NJ	Yes	No; insufficient unit process data*
Oklahoma City, OK	No; utility did not report natural gas use	Yes
Omaha, NE	No; flagged as unreliable due to unusually high energy intensity	Yes
Ogden, UT	Yes	No; unable to identify facility in 2012 CWNS
Portland, ME	No; utility provided incomplete energy use and flow rate data	No; insufficient unit process data*
Portland, OR	No; utility provided incomplete energy use and flow rate data	Yes
Raleigh, NC	No; utility did not report both energy use and flow rate	Yes
Reno, NV	Yes	No; insufficient unit process data*
Salt Lake City, UT	No; utility provided incomplete energy use and flow rate data	Yes
San Diego, CA	Yes	No; insufficient unit process data*
San Francisco, CA	Yes	No; insufficient unit process data*
Santa Fe, NM	Yes	No; insufficient unit process data*
Savannah, GA	No; utility did not report both energy use and flow rate	Yes

Sioux Falls, SD	No; utility did not report both energy use and flow rate	Yes
Springfield, MA	Yes	No; insufficient unit process data*
Tallahassee, FL	Yes	No; insufficient unit process data*
Tampa, FL	Yes	No; insufficient unit process data*
Tulsa, OK	No; utility did not report both energy use and flow rate	Yes
Washington, DC	Yes	No; insufficient unit process data*
Worcester, MA	No; utility did not report both energy use and flow rate	No; insufficient unit process data*

*Note, insufficient unit process data is considered not enough unit process data reported in the 2004, 2008, and 2012 CWNS [7, 13, 14] to assign a treatment train using the Configuration A method. See tt_assignment.ipynb in the project's GitHub for more details on what unit processes are necessary to assign treatment trains in this method.

Table S4: Summary of manual corrections to Chini and Stillwell [6] dataset used for validation

Location	**Adjustments**
Alexandria, VA	Separated total and imported electricity consumption
Bakersfield, CA	Separated total and imported electricity consumption; corrected biogas values
Baltimore, MD	Separated total and imported electricity consumption; corrected biogas values
Eugene, OR	Separated total and imported electricity consumption
Oakland, CA	Separated total and imported electricity consumption
Salem, OR	Separated total and imported electricity consumption; corrected biogas values
San Francisco, CA	Modified to include only Oceanside Water Pollution Control Plant, as this is the only plant that sent complete flow rate and energy data

St. Louis, MO	Separated total and imported electricity consumption; corrected biogas values
Tacoma, WA	Separated total and imported electricity consumption
Toledo, OH	Corrected biogas values; substituted landfill gas for natural gas, assuming one standard cubic foot of landfill gas is equivalent to 0.005 therms
Tucson, AZ	Separated total and imported electricity consumption; corrected natural gas values

Table S5: Limitations of water resource recovery facility energy estimation methods

Method name[*]	**Source**	**Limitations**
Flow rate method	Pabi *et al* [4]	Does not specify whether the collection system or auxiliary needs are considered
Effluent treatment level **A** method	Pabi *et al* [4]	Does not account for the collection system, and does not specify whether auxiliary needs are considered
Effluent treatment level **B** method	Li *et al* [8]	Does not account for the collection system or auxiliary needs
Treatment train **Configuration A (T/BP)** method[+]	Tarallo *et al* [10]	Requires sufficient unit process data to form a treatment train assignment; does not provide a methodology for transforming unit process data into a treatment train assignment; possible treatment train assignments are limited to the 25 most common configurations in North America, as of 2008; designed for facilities that treat over 18,927 m^3/day (5 MGD); does not account for the collection system, aside from the influent pump station; and assumes medium-strength domestic wastewater
Treatment train **Configuration B (T/BP)** method[+]	El Abbadi *et al* [11]	Does not account for the collection system, aside from the influent pump station; designed for facilities that treat over 18,927 m^3/day (5 MGD); and assumes medium-strength domestic wastewater

Unit **Process A** method	Plappally and Leinhard [9]	Requires detailed unit process data; does not account for the collection system and auxiliary needs
Unit **Process B** method	Pabi *et al* [4]	Does not account for the collection system and requires detailed unit process data
Regression method	Carlson and Walburger [19]	Designed for facilities with a design flow over 6,819 m^3/day (1.5 MGD) and facilities serving a population of 10,000 or more
Biogas A method	ERG and RDC [12]	Assumes a mesophilic digester
Biogas B method	ERG and RDC [12]	Assumes a mesophilic digester
Biogas C method	Li *et al* [8]	Assumes idealized medium-strength domestic wastewater and a uniform combined heat and power efficiency (30%) across all facilities
*Methods are referenced throughout this study as the bolded portion of the method name. +Method includes variations for typical (T) and best practice (BP) configurations.		

