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LONG-TERM ASSESSMENT OF ELECTRICITY RECOVERY RELATIVE TO WASTEWATER COD ENERGY POTENTIAL IN AN ANAEROBIC DIGESTION AND CHP SYSTEM

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Abstract:
This paper assesses electricity recovery from biogas relative to the theoretical chemical energy potential of wastewater COD using long-term operational data from a municipal wastewater treatment plant collected between 2013 and 2024. The analysis covered biogas production and utilization pathways, electricity generation, HHV-based CHP electrical efficiency, operational availability and load, and the theoretical COD energy potential calculated using an energy equivalent of 3.9 kWh/kg COD. Biogas volumes were converted to normal conditions, and chemical energy was determined from methane content and the estimated higher heating value. Electricity recovery relative to the theoretical COD energy potential was decomposed into three components: the ratio of biogas chemical energy to COD energy potential, the share of biogas energy directed to CHP, and HHV-based CHP electrical efficiency. HHV-based CHP electrical efficiency remained relatively stable at 26.2-31.2%, whereas greater variability occurred at earlier stages of the conversion chain. Electricity recovery relative to COD energy potential ranged from 4.51% to 13.07%. In 2020, when the lowest recovery was recorded, approximately 44% of biogas chemical energy was directed to CHP and about 42% was flared. In contrast, in 2017 the lowest HHV-based CHP electrical efficiency coincided with a high share of biogas directed to cogeneration and substantially higher electricity recovery. The results show that reduced electricity recovery may arise at different stages of the COD-biogas-CHP-electricity chain and cannot be assessed solely from biogas production or HHV-based CHP electrical efficiency. The proposed decomposition may support operational management and modernization planning. Because continuous annual heat-use measurements were unavailable, the analysis concerns electricity recovery and does not represent total energy recovery from wastewater.

Key words: anaerobic digestion, biogas, COD energy potential, combined heat and power, electricity recovery

INTRODUCTION

Municipal wastewater treatment plants are major energy consumers but also contain organic matter that can support energy recovery [1, 2, 3, 4, 5, 6]. In plants with anaerobic digestion, biogas can be used in CHP systems [7, 8, 9, 10, 11], but overall performance depends on the complete COD-biogas-CHP-electricity chain.

Previous studies have examined anaerobic digestion, biogas enhancement, CHP performance, treatment energy demand and energy-neutrality potential [1, 2, 3, 9-20]. However, long-term full-scale analyses quantifying how the COD-biogas-CHP-electricity chain determines electricity recovery remain limited. This study therefore assessed 2013-2024 operational data and decomposed electricity recovery

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relative to theoretical COD energy potential into the biogas-energy-to-COD ratio, CHP biogas share and HHV-based CHP electrical efficiency.

LITERATURE REVIEW

Anaerobic digestion and CHP use of sewage-sludge biogas are established energy-recovery routes [7, 8, 9, 11,14,15]. Energy performance depends on plant configuration, treatment processes and equipment efficiency [1, 2, 3, 15, 16, 17, 18]. Wastewater chemical energy passes through organic-matter capture, sludge production, digestion, biogas production, gas utilization and final conversion [5, 6, 19], so losses at any stage can reduce electricity recovery [9, 10, 14, 15, 20]. However, the relative contribution of these stages to interannual changes in electricity recovery is rarely quantified using long-term full-scale data. Figure 1 summarizes the conversion chain and its main loss points.

