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Research Paper

Assessment of whole-site methane emissions from anaerobic digestion plants: Towards establishing emission factors for various plant configurations

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ABSTRACT

This study examines methane (CH_4) emission factors from biogas and wastewater treatment plants, based on primary and secondary data collected from 109 facilities. Primary emission data were measured at 19 facilities representing prevalent plant configurations across Europe. Statistical analysis highlights two categorical variables, namely primary feedstock and plant size, expressed as CH_4 production (≤ 250 kg h^{-1}: small and medium-sized plants, > 250 kg h^{-1}: large plants), each of which has a significant impact on whole-site CH_4 emissions. Additionally, digestate storage (gastight vs. not-gastight) has a meaningful effect when considering CH_4 production as a continuous variable in the statistical analysis.

Our results indicate that wastewater treatment plants have the highest average CH_4 losses (7.0 % of CH_4 produced, n = 31 or 0.10 kg population equivalent (PE)$^{-1}$ yr^{-1}, n = 28), followed by manure-based plants (3.7 %, n = 49), biowaste treatment facilities (2.8 %, n = 11) and energy crop-processing plants (1.9 %, n = 14). Furthermore, small and medium-sized plants have elevated emissions (5.6 %, n = 67) compared to larger counterparts (2.2 %, n = 42), primarily attributed to the absence of gastight digestate storage. Emissions tend to be lower with gastight digestate storage (2.7 %, n = 61) than not-gastight storage options (6.2 %, n = 48).

Emission factors were determined for normal operating conditions, with a further investigation into other-than-normal operating conditions revealing temporal or constant emission peaks in eight out of 19 facilities. These peaks, suggesting potential areas for targeted mitigation strategies, were attributed to pressure relief valves, flare ignition problems and major leakages.

1. Introduction

Biogas and biomethane production from organic feedstock, such as agricultural residues, biowaste, livestock manure and sewage sludge, plays a crucial role in renewable energy and waste management. However, anaerobic digestion (AD) facilities can also be a source of methane (CH_4) emissions, which in turn can undermine their ecological benefits (Liebetrau et al., 2017; Scheutz & Fredenslund, 2019). Previous studies, such as those by Wechselberger et al. (2023), Bakkaloglu et al. (2022), Parravicini et al. (2022) and Song et al. (2023) provide a general overview of potential sources and leakages from these facilities.

The political landscape surrounding CH_4 emissions emphasises the

Abbreviations: AD, anaerobic digestion; ANOVA, Analysis of Variance; BAT, best available technology; bLS, backward Lagrangian stochastic; C_2H_2, acetylene; CH_4, methane; CHP, combined heat and power; EFs, emission factors; EU, European Union; GHG, greenhouse gas; IDM, inverse dispersion modelling method; IPCC, Intergovernmental Panel on Climate Change; OTNOC, other-than-normal operating conditions; PE, population equivalent; PRVs, pressure relief valves; RED, Renewable Energy Directive; SD, standard deviation; SI, supplementary information; TDM, tracer gas dispersion method; WWTPs, wastewater treatment plants.

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need for measuring, reporting and mitigating emissions from various sources, including biogas production and wastewater treatment. This is driven by the recognition of CH_4 as a potent greenhouse gas (GHG) with a significant impact on global warming. The Global Methane Pledge, launched in 2021, underscores the international commitment to cut global CH_4 emissions by 30 % by 2030 (EC & United States of America, 2021). This pledge has garnered support from various countries and organisations, thus highlighting the urgent need to address CH_4 emissions. Furthermore, the European Union (EU) is at the forefront of these efforts, with its Methane Strategy marking a significant milestone by addressing CH_4 emissions across key sectors, including energy, agriculture and waste management (EC, 2020). In the energy sector, there have been policy proposals to tackle this issue. One such initiative is Regulation (EU) 2019/942 of the European Parliament and of the Council (2019), which seeks to harmonise monitoring, reporting and abatement rules on CH_4 emissions, including the production of biogas and biomethane. Additionally, some AD facilities (existing and future ones) must prove their GHG savings relative to fossil fuels according to the EU's Renewable Energy Directive (RED III) (Directive (EU) 2023/2413 of the European Parliament and Council, 2023), in order to minimise the risk of unsustainable bioenergy production. Furthermore, the proposal to revise the EU's Urban Wastewater Treatment Directive (Council Directive 91/271/EEC, 1991) addresses GHG emissions, including CH_4, for the first time.