Table S6: Electricity consumption intensity by flow rate (Flow method [4])

Flow rate [m^3/day]	**Electricity consumption intensity [kWh/m^3]**
Less than 7,570 (2 MGD)	0.870
7,570 - 15,100 (2 - 4 MGD)	0.790
15,100 - 26,500 (4 - 7 MGD)	0.630
26,500 - 60,600 (7 - 16 MGD)	0.530
60,600 - 174,000 (16 - 46 MGD)	0.450
174,000 - 379,000 (46 - 100 MGD)	0.450
379,000 and above (100 MGD)	0.420

Table S7: Electricity consumption intensity by effluent treatment level (Effluent A method [4])

Effluent treatment level	**Electricity consumption intensity [kWh/m^3]**
Raw discharge	0.000
Primary	0.198
Advanced primary	0.198

Secondary	0.550
Advanced	0.711

Table S8: Electricity consumption intensity by effluent treatment level (Effluent B method [8])

Effluent treatment level	Electricity consumption intensity [kWh/m^3]
Raw discharge	0.000
Primary	0.110
Advanced primary	0.141
Secondary	0.352
Advanced	0.487

Table S9: Electricity consumption intensity by unit process (Process A method [9])

Unit process	Average electricity consumption intensity [kWh/m^3]
Activated sludge, anaerobic/anoxic	0.465
Activated sludge, anaerobic/anoxic/oxic	0.465
Activated sludge, complete mix	0.465
Activated sludge, contact stabilization	0.465
Activated sludge, conventional	0.465
Activated sludge, extended aeration	0.465
Activated sludge, high rate	0.465
Activated sludge, other mode	0.465
Activated sludge, pure oxygen	0.465
Activated sludge, step aeration	0.465
Activated sludge with biological denitrification	0.550
Aerated grit chambers	0.015
Aeration (post-treatment)	0.009
Aeration (pre-treatment)	0.009
Biological nitrification - separate stage	0.085
Biological phosphorus removal	0.100
Biosolids aerobic digestion, air	0.175
Biosolids aerobic digestion, autothermal thermophilic	0.175

Biosolids aerobic digestion, oxygen	0.175
Biosolids aerobic digestion, other	0.265
Biosolids anaerobic digestion, thermophilic	0.265
Biosolids chemical addition (polymer)	0.150
Biosolids mechanical dewatering (centrifuge)	0.015
Biosolids mechanical dewatering (filter press)	0.015
Biosolids mechanical dewatering (pressure filter)	0.015
Biosolids mechanical dewatering (vacuum filter)	0.015
Clarification, in-channel	0.010
Clarification, intermediate	0.010
Clarification, secondary	0.010
Clarification, tube settlers	0.010
Dechlorination	0.090
Disinfection, chlorination	0.000
Disinfection, gaseous chloride	0.000
Disinfection, liquid chloride	0.000
Disinfection, ultraviolet radiation	0.041
Filter, denitrification with coarse media	0.010
Filter, denitrification with fine media	0.010
Filter, mixed media	0.010
Filter, other	0.010
Filter, pressure	0.010
Filter, rapid sand	0.010
Filter, rock	0.010
Filter, slow sand	0.010
Grit removal	0.015
Lagoon, aerated	0.199
Lagoon, polishing	0.190
Nitrification, biological (combined and biological oxygen demand reduction)	0.085

Nitrification, biological (separate stage)	0.085
Phosphorus removal, biological	0.100
Phosphorus removal, biological (modified Bardenpho)	0.100
Pond, stabilization	0.009
Reactor, oxidation ditch	0.330
Reactor, sequencing batch	0.465
Sedimentation	0.009
Sedimentation, chemical precipitation	0.009
Sedimentation, primary	0.009
Trickling filter, other media	0.321
Trickling filter, plastic media	0.321
Trickling filter, redwood slats	0.321
Trickling filter, rock media	0.321
Filter, moving bed	0.010
Biological nutrient removal, membrane bioreactor	0.085
Biological nutrient removal	0.650
Activated sludge with phosphorus removal	0.565
Disinfection, sodium hypochlorite	0.000
Clarification, other	0.010
Phosphorus removal, biological (Phostrip)	0.100
Trickling filter, biofilter	0.321
Aerobic unit	0.009