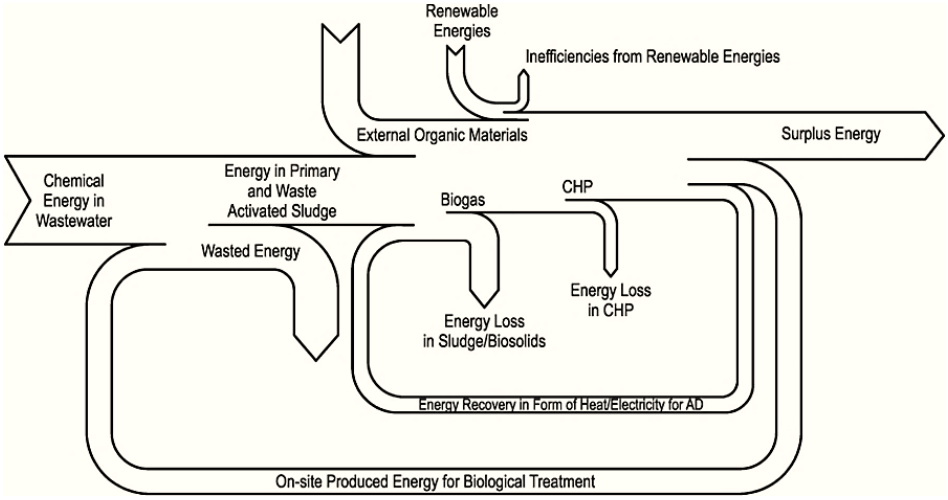


Fig. 1 Energy flows and losses in a municipal wastewater treatment plant with anaerobic digestion and CHP
Alt-text: *Energy flows from wastewater to digestion, biogas and CHP, with losses at each stage.*
Source: Reproduced from Maktabifard et al. [1], Fig. 1, under the CC BY 4.0 licence.

MATERIALS AND METHODS

Characteristics of the Study Facility

The study was conducted at the Rybnik-Orzepowice municipal wastewater treatment plant, a mechanical-biological facility with nutrient removal and mesophilic anaerobic sludge digestion [21, 22], supplemented by company energy-audit data [23]. The system comprised two closed digesters and one 190 kW PETRA 250C CHP unit; biogas was directed to CHP, boilers or the flare, and the same unit was analysed throughout 2013-2024.

Operational data for 2013-2024 came from SCADA, dedicated meters, laboratory records and operating reports. Gas meters recorded biogas production and flows to CHP, boilers and the flare, while gross CHP electricity was measured at the generator output. Annual COD loads were calculated from influent COD concentrations and wastewater volumes; methane content and CHP operating parameters came from plant monitoring and records.

Annual aggregates were validated by comparing total biogas production with CHP, boiler and flare streams (residuals ≤1 MWh) and by cross-checking CHP electricity against operating time, average power and independent meter reports where available. Full retrospective uncertainty propagation was not possible; sensitivity analyses were therefore used to test robustness.

Scope of the Analysed Data

The scope of operational data is summarized in Table 1.

Table 1

Operational data used in the analysis

Data category	Scope
Analysis period	2013-2024
Biogas production	Nm³/year
Biogas consumption in the CHP system	Nm³/year
Biogas consumption in boilers	Nm³/year
Biogas flared	Nm³/year
Electricity generation in the CHP system	MWh/year
HHV-based CHP electrical efficiency	%
CHP unit availability	%
Operating time and downtime	%
COD load	kg/year
COD energy potential	MWh/year
Biogas methane content	%
Average CHP unit load during operation	%

Energy Calculation Methodology

Biogas volumes recorded under operating conditions were converted to normal conditions according to:

$$V_N = V \frac{p}{p_N} \frac{T_N}{T}, \tag{1}$$

where:

V_N and V are the biogas volumes at normal and measured conditions, respectively,

p and T are the absolute pressure and absolute temperature,

p_N = 1013.25 hPa,

T_N = 273.15 K denote normal conditions.

The annual higher heating value of biogas was estimated from methane content as:

$$H_{s,y} \approx \frac{CH_{4,y}}{100} \cdot 39.8, \tag{2}$$

where:

$H_{s,y}$ is the annual biogas higher heating value [MJ/Nm³],

$CH_{4,y}$ is the annual methane content [%],

39.8 MJ/Nm³ was adopted for pure methane.

The chemical energy of biogas was then calculated as:

$$E_{bg} = \frac{V_N H_s}{3600}, \tag{3}$$

where:

E_{bg} is biogas chemical energy [MWh],

V_N is the normalized biogas volume [Nm³],

H_s is its higher heating value [MJ/Nm³],

3600 converts MJ to MWh.

Annual methane content was available for 2015-2024 (61-70%); 60% was adopted for 2013-2014. Dry gas was assumed (estimated moisture effect: 1-3%). Biogas energy was allocated to CHP, boilers and flaring. Sensitivity scenarios of 55% and 65% CH_4 were tested for 2013-2014 with measured data unchanged; these were not treated as historical estimates.