Recent advancements in measurement methods have enabled more precise quantification of whole-site emissions from AD facilities including wastewater treatment plants (WWTPs) which exhibit sewage sludge as primary feedstock (Clauß et al., 2019; Feitz et al., 2018; Fredenslund et al., 2019; Hrad et al., 2022; Mønster et al., 2014; Reinelt et al., 2017). Quantification approaches have mainly included the inverse dispersion modelling method (IDM) (Bühler et al., 2022; Hrad et al., 2021) or the tracer gas dispersion method (TDM) (Delre et al., 2017; Fredenslund et al., 2019, 2023; Yoshida et al., 2014). IDM relies on measuring CH_4 concentrations at upwind and downwind locations, along with atmospheric conditions, and then using a dispersion model to calculate the emissions. TDM involves releasing a tracer gas at a known rate within the source, combined with downwind measurements of atmospheric concentrations of CH_4 and tracer gas.

Initial emission factors (EFs) for AD facilities have been established primarily through production-weighted CH_4 emission averages, with variations observed based on the origin of the feedstock and plant size (Bakkaloglu et al., 2021; Fredenslund et al., 2023; Scheutz & Fredenslund, 2019). Agricultural facilities typically experienced lower CH_4 losses than WWTPs, while smaller facilities emitted a higher proportion of their produced CH_4 compared to larger plants.

However, recent advancements in on-site measurements have revealed notable differences in EFs, depending on technology (e.g., gastight vs. not-gastight coverage of digestate) and biogas utilisation (e.g., combined heat and power vs. biogas upgrading) (Kvist & Aryal, 2019; Wechselberger et al., 2023). Bakkaloglu et al. (2022) suggests that existing EFs for biogas and biomethane supply chains are likely underestimating CH_4 emissions, thereby highlighting the need for substantial refinements.

Furthermore, distinguishing between normal operations and other-than-normal operating conditions (OTNOC) is crucial, as OTNOC events can result in temporarily elevated emission peaks, thereby posing environmental and safety concerns (Baldé et al., 2022; Flesch et al., 2011; Reinelt & Liebetrau, 2020). These events can include the activation of pressure relief valves (PRVs), equipment failures (e.g., flare ignition problems), leakages or other unexpected incidents that require attention or corrective action to ensure safe and effective plant operation.

The diverse range of plant configurations, feedstock composition and operational characteristics across countries underscores the need to refine these EFs to enhance the accuracy and reliability of GHG inventories and to develop targeted strategies to mitigate CH_4 emissions effectively.

In this study, a systematic analysis was conducted to assess comprehensively CH_4 emissions from biogas production, including agricultural AD facilities, biowaste and WWTPs, with the aim to propose EFs applicable for various plant configurations based on the current state of knowledge. The analysis involved collecting and examining both primary and secondary data obtained from various sources. Primary data encompassed whole-site measurement by IDM and TDM, while secondary data included comprehensive literature reviews and existing datasets from relevant studies, including previously published studies by the authors.

Using statistical methodologies, this study seeks to discern patterns, trends and variations in CH_4 emissions across different types of AD facilities. The resulting EFs can foster a more transparent, accountable and adaptable approach to reporting CH_4 emissions, and by providing a reliable basis for reporting, the findings of this study can facilitate better comparability between different facilities and allow for the identification of outliers or areas for improvement in emission management strategies.

2. Material and methods

2.1. Investigated anaerobic digestion facilities

All AD facilities investigated in this study continuously processed feedstock without any post-rotting stages. We analysed 19 AD facilities, covering various prevalent plant configurations in Europe; differences between them related, for example, to feedstock, plant size and technology used, and most of them primarily utilised energy crops (n = 8) or biowaste (n = 6), usually in combination with manure as a co-substrate (share of manure: 4–50 % wet weight of total feedstock input). In addition, four facilities treated mainly manure and one plant sewage sludge (95,000 population equivalent (PE)), whilst all of them co-digested biowaste (8–30 % of total feedstock input) and/or energy crops (30 %).