Table S10: Electricity consumption intensity by unit process (Process B method [4])

Unit process	**Flow rate [Mm^3/year]**						
	1.38	**6.91**	**13.8**	**27.6**	**69.1**	**138**	**346**
Wastewater pumping	0.058	0.058	0.058	0.058	0.058	0.058	0.059
Odor control	0.040	0.032	0.041	0.066	0.063	0.058	0.055
Grit removal,	0.034	0.008	0.007	0.004	0.004	0.004	0.004

aerated							
Grit removal, forced vortex	0.042	0.011	0.006	0.003	0.002	0.002	0.002
Primary clarifiers	0.008	0.007	0.008	0.008	0.008	0.008	0.006
Ballasted sedimentation	0.020	0.020	0.020	0.020	0.020	0.020	0.018
Trickling filters	0.166	0.134	0.134	0.134	0.134	0.134	0.134
Biological nutrient removal mixing	0.029	0.029	0.029	0.028	0.027	0.029	0.025
Aeration without nitrification	0.190	0.190	0.190	0.183	0.177	0.168	0.162
Aeration with nitrification	0.285	0.285	0.285	0.273	0.265	0.251	0.243
Aeration with biological nutrient removal	0.314	0.314	0.314	0.301	0.292	0.280	0.268
Secondary clarifiers	0.022	0.018	0.018	0.018	0.019	0.018	0.019
Sequencing batch reactors	0.288	0.288	0.288	0.277	0.268	N/A	N/A
Membrane bioreactors	0.713	0.715	0.715	0.715	0.715	N/A	N/A
Aerobic digestion	0.264	0.264	0.264	N/A	N/A	N/A	N/A
Anaerobic digestion	N/A	0.029	0.029	0.028	0.026	0.026	0.026
Gravity belt thickener	0.008	0.007	0.006	0.006	0.006	0.006	0.006
Dissolved air flotation	N/A	N/A	0.048	0.039	0.033	0.031	0.047
Centrifuge thickening	0.021	0.015	0.010	0.010	0.010	0.010	0.010
Belt filter press	N/A	0.012	0.012	0.009	0.007	0.007	0.005
Screw press	0.005	0.005	0.004	0.004	0.003	0.003	0.003
Centrifuge dewatering	0.069	0.069	0.069	0.069	0.069	0.069	0.069

Thermal drying	0.058	0.058	0.058	0.058	N/A	N/A	N/A
Ultraviolet disinfection	0.059	0.062	0.062	0.062	0.062	0.062	0.062
Depth filtration	0.026	0.018	0.015	0.015	0.015	0.015	0.015
Surface filtration	0.013	0.009	0.008	0.008	0.008	0.008	0.008
Plant utility water	0.012	0.012	0.011	0.011	0.011	0.011	0.011
Nonprocess loads (buildings, lighting, computers, pneumatics, etc.)	0.079	0.063	0.055	0.048	0.048	0.048	0.048
Energy recovery	N/A	-0.076	-0.076	-0.076	-0.076	-0.076	-0.076
Total baseload (wastewater pumping, odor control, utility water, non-process loads)	0.189	0.165	0.166	0.182	0.180	0.174	0.172

Table S11a: Electricity consumption, electricity generation, and natural gas consumption intensity by treatment train (typical) (Configuration A (T) method [10])

Treatment train	**Electricity consumption intensity [kWh/m^3]**	**Electricity generation intensity [kWh/m^3]**	**Natural gas consumption intensity [MJ/m^3]**
B1	0.352	0.000	0.000
B1E	0.352	0.167	0.000
B4	0.399	0.000	0.000
B5	0.394	0.000	1.120
B6	0.360	0.000	0.157
C3	0.391	0.000	0.157
D1	0.279	0.000	0.000
E2	0.549	0.000	0.157
E2P	0.536	0.000	0.157
F1	0.448	0.000	0.000