The electrical efficiency of the CHP unit was calculated as:

$$\eta_{el} = \frac{E_{el,CHP}}{E_{bg,CHP}}, \tag{4}$$

where:
$E_{el,CHP}$ is annual CHP electricity generation,
$E_{bg,CHP}$ is the chemical energy of biogas used in CHP [MWh].
Because $E_{bg,CHP}$ was calculated using the higher heating value (HHV), η_{el} represents HHV-based CHP electrical efficiency throughout this study. The dimensionless ratio was reported as a percentage and should not be directly compared with electrical-efficiency values reported on an LHV basis.
CHP availability was calculated as:

$$A = \frac{t_{op}}{t_{cal}} \cdot 100\%, \tag{5}$$

where:
t_{op} is CHP operating time,
t_{cal} is total calendar time.
Average CHP load during operation was calculated as:

$$L = \frac{P_{avg,op}}{P_{nom}} \cdot 100\%, \tag{6}$$

where:
$P_{avg,op}$ is average electrical power during CHP operation,
P_{nom} = 190 kW is nominal electrical output.
Annual nominal capacity utilization was calculated as:

$$CF = \frac{P_{avg,cal}}{P_{nom}} \cdot 100\%, \tag{7}$$

where:
$P_{avg,cal}$ is average electrical power over the entire period, including downtime.
CF was treated as a composite indicator of availability and operating load rather than as an independent measure of availability.

$$CF \approx \frac{A \cdot L}{100}. \tag{8}$$

For percentage values of A and L, their relationship to CF is approximated by Eq. (8).
The theoretical COD energy potential was calculated as:

$$E_{COD} = \frac{L_{COD} \cdot 3.9}{1000}, \tag{9}$$

where:
L_{COD} is the annual influent COD load [kg/year],
E_{COD} is the theoretical COD energy potential [MWh/year].
The value represents the chemical energy of raw influent COD, not the fraction actually available for anaerobic digestion.
Electricity recovery relative to the COD energy potential was calculated as:

$$R_{el,COD} = \frac{E_{el,CHP}}{E_{COD}}, \tag{10}$$

where:
$R_{el,COD}$ is the dimensionless ratio of CHP electricity generation to the theoretical COD energy potential and was reported as a percentage.
It represents electricity recovery, not total energy recovery from wastewater.
Sensitivity was tested using 3.51 and 4.29 kWh/kg COD (±10% around 3.9), with measured operational data unchanged.
Electricity recovery was decomposed into three dimensionless components:

$$\frac{E_{el,CHP}}{E_{COD}} = \frac{E_{bg,total}}{E_{COD}} \cdot \frac{E_{bg,CHP}}{E_{bg,total}} \cdot \frac{E_{el,CHP}}{E_{bg,CHP}}, \tag{11}$$

$$R_{el,COD} = Y_{bg,COD} \cdot U_{CHP} \cdot \eta_{el}, \tag{12}$$

where:
$Y_{bg,COD} = E_{bg,total}/E_{COD}$ is the biogas-energy-to-COD ratio,
$U_{CHP} = E_{bg,CHP}/E_{bg,total}$ is the share of biogas energy directed to CHP,
$\eta_{el} = E_{el,CHP}/E_{bg,CHP}$ is HHV-based CHP electrical efficiency.
All ratios were reported as percentages.
A logarithmic decomposition relative to 2013, the year with the highest $R_{el,COD}$, was used to identify the dominant limiting component:

$$\ln\left(\frac{R_y}{R_{ref}}\right) = \ln\left(\frac{Y_y}{Y_{ref}}\right) + \ln\left(\frac{U_y}{U_{ref}}\right) + ln\left(\frac{\eta_y}{\eta_{ref}}\right), \quad (13)$$

where:
R, Y, U and η denote $R_{el,COD}$, $Y_{bg,COD}$, U_{CHP} and η_{el}, respectively.
The component with the largest negative logarithmic contribution was defined as the dominant limiting component relative to 2013. This comparison does not imply causality.
The percentage contribution of each component to the total relative change in $R_{el,COD}$ was calculated as:

$$C_{i,y} = \frac{ln(X_{i,y}/X_{i,ref})}{ln(R_y/R_{ref})} \cdot 100\%, \quad (14)$$

where:
$C_{i,y}$ is the percentage contribution of component i in year y,
X_i denotes Y, U, or η.
Positive contribution values indicate components acting in the same direction as the total change in $R_{el,COD}$, whereas negative values indicate an offsetting effect. The component contributions sum to 100%, apart from rounding.
The remaining biogas-utilization shares were:

$$U_{boiler} = \frac{E_{bg,boiler}}{E_{bg,total}}. \quad (15)$$

The flaring share was:

$$F_{flare} = \frac{E_{bg,flare}}{E_{bg,total}}, \quad (16)$$

where:
U_{boiler} and F_{flare} denote the boiler and flaring shares, respectively.
The utilization balance satisfies:

$$U_{CHP} + U_{boiler} + F_{flare} = 1. \quad (17)$$

The shares sum to 1, or 100% when expressed as percentages. $Y_{bg,COD}$ was treated as an energy-balance indicator and not as anaerobic-digestion efficiency.
Thermal energy was excluded from $R_{el,COD}$ because continuous annual heat-use data were unavailable.

RESULTS

Biogas Production and Utilization

Biogas production and CHP use did not vary proportionally (Table 2, Figure 2).

Table 2

Annual biogas energy balance, 2013-2024

Year	Total energy available from biogas [MWh]	Energy utilized in boilers [MWh]	Energy utilized in the CHP system [MWh]	Energy lost through flaring [MWh]
2013*	7308	483	4747	2078
2014*	7428	435	4563	2430
2015	6784	630	4212	1942
2016	6492	1089	4079	1324
2017	6969	901	5204	864
2018	7561	798	5052	1711
2019	8318	1113	4676	2529
2020	8686	1162	3839	3685
2021	8228	750	5355	2123
2022	8420	1210	4473	2737
2023	7410	1015	4010	2385
2024	9115	913	4931	3272

** 2013-2014: methane content assumed at 60% due to incomplete composition data*

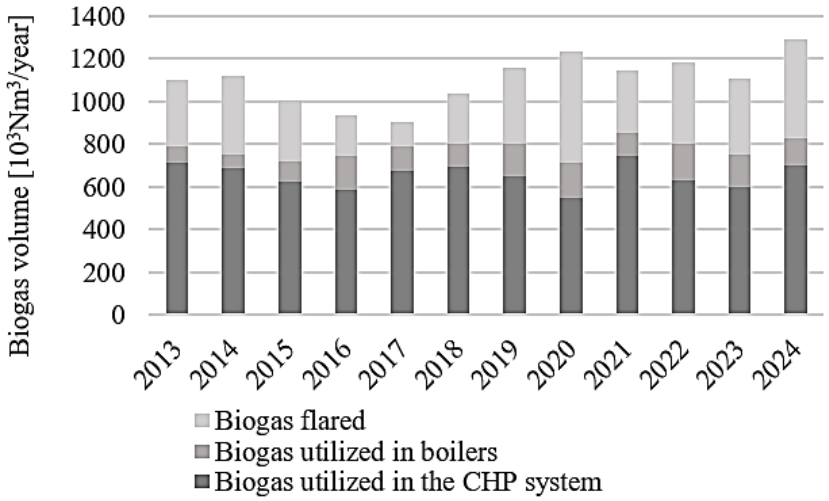


Fig. 2 Biogas utilization pathways at the Rybnik-Orzepowice wastewater treatment plant, 2013-2024
Alt-text: *Biogas use in CHP, boilers and flaring varied between 2013 and 2024.*

In 2017, 5.20 of 6.97 GWh was directed to CHP and 0.86 GWh flared, whereas in 2020 only 3.84 of 8.69 GWh reached CHP and 3.69 GWh was flared. Biogas allocation, not production alone, therefore affected electricity-generation potential; annual energy-balance residuals were ≤ 1 MWh due to rounding.

Performance of the Combined Heat and Power System

HHV-based CHP electrical efficiency varied from 26.17% to 31.20%, while availability and operating load ranged from 70.90% to 97.15% and 85.7% to 94.6%, respectively (Tables 3-5).