Feedstock input ranged from 5,640 to 90,000 tons fresh matter per year, resulting in CH_4 production between 20 and 530 $kg\ h^{-1}$. Based on CH_4 production, we classified two AD facilities as small ($< 50\ kg\ h^{-1}$), most (n = 14) as medium-sized (≥ 50 to $\leq 250\ kg\ h^{-1}$) and three as large ($> 250\ kg\ h^{-1}$) (cf. Fredenslund et al., 2023).

Technological differences were related to the storage of digestate and utilisation of biogas. About half of the plants (ten out of 19) had integrated gastight storage for 100 % of their digestate, one of which (DE-08) implemented a gastight cover in between measurement campaigns. Eleven plants cogenerated electricity and heat as part of a major biogas utilisation strategy, and seven primarily upgraded biogas via chemical (amine) scrubbing, water scrubbing or pressure swing adsorption. Two plants utilised part of the biogas (88 % and 17 %, respectively) in off-site facilities. An overview of plant characteristics is given in Fig. 1, and further details are provided in Supplementary Information (SI) A and Table 2.

2.2. Measurement of whole-site methane emissions

Whole-site CH_4 emissions were determined by five measurement teams (A-E) using two ground-based remote sensing methods: IDM (cf. section 2.2.1; teams A-D) and TDM (cf. section 2.2.2; team E).

Measurements were performed between 2018 and 2021, mostly for several hours over one to four days per plant. At three plants, measured by team D, the campaigns took several weeks. An overview of the measurements, including information on the occurrence of OTNOC, is given in Table 1. Details on individual measurement days are provided in SI B.

2.2.1. Inverse dispersion modelling method

The IDM combines concentration measurements taken upwind

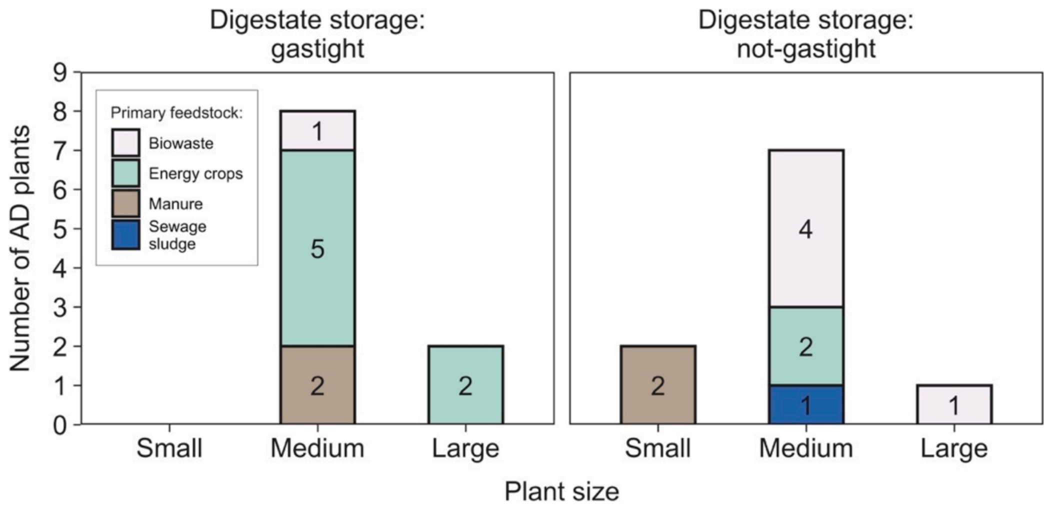

Fig. 1. Plant characteristics of 19 AD facilities, including plant size (small: CH_4 production < 50 kg h^{-1}, medium: ≥ 50 to ≤ 250 kg h^{-1}, large: > 250 kg h^{-1}; cf. Fredenslund et al., 2023), primary feedstock and digestate storage. One plant (DE-08) is counted twice, as a gastight cover was installed at the digestate storage tank in between measurement campaigns.

Table 1
Overview of CH_4 emission measurements at 19 AD facilities.