G1	0.495	0.000	0.000
G1E	0.495	0.148	0.000
H1	0.484	0.000	0.000
I2	0.645	0.000	0.157
I3	0.598	0.000	0.157
N1	1.499	0.000	0.000
N2	1.571	0.000	0.157
O1	0.388	0.000	0.000

Table S11b: Electricity consumption, electricity generation, and natural gas consumption intensity by treatment train (best practice) (Configuration A (BP) method [10])

Treatment train	**Electricity consumption intensity [kWh/m^3]**	**Electricity generation intensity [kWh/m^3]**	**Natural gas consumption intensity [MJ/m^3]**
B1	0.230	0.000	0.000
B1E	0.230	0.214	0.000
B4	0.263	0.000	0.000
B5	0.300	0.000	1.120
B6	0.265	0.000	0.157
C3	0.271	0.000	0.157
D1	0.209	0.000	0.000
E2	0.364	0.000	0.157
E2P	0.342	0.000	0.157
F1	0.284	0.000	0.000
G1	0.299	0.000	0.000
G1E	0.299	0.207	0.000
H1	0.291	0.000	0.000
I2	0.384	0.000	0.157
I3	0.356	0.000	0.157
N1	0.744	0.000	0.000

N2	0.814	0.000	0.157
O1	0.304	0.000	0.000

Table S12a: Electricity consumption, electricity generation, and natural gas consumption intensity by treatment train (typical) (Configuration B (T) method [11])

Treatment train	**Electricity consumption intensity [kWh/m^3]**	**Electricity generation intensity [kWh/m^3]**	**Natural gas consumption intensity [MJ/m^3]**
*A1	0.352	0.000	0.000
*A1e	0.352	0.167	0.000
*A2	0.399	0.000	0.727
*A5	0.394	0.000	1.78
*A6	0.360	0.000	0.684
A4	0.391	0.000	0.165
*C1	0.279	0.000	0.000
E3	0.549	0.000	0.165
*E3	0.536	0.000	0.165
*E1	0.448	0.000	0.000
*G1	0.495	0.000	0.000
*G1e	0.495	0.148	0.000
*G1-p	0.484	0.000	0.000
F3	0.645	0.000	0.165
F4	0.598	0.000	0.165
*D1	1.50	0.000	0.000
*D3	1.57	0.000	0.165
*B1	0.388	0.000	0.000
*A3	0.460	0.000	0.165
*A4	0.329	0.000	0.165
A1	0.418	0.000	0.000
A1e	0.418	0.143	0.000
A3	0.498	0.000	0.165
A5	0.455	0.000	1.78

A6	0.421	0.000	0.684
*C1E	0.279	0.120	0.000
*C3	0.358	0.000	0.165
*C4	0.250	0.000	0.165
*C5	0.314	0.000	1.78
*C6	0.281	0.000	0.684
*E1e	0.448	0.154	0.000
*G3	0.597	0.000	0.165
*G4	0.459	0.000	0.165
*G5	0.523	0.000	1.78
*G6	0.489	0.000	0.684
*G1e-p	0.484	0.148	0.000
F1	0.633	0.000	0.000
F1e	0.633	0.112	0.000
F5	0.663	0.000	1.78
F6	0.629	0.000	0.684
*D1e	1.50	0.172	0.000
*B1e	0.388	0.167	0.000
*B3	0.497	0.000	0.165
*B4	0.359	0.000	0.165
*B5	0.423	0.000	1.78
*B6	0.390	0.000	0.684
L-u	0.003	0.000	0.000
L-a	0.004	0.000	0.000
L-n	0.002	0.000	0.000
L-f	0.002	0.000	0.000

Table S12b: Electricity consumption, electricity generation, and natural gas consumption intensity by treatment train (best practice) (Configuration B (BP) method [11])

Treatment train	**Electricity consumption intensity [kWh/m^3]**	**Electricity generation intensity [kWh/m^3]**	**Natural gas consumption intensity [MJ/m^3]**