Table 3

Annual HHV-based CHP electrical efficiency, 2013-2024

Year	Electricity generated by the CHP unit $E_{el,CHP}^{(year)}$ [MWh]	Chemical energy of biogas utilized in the CHP system $E_{bg,CHP}^{(year)}$ [MWh]	HHV-based electrical efficiency $\eta_{el(year)}$ [%]
2013*	1480.97	4747	**31.20**
2014*	1406.82	4563	**30.83**
2015	1286.44	4212	**30.55**
2016	1161.51	4079	**28.47**
2017	1361.87	5204	**26.17**
2018	1376.73	5052	**27.25**
2019	1298.32	4676	**27.76**
2020	1088.95	3839	**28.37**
2021	1526.07	5355	**28.50**
2022	1284.17	4473	**28.71**
2023	1202.48	4010	**29.99**
2024	1422.79	4931	**28.86**

** 2013-2014: methane content assumed at 60% due to incomplete composition data*

Table 4

CHP electricity generation and capacity utilization, 2013-2024

Year	Electricity generation [MWh]	Average power during operation [kW]	Average power including downtime [kW]	Nominal capacity utilization [%]
2013	1480.97	176.28	169.04	88.97
2014	1406.82	176.34	160.67	84.56
2015	1286.44	173.89	147.13	77.43
2016	1161.51	162.77	132.44	69.71
2017	1361.87	164.77	156.18	82.20
2018	1376.73	176.38	157.45	82.87
2019	1298.32	179.65	148.21	78.01
2020	1088.95	175.49	124.42	65.48
2021	1526.07	179.80	174.67	91.93
2022	1284.17	172.99	146.82	77.27
2023	1202.48	170.17	137.53	72.38
2024	1422.79	179.20	161.90	85.20

Table 5

CHP operating parameters, 2013-2024

Year	CHP unit operating time [%]	CHP unit downtime [%]	Average unit load during operation [%]
2013	95.89	4.11	92.8
2014	91.11	8.89	92.8
2015	84.61	15.39	91.5
2016	81.37	18.63	85.7
2017	94.78	5.22	86.7
2018	89.27	10.73	92.8
2019	82.50	17.50	94.6
2020	70.90	29.10	92.4
2021	97.15	2.85	94.6
2022	84.87	15.13	91.0
2023	80.82	19.18	89.6
2024	90.30	9.70	94.3

Figure 3 shows annual nominal capacity utilization, ranging from 65.48% to 91.93%.

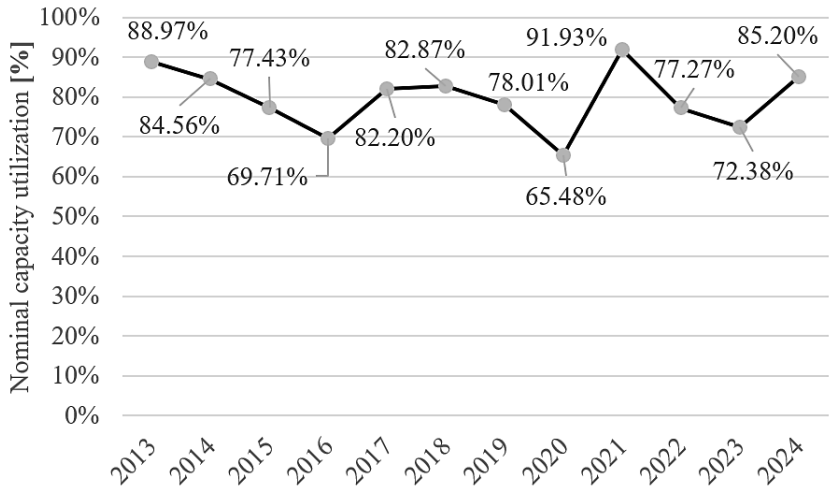


Fig. 3 Annual nominal CHP capacity utilization at the Rybnik-Orzepowice wastewater treatment plant, 2013-2024

Alt-text: *Annual CHP capacity utilization ranged from 65.48% to 91.93%.*

Electricity Recovery Relative to the Theoretical COD Energy Potential

The theoretical COD energy potential ranged from 11.33 to 24.65 GWh/year, compared with 1.09-1.53 GWh/year of CHP electricity, corresponding to electricity recovery of 4.51-13.07% (Table 6; Figure 4). For 3.51 and 4.29 kWh/kg COD, recovery ranged from 5.01-14.52% and 4.10-11.88%, respectively, while 2013 remained highest and 2020 lowest.