Plant no.	Plant ID	Measurement team	Measurement method[a]	Number of measurement days	Number of measurements (IDM: 10-min/30-min averages[b], TDM: plume traverses)	Share of measurements covering OTNOC[c] [% of total measurements]	Description of OTNOC
1	AT-01	A	IDM	2	44	100	Major leakage
2	AT-02	A	IDM	1	37	100	Major leakage and not specified OTNOC
3	AT-03	A	IDM	3	67	9	Activation of PRV[e]
4	AT-09	A	IDM	1	18	0	
5	AT-12	A	IDM	3	85	34	PRV maintenance
6	DE-01	B	IDM	2	23	0	
7	DE-07	C	IDM	3	59	0	
8[d]	DE-08–1	C	IDM	2	45	0	
8	DE-08–2	C	IDM	2	34	38	Flare ignition problems
9	DE-09	C	IDM	2	29	0	
10	DE-10	C	IDM	3	63	3	Activation of PRV
11	DE-11	C	IDM	3	49	0	
12	DE-12	C	IDM	3	62	0	
13	CH-01	D	IDM	85	388	0	
14	CH-02	D	IDM	64	275	100	Major leakage
15	CH-04	D	IDM	16	121	0	
16	SE-01	E	TDM	1	55	18	Major leakage
17	SE-02	E	TDM	1	55	0	
18	SE-03	E	TDM	1	15	0	
19	SE-06	E	TDM	2	83	0	

[a] IDM: inverse dispersion modelling method, TDM: tracer gas dispersion method.
[b] Measurement team A-C: 10-min averages, measurement team D: 30-min averages.
[c] OTNOC: other-than-normal operating conditions.
[d] A gastight cover was installed at the digestate storage tank between measurement campaigns (DE-08–1: not-gastight digestate storage tank, DE-08–2: gastight digestate storage tank).
[e] PRV: pressure relief valve.

(background) and downwind of the source with an atmospheric dispersion model. As an atmospheric dispersion model, the backward Lagrangian stochastic (bLS) model, provided by Flesch et al. (2004), was used in this study to simulate a concentration-emission ratio, which, along with concentration data, allowed us to determine source emissions. To fulfill the model's requirements, concentration and turbulence measurements should be conducted at a distance of at least ten times the height of the highest building at the site away from the source (Gao et al., 2010).

CH_4 concentrations were measured with open-path tunable diode laser absorption spectrometers. Micrometeorological parameters required for the bLS model were measured downwind of the AD plants, using an 3D ultrasonic anemometer. All downwind instruments were placed at the necessary distance away from the AD plant. Instruments deployed by the different IDM teams are listed in SI B.

While measurement teams C and D simultaneously determined upwind and downwind CH_4 concentrations, teams A and B performed sequential measurements while assuming the background concentration to be constant. Through sequential measurements, background concentrations were determined at the beginning and end of each measurement day.

The measured micrometeorological and concentration data were

Table 2
Whole-site CH_4 EFs (% of CH_4 production) during the normal operation of 16 AD facilities (at further three facilities, measurements covered other-than-normal operating conditions only).

Plant no.	Plant ID	CH_4 EF [% of CH_4 produced]			Primary feedstock	Plant size[c]	Technology used	
		Mean	SD[b]	n[a]			Digestate storage	Biogas utilisation
4	AT-09	0.4	0.3	18	Energy crops	Medium	Gastight[d]	BAT[f]
6	DE-01	0.8	0.6	23	Energy crops	Large	Gastight	BAT
12	DE-12	1.0	1.1	62	Energy crops	Medium	Gastight	Other[g]
11	DE-11	1.4	1.3	49	Energy crops	Medium	Not-gastight	Other
10	DE-10	1.4	1.1	61	Energy crops	Medium	Gastight	Other
15	CH-04	1.5	1.1	121	Manure	Small	Not-gastight	Other
8	DE-08–2	1.6	1.0	21	Energy crops	Medium	Gastight	Other
5	AT-12	1.9	1.7	56	Energy crops	Medium	Gastight	Other
9	DE-09	1.9	0.6	29	Energy crops	Large	Gastight	Other
7	DE-07	2.1	1.4	59	Manure	Medium	Gastight	Other
3	AT-03	2.4	2.6	61	Biowaste	Medium	Gastight	Other
13	CH-01	2.6	4.1	388	Manure	Small	Not-gastight	Other
8	DE-08–1	3.0	1.6	45	Energy crops	Medium	Not-gastight	Other
17	SE-02	3.4	0.1	55	Biowaste	Medium	Not-gastight	BAT
19	SE-06	5.5	1.5	83	Biowaste	Large	Not-gastight	Other
18	SE-03	6.5	0.4	15	Biowaste	Medium	Not-gastight	BAT
16	SE-01	6.9	0.3	45	Sewage sludge	Medium	Not-gastight	BAT