*A1	0.230	0.000	0.000
*A1e	0.230	0.214	0.000
*A2	0.263	0.000	0.000
*A5	0.300	0.000	1.12
*A6	0.265	0.000	0.157
A4	0.271	0.000	0.157
*C1	0.209	0.000	0.000
E3	0.364	0.000	0.157
*E3	0.342	0.000	0.157
*E1	0.284	0.000	0.000
*G1	0.299	0.000	0.000
*G1e	0.299	0.207	0.000
*G1-p	0.291	0.000	0.000
F3	0.384	0.000	0.157
F4	0.356	0.000	0.157
*D1	0.744	0.000	0.000
*D3	0.814	0.000	0.157
*B1	0.304	0.000	0.000
*A3	0.304	0.000	0.157
*A4	0.233	0.000	0.157
A1	0.269	0.000	0.000
A1e	0.269	0.168	0.000
A3	0.327	0.000	0.157
A5	0.337	0.000	1.12
A6	0.302	0.000	0.157
*C1E	0.209	0.165	0.000
*C3	0.276	0.000	0.157
*C4	0.211	0.000	0.157
*C5	0.278	0.000	1.12
*C6	0.243	0.000	0.157
*E1e	0.284	0.203	0.000

*G3	0.377	0.000	0.157
*G4	0.300	0.000	0.157
*G5	0.367	0.000	1.12
*G6	0.332	0.000	0.157
*G1e-p	0.291	0.200	0.000
F1	0.356	0.000	0.000
F1e	0.356	0.117	0.000
F5	0.424	0.000	1.12
F6	0.389	0.000	0.157
*D1e	0.744	0.234	0.000
*B1e	0.304	0.218	0.000
*B3	0.380	0.000	0.157
*B4	0.306	0.000	0.157
*B5	0.373	0.000	1.12
*B6	0.338	0.000	0.157
L-u	0.003	0.000	0.000
L-a	0.004	0.000	0.000
L-n	0.002	0.000	0.000
L-f	0.002	0.000	0.000

Table S13: Electricity generation intensity by prime mover (Biogas B method [12])

Prime mover	**Electricity generation intensity [kWh/m^3]**
Reciprocating engine	0.146
Microturbine	0.130
Fuel cell	0.212

Table S14: Summary of biogas data sources

Source	**Biogas dataset**	**Reporting year(s)**	**Notes**
U.S. Environmental Protection Agency [7, 13, 14, 15]	Clean Watersheds Needs Survey	2004, 2008, 2012, and 2022	2004-2012 releases do not specify whether biogas is used for electricity production; not used for

			electricity generation baseline estimations
U.S. Department of Energy [16]	Combined Heat and Power Installation Database	1961-2025	Specifies whether biogas is used for electricity production and prime mover type; used for Configuration A and B, Process A and B, and Biogas A, B, and C methods
Water Environment Federation [17]	Water Resource Recovery Facilities Biogas Database	2013	Specifies whether biogas is used for electricity production and prime mover type; used for Configuration A and B, Process A and B, and Biogas A, B, and C methods. Assumed that electricity-producing facilities identified in this dataset were producing electricity in 2012; note that this dataset was accessed before a website update that removed the option for direct downloads
U.S. Energy Information Administration [18]	Survey Form EIA-923	2012	Only applicable for large facilities, but specifies whether biogas is used for electricity production and prime mover; used for Configuration A and B, Process A and B, and Biogas A, B, and C methods

Table S15: Percent of reported energy consumption intensity by facility characteristics

			Percent of reported energy consumption intensity [%]				
		Number of cities	**Configuration A (T)**	**Configuration A (BP)**	**Configuration B (T)**	**Configuration B (BP)**	**Regression**
Flow rate [10^3 m^3/day]	43.8-126	19	**117**	78	122	81	300
	126-274	16	112	75	**107**	70	239
	274+	27	95	63	**101**	67	209
Effluent treatment level	Primary	1	245	**168**	245	**168**	221
	Secondary	22	124	84	133	**89**	275

	Advanced	39	**93**	61	**93**	60	242
	Multiple	4	79	52	**81**	52	201
Latitude	< 35°	15	127	84	131	**87**	289
	35-42.5°	37	86	57	**89**	59	217
	> 42.5°	14	132	**87**	133	**87**	297

*Note, bolded values represent the most accurate estimation method for the given subset of cities in the validation set.