Table 6

COD load, energy potential and CHP electricity recovery, 2013-2024

Year	Average COD concentration [mg/L]	COD load [kg/year]	COD energy potential [MWh/year]	Electricity generated by the CHP system [MWh/year]	Share of electricity recovery relative to COD energy potential [%]
2013	789.75	2 905 111	11 329.93	1 480.97	13.07
2014	919.00	4 612 472	17 988.64	1 406.82	7.82
2015	886.79	5 485 881	21 394.94	1 286.44	6.01
2016	938.95	5 617 076	21 906.60	1 161.51	5.30
2017	621.63	3 107 729	12 120.14	1 361.87	11.24
2018	576.50	3 678 520	14 346.23	1 376.73	9.60
2019	767.75	5 019 012	19 574.15	1 298.32	6.63
2020	862.54	6 186 223	24 126.27	1 088.95	4.51
2021	796.92	5 982 295	23 330.95	1 526.07	6.54
2022	721.38	4 999 322	19 497.36	1 284.17	6.59
2023	810.50	5 894 815	22 989.78	1 202.48	5.23
2024	860.92	6 321 443	24 653.63	1 422.79	5.77

Source: own elaboration from PWiK Rybnik data; COD energy potential calculated using [5, 6].

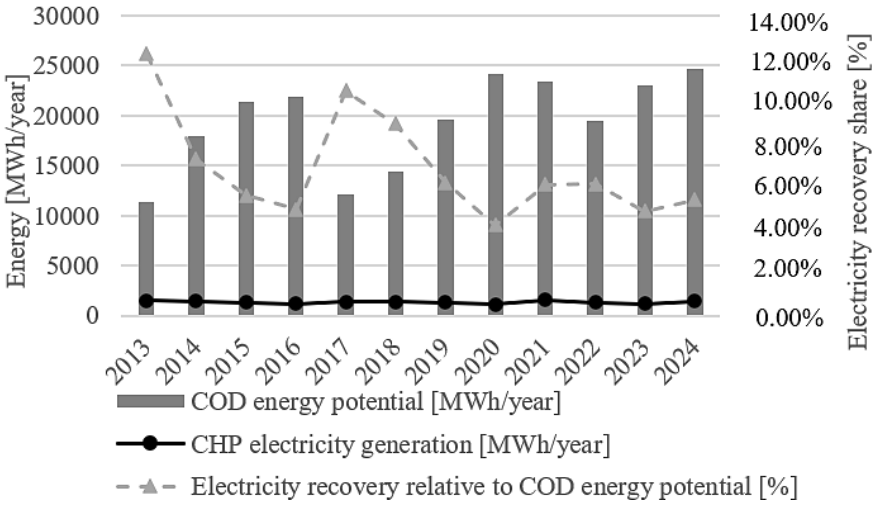


Fig. 4 COD energy potential, CHP electricity generation and electricity recovery at the Rybnik-Orzepowice wastewater treatment plant, 2013-2024

Alt-text: *COD energy potential exceeded CHP electricity generation; recovery ranged from 4.5% to 13.1%.*
Source: own elaboration from PWiK Rybnik data; COD energy potential calculated using [5, 6].

Table 7 decomposes $R_{el,COD}$, highest in 2013 (13.07%) and lowest in 2020 (4.51%), into $Y_{bg,COD}$, U_{CHP} and η_{el}.

Table 7

Decomposition of electricity recovery relative to COD energy potential, 2013-2024

Year	Ybg, COD [%]	CHP share [%]	Boiler share [%]	Flaring share [%]	ηel (HHV-based) [%]	$R_{el,COD}$ [%]
2013*	64.50	64.96	6.61	28.43	31.20	13.07
2014*	41.29	61.42	5.86	32.72	30.83	7.82
2015	31.71	62.08	9.29	28.63	30.55	6.01
2016	29.63	62.84	16.77	20.39	28.47	5.30
2017	57.50	74.68	12.93	12.39	26.17	11.24
2018	52.70	66.82	10.56	22.62	27.25	9.60
2019	42.49	56.22	13.38	30.40	27.76	6.63
2020	**36.00**	**44.20**	**13.38**	**42.43**	**28.37**	**4.51**
2021	35.27	65.09	9.11	25.80	28.50	6.54
2022	43.18	53.12	14.37	32.51	28.71	6.59
2023	32.23	54.12	13.70	32.18	29.99	5.23
2024	36.97	54.09	10.01	35.90	28.86	5.77

** 2013-2014: methane content assumed at 60% due to incomplete composition data.*

In 2020, the lowest $R_{el,COD}$ (4.51%) coincided with $Y_{bg,COD}$ of 36.00%, the lowest CHP share (44.20%) and availability (70.90%), and the highest flaring share (42.43%). Relative to 2013, logarithmic decomposition using Eq. (14) attributed 54.8% of the decline to $Y_{bg,COD}$, 36.2% to CHP allocation and 8.9% to η_{el}, identifying $Y_{bg,COD}$ as the dominant limiting component.