[a] n: number of measurements: 10-min/30-min means (IDM), number of plume traverses (TDM).
[b] SD: standard deviation.
[c] Large: CH_4 production > 250 kg h^{-1}, medium: ≥ 50 kg h^{-1} and ≤ 250 kg h^{-1}, small: < 50 kg h^{-1}.
[d] 100 % of digestate storage tanks are gastight covered.
[f] BAT (best available technology): 100 % biogas upgrading by chemical scrubbing or off-gas treatment.
[g] Biogas utilisation other than BAT.

prepared in time series of 10-minute averages (teams A-C) and 30-minute averages (team D) before being input into the bLS model. Measurement teams A-C used the bLS model implemented by Windtrax (version 2.0.8.9, Thunderbeach Scientific, Canada), and concentration, turbulence and output data were filtered based on quality criteria described in Clauß et al. (2019) and Hrad et al. (2021). Team D used the same bLS model but implemented it in the R package bLSmodelR (Häni et al., 2018). At team D's measurement sites, external emissions from adjacent livestock were present, so CH_4 emissions were corrected based on expected CH_4 EFs for livestock. Detailed information on the measurements, quality filtering and emission corrections done by team D is given in Bühler et al. (2022).

2.2.2. Tracer gas dispersion method

The TDM combines the controlled onsite release of a tracer gas with subsequent downwind measurements of this gas as well as CH_4 concentrations (Delre et al., 2017; Fredenslund et al., 2019, 2023; Reinelt et al., 2017; Scheutz & Fredenslund, 2019; Yoshida et al., 2014). Following onsite emission screening to identify representative tracer placements, acetylene (C_2H_2) was used as the tracer and released by 150 mm variable-area flowmeters from one or two locations at rates between 0.7 and 1.4 kg C_2H_2 h^{-1} (cf. SI B).

Gas concentrations were measured using a cavity ring-down spectrometer (cf. SI B), traversing the emission plume a minimum of ten times. Measurements and data processing were conducted following the best practice protocol described by Scheutz & Kjeldsen (2019).

2.2.3. Measurement uncertainty and limitations

Controlled CH_4 release experiments showed that measurement uncertainty for IDM and TDM was less than 20 %, if data quality criteria were met (Feitz et al., 2018; Fredenslund et al., 2019; Gao et al., 2010; Hrad et al., 2022; Mønster et al., 2014; Ro et al., 2014). Uncertainties may arise from non-representativeness of measurement conditions (systematic error) and measurement errors caused by instrument precision, data processing as well as approximations and assumptions incorporated in the measurement method (systematic and random errors) (IPCC, 2006). Fredenslund et al. (2019) identified various potential factors that can contribute to overall TDM uncertainty, including analytical uncertainty, data processing, tracer gas release rate, tracer gas placement and source simulation. With the IDM, the main uncertainties arise from the used dispersion model and provided model inputs such as measurement data, source characteristics and terrain complexity (Hrad et al., 2021). However, unlike point sources, complex sources and physical structures such as AD facilities present greater challenges for accurate measurement (Bühler et al., 2021; Hrad et al., 2022; Reinelt et al., 2017).

Whole-site CH_4 emissions were determined within a timeframe ranging from one to four days (cf. Table 1), except for three plants, which were evaluated for several weeks. Nonetheless, emissions can fluctuate temporarily (due to varying operating states) and seasonally (due to weather and climate conditions). While seasonal variations were not accounted for, we differentiated between normal operations and OTNOCs when reporting CH_4 emissions, to address temporary changes. OTNOCs were defined as events usually leading to temporarily increased CH_4 losses that can be minimised by the mode of plant operation. They can result from either safety measures, such as active pressure relief valves (PRVs) and flaring, or from unintended leakages from biogas-bearing plant components (Baldé et al., 2022; Bühler et al., 2022; Flesch et al., 2011; Groth, Maurer, Reiser, et al., 2015; Reinelt & Liebetrau, 2020). In addition, while temporary emission peaks during the agitation of not-gastight covered digestate are part of normal procedures, we excluded them when reporting CH_4 losses during regular operations (except for measurements from team D, lasting several weeks). This is because they are anticipated to have a minor impact on annual average emissions (Baldé et al., 2016; VanderZaag et al., 2014), and we aimed to avoid overrating CH_4 losses from individual AD facilities. Information on OTNOCs on individual measurement days is provided in SI B.

2.3. Calculation of CH_4 emission factors

For all AD facilities, we related whole-site CH_4 emission rates [Q_E in kg h^{-1}] to the amount of CH_4 produced [kg h^{-1}], which is defined as the sum of CH_4 generated (Q_P) and CH_4 emitted to the environment (Q_E) (cf. Fredenslund et al. (2023) – Eq. (1):

$$CH_4\,emission\,factor\,(\%\,of\,CH_4\,produced) = \frac{Q_E}{Q_P + Q_E} \tag{1}$$

Q_P was either recorded on the measurement day (three plants) or calculated based on the annual average data provided by plant operators via questionnaires (16 plants) (cf. SI A).

In addition, specific to WWTPs, we scaled CH_4 emission rates to organic load, resulting in a CH_4 EF [kg CH_4 PE^{-1} yr^{-1}].

2.4. Dataset for the statistical analysis and reporting of CH_4 emission factors

Supplementing the generated primary data, we collected secondary measurement data on whole-site CH_4 emissions and plant characteristics, including plant size (CH_4 production), feedstock and technology used (e.g., digestate storage and biogas utilisation technology), from relevant studies. After calculating CH_4 EFs, the dataset was prepared for statistical analysis (cf. section 2.5) using various filter criteria. Detailed information on these criteria (e.g., required minimum number of measurements, exclusion of CH_4 losses during OTNOC) and filtered data is given in SI C.

The final dataset contained 109 facilities, including whole-site CH_4 EFs (% of CH_4 produced) of 78 agricultural and biowaste treatment facilities and 31 WWTPs. Specific to WWTPs, the dataset comprised CH_4 EFs (kg CH_4 PE^{-1} yr^{-1}) and plant data for 28 plants. The final dataset is provided in an open access data repository (cf. data availability section).

2.5. Statistical analysis

2.5.1. Modelling methane emission factors

A statistical model (cf. SI D) tested whether CH_4 EFs (% of CH_4 produced) could be predicted from measured whole-site CH_4 EFs and available plant data, including primary feedstock, plant size, digestate and biogas utilisation technology as explanatory variables. Among them, plant size, expressed as CH_4 production in kg h^{-1}, was a continuous variable, while the others were classified as categorical. Primary feedstock comprised four categories, namely “biowaste”, “energy crops”, “manure” and “sewage sludge”, depending on which option provided the largest input (tons fresh matter yr^{-1}). Digestate storage was classified into two categories: “gastight” was applied when all digestate storage tanks had a gastight cover; otherwise, “not-gastight” was used. For biogas utilisation technology, we differentiated between “best available technology (BAT), off-site” and “other”. As “BAT, off-site” we classified technologies from which we expected negligible (onsite) CH_4 losses, namely if 100 % of the biogas was utilised by off-site facilities or if it was upgraded at the site, using low-emission technologies such as chemical scrubbing and/or off-gas treatment (Kvist & Aryal, 2019; Wechselberger et al., 2023). The second category, “other”, included all other biogas upgrading and cogeneration technologies.

2.5.2. Analysis of variance (ANOVA)

Multi-factorial ANOVA models, including only the main effects, were used to identify plant characteristics significantly affecting whole-site CH_4 EFs (% of CH_4 produced). In this regard, we used the same explanatory variables as described in section 2.5.1, except that we replaced continuous variables with categorical (to support reporting CH_4 EFs for different categories of AD facilities – cf. section 3.1.3). Consequently, for plant size, we introduced the categories “> 250 kg h^{-1}” for large AD plants and “≤ 250 kg h^{-1}” for small and medium-sized facilities (cf. Fredenslund et al. (2023)), which were summarised due to the low number of small plants (n = 10) included in the dataset.

In order to analyse wastewater-specific CH_4 EF (kg CH_4 PE^{-1} yr^{-1}), we did not consider the explanatory variable “primary feedstock”, as only one category, i.e., “sewage sludge”, was available. In addition, we included PE as an explanatory (categorical) variable, and in this case the same distinction (small and medium vs. large) was made, introducing “$< 100{,}000$ PE” and “$\geq 100{,}000$ PE”, based on the definition of larger facilities in the proposal for revising the EU’s Urban Wastewater Treatment Directive (Council Directive 91/271/EEC, 1991) and Parravicini et al. (2022).

Where appropriate, post-hoc tests using Tukey contrasts were applied. When deciding on hypotheses, *p*-values smaller than 0.05 were regarded as statistically significant.

3. Results

3.1. Methane losses during normal plant operation

3.1.1. Measurement results (primary data)

Of the 19 AD facilities investigated, 16 operated under normal conditions, resulting in whole-site CH_4 EFs between 0.4 and 6.9 % of the CH_4 produced (Table 2). Agricultural biogas facilities (mostly co-digestion of energy crops and manure) emitted less (CH_4 EFs 0.4–3.0 %, n = 11) compared to biowaste treatment plants (EF = 2.4–6.5 %, n = 4) and the WWTP (EF = 6.9 %, n = 1). However, most agricultural facilities had gastight digestate storage, whereas only one biowaste plant did, and the WWTP did not. The agricultural facilities primarily used air-inflated double membrane domes for gastight digestate, followed by single membrane domes. Both types show mainly negligible methane diffusion, as confirmed, e.g. by Wechselberger et al. (2023) and Clemens et al. (2014).

In addition, AD facilities with the lowest CH_4 EFs (0.4 and 0.8 %) had low-emission technologies for biogas upgrading (chemical scrubbing and off-gas treatment after pressure swing adsorption).

At the energy crop-based facility DE-08, CH_4 EFs losses could be reduced from 3.0 to 1.6 % when a gastight cover was installed at the digestate storage tank between measurements. An overview of whole-site CH_4 EFs is provided in Table 2.

3.1.2. Results of the statistical analyses

Using the statistical model described in section 2.5.1, the current data basis (primary and secondary data) did not allow us to model and predict CH_4 EFs, thus suggesting the need for additional data. Nevertheless, as this model is one of the most sophisticated published in this field of research to date, we provide it in SI D to support further research and enhance GHG inventory reporting in the industry.

With ANOVA (cf. section 2.5.2), based on data from 109 AD facilities, we identified two variables having a significant effect ($p < 0.05$) on whole-site CH_4 EFs (% of CH_4 produced), namely primary feedstock (biowaste, energy crops, manure, sewage sludge) and plant size (Table 3). Facilities primarily using energy crops had the lowest CH_4 losses (1.9 % of CH_4 produced, n = 14), followed by biowaste treatment facilities (2.8 %, n = 11), manure-based plants (3.7 %, n = 49) and WWTPs (7.0 %, n = 31). The post-hoc analysis revealed that, regarding CH_4 EFs, WWTPs were significantly different from biowaste-treating facilities and energy crop-based facilities, while manure-based facilities significantly differed from energy crop-based ones (Table 3, (cf. discussion section 4.1).

Concerning plant size, large AD facilities (CH_4 production > 250 kg h^{-1}) lost on average 2.2 % of the CH_4 produced (n = 42) and therefore less than half compared to small and medium-sized facilities (CH_4 production ≤ 250 kg h^{-1}; CH_4 EF = 5.6 %, n = 67). Digestate storage (gastight vs. not-gastight storage) was significant if CH_4 production was included as a numeric variable in the statistical model (data not shown), but not if introduced as categorical ($>/\leq 250$ kg h^{-1}) – as illustrated in Table 3 ($p = 0.06$). AD facilities with gastight digestate storage emitted on average 2.7 % (n = 48) of the CH_4 produced, while plants with not-gastight storage lost more than double this amount (6.2 %, n = 61). For biogas utilisation technology, ANOVA showed a *p*-value higher than the significance level 0.05 ($p = 0.77$), meaning that its effect on CH_4 losses cannot be regarded as statistically significant.

Fig. 2 shows the distribution of CH_4 EFs (% CH_4 produced) of individual AD facilities by primary feedstock, plant size and digestate storage. Most large AD facilities (86 %) had gastight digestate storage tanks, whereas 44 % of the medium-sized facilities and none of the small

Table 3
Results of the statistical analysis of 109 AD facilities: effect of primary feedstock, digestate storage, biogas utilisation and plant size (CH_4 production) on the CH_4 EF (% of CH_4 produced). The complete dataset and associated references are provided in an open access repository (cf. data availability section).

Variable	Group	CH_4 EF [% of CH_4 produced]			ANOVA	Post-hoc test
		Mean	SD[a]	n[b]	*p*-value	Homogenous subgroups
Primary feedstock	Biowaste	2.8	2.0	11	**0.0002**[c]	ab
	Energy crops	1.9	1.2	14		a
	Manure	3.7	3.6	49		bc
	Sewage sludge	7.0	3.8	31		c
	NA[d]	3.1	2.0	4		
Digestate storage	Gastight	2.7	2.7	61	0.0611	
	Not-gastight	6.2	4.0	48		
Biogas utilisation	BAT, off-site	3.5	3.3	35	0.7666	
	Other	4.6	3.9	74		
CH_4 production	≤ 250 kg h^{-1}	5.6	4.0	67	**0.0004**	
	> 250 kg h^{-1}	2.2	1.8	42		

[a] SD: standard deviation.
[b] n: number of AD plants.
[c] in bold: *p*-value < 0.05.
[d] NA: data on primary feedstock not available.

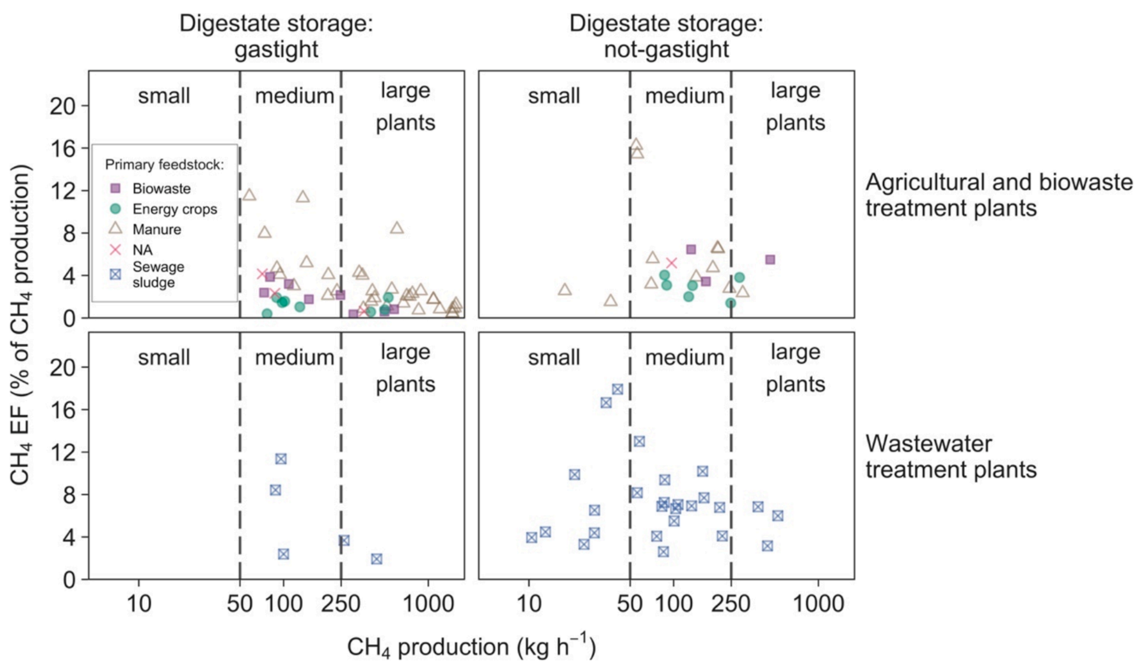

Fig. 2. Whole-site CH_4 emission factors (% of CH_4 produced) for 78 agricultural and biowaste treatment facilities (upper charts) and 31 WWTPs (lower charts), by plant size (CH_4 production in kg h^{-1}), digestate storage and primary feedstock used.

facilities used this type of storage. In addition, manure-based facilities and WWTPs represented the largest share in the dataset (49 and 31 out of 109, respectively