Table S16: Percent of reported electricity generation intensity by facility characteristics

			Percent of reported electricity generation intensity [%]						
		Number of cities	**Configuration A (T)**	**Configuration A (BP)**	**Configuration B (T)**	**Configuration B (BP)**	**Biogas A**	**Biogas B**	**Biogas C**
Flow rate [10^3 m^3/day]	43.8-126	2	22	28	57	64	**98**	110	335
	126-274	6	62	82	**94**	122	89	98	306
	274+	12	15	20	75	**99**	94	106	323
Effluent treatment level	Secondary	7	14	17	66	**88**	72	80	35
	Advanced	13	39	51	87	113	**109**	120	29
Latitude	< 35°	3	83	**107**	162	212	136	147	1,390
	35-42.5°	12	6	8	65	85	**99**	113	4,070
	> 42.5°	6	46	61	84	**109**	78	85	1,610

*Note, bolded values represent the most accurate estimation method for the given subset of cities in the validation set.

Table S17: p-values for Levene's test on electricity consumption estimation methods

Method	**Flow**	**Effluent A**	**Effluent B**	**Configuration A (T)**	**Configuration A (BP)**	**Configuration B (T)**	**Configuration B (BP)**	**Process A**	**Process B**
Flow	N/A	0.000*	0.204	0.795	0.000*	0.810	0.000*	0.000*	0.158*
Effluent A	0.000*	N/A	0.000*	0.000*	0.000*	0.000*	0.000*	0.020*	0.037*
Effluent B	0.204	0.000*	N/A	0.104	0.000*	0.263	0.000*	0.000*	0.014*
Configuration A (T)	0.795	0.000*	0.104	N/A	0.000*	0.591	0.000*	0.0000*	0.210
Configuration A (BP)	0.000*	0.000*	0.000*	0.000*	N/A	0.000*	0.110	0.000*	0.000*
Configuration B (T)	0.810	0.000*	0.263	0.591	0.000*	N/A	0.000*	0.000*	0.096*

Configuration B (BP)	0.000*	0.000*	0.000*	0.000*	0.110	0.000*	N/A	0.000*	0.000*
Process A	0.000*	0.012*	0.000*	0.000*	0.000*	0.000*	0.000*	N/A	0.000*
Process B	0.158	0.037*	0.014*	0.210	0.000*	0.096*	0.000*	0.001*	N/A

*Note, p-values with a * indicate that, at the 10% significance level, the two methods have a statistically significant difference in variance of mean absolute percent error; in this instance, a statistically significant difference indicates that the methods are not equally sensitive to changes in the validation set.

Table S18: Estimated U.S. electricity consumption, energy consumption, and electricity generation by water resource recovery facilities in 2012

Method	National electricity consumption [TWh/year]	National energy consumption [TJ/year]	National electricity generation [TWh/year]
Flow	24.4	N/A	N/A
Effluent A	29.0*	N/A	N/A
Effluent B	19.5	N/A	N/A
Configuration A (T)	10.6*	46.5 x 10^3*	0.387*
Configuration B (T)	17.5	77.1 x 10^3	0.896*
Configuration A (BP)	6.97*	31.0 x 10^3*	0.505*
Configuration B (BP)	11.1	50.9 x 10^3	1.15*
Process A	36.0*	N/A	N/A
Process B	29.7*	N/A	N/A
Biogas A	N/A	N/A	1.24*
Biogas B	N/A	N/A	1.42*
Biogas C	N/A	N/A	4.23*
Regression	N/A	221 x 10^3*	N/A
*Excluded from the final range of national energy use and potential estimates.			

Table S19: Estimated U.S. electricity consumption, energy consumption, and electricity generation by water resource recovery facilities in 2042

Method	National electricity consumption [TWh/year]	National energy consumption [TJ/year]	National electricity generation [TWh/year]
Flow	39.6	N/A	N/A
Effluent A	49.9*	N/A	N/A
Effluent B	33.6	N/A	N/A

Configuration A (T)	17.0*	71.6×10^{3}*	0.824*
Configuration B (T)	27.9	123×10^{3}	3.07*
Configuration A (BP)	10.9*	47.6×10^{3}*	1.07*
Configuration B (BP)	16.5	81.1×10^{3}	3.94*
Process A	60.4*	N/A	N/A
Process B	48.8*	N/A	N/A
Biogas A	N/A	N/A	2.62*
Biogas B	N/A	N/A	2.96*
Biogas C	N/A	N/A	8.97*
Regression	N/A	304×10^{3}*	N/A
*Excluded from the final range of national energy use and potential estimates.			

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