For 2013-2014, varying the assumed methane content from 55% to 65% changed $Y_{bg,COD}$ and HHV-based η_{el} but not $R_{el,COD}$, and did not change the 2020–2013 limiting-component identification. Table 7 also shows that HHV-based η_{el} alone does not determine electricity recovery: in 2017, its minimum value (26.17%) coincided with the highest CHP share (74.68%), the lowest flaring share (12.39%) and $R_{el,COD}$ of 11.24%.

DISCUSSION

The decomposition shows that electricity recovery should be assessed across the COD-biogas-CHP-electricity chain rather than through HHV-based CHP electrical efficiency alone. Its wider interannual variation (4.51-13.07%) compared with HHV-based CHP electrical efficiency (26.17-31.20%) indicates a greater role of earlier stages, particularly the biogas-energy-to-COD ratio and biogas allocation to CHP.

The 2020-2017 contrast highlights the importance of biogas allocation: flaring was 42.43% versus 12.39% and CHP shares 44.20% versus 74.68%, consistent with studies on effective biogas utilization [9, 10, 14, 15, 20]. Annual data cannot identify the operational causes of flaring. Capacity utilization was treated as a composite of availability and operating load rather than an independent CHP-performance indicator.

Consistent with integrated energy-management studies [1, 10, 11, 24, 25], the contribution of the present study is not the introduction of a new physical model of wastewater energy conversion, but the application of a transparent decomposition framework to a 12-year full-scale operational data set. The decomposition should therefore be regarded as a comparative diagnostic framework that indicates which component merits further investigation, rather than as a method for identifying the underlying technical or operational cause.

The main limitations of the study arise from the single-plant design and the use of annual aggregated operational data. Therefore, the results should be interpreted as a long-term case-study assessment rather than as universally applicable performance benchmarks. The theoretical influent COD energy potential does not represent the biodegradable COD fraction actually available for anaerobic digestion, and full retrospective propagation of instrument-specific measurement uncertainty was not possible. Measurement uncertainty in influent COD load, biogas flow and methane content may propagate to the calculated biogas-energy-to-COD ratio, while uncertainty in electricity generation and biogas use in CHP may affect the calculated HHV-based CHP electrical efficiency. In addition, annual aggregation does not allow short-term operational events responsible for changes in biogas allocation, flaring or CHP availability to be identified. Continuous annual heat-use measurements were also unavailable, so the analysis concerns electricity recovery rather than total useful-energy recovery from wastewater. Nevertheless, the sensitivity analyses showed that the principal interpretation of the interannual differences remained unchanged under the tested assumptions.

CONCLUSIONS

The analysis of data from 2013-2024 showed that variability in electricity recovery was more strongly associated with the stages preceding final conversion in the CHP system than with changes in HHV-based CHP electrical efficiency itself. Decomposition of the decline in electricity recovery in 2020 relative to 2013 indicated that 54.8% of the change was related to the biogas-energy-to-COD ratio, 36.2% to the share of biogas directed to CHP, and 8.9% to HHV-based CHP electrical efficiency. These results indicate that electricity recovery should be assessed across the entire COD-biogas-CHP-electricity chain rather than on the basis of biogas production or HHV-based CHP electrical efficiency alone.

The applied decomposition can support comparative analysis of the individual stages of this chain and indicate which area requires more detailed assessment, but it should not be regarded as a method for identifying direct technical or operational causes. The findings should be interpreted as a single-plant case study based on annual aggregated data. Further research should combine this approach with higher-resolution process data and a more detailed characterization of COD, particularly the biodegradable fraction actually available for anaerobic digestion. This could provide a clearer link between changes in substrate energy potential, biogas utilization and operational losses such as increased flaring or reduced CHP utilization.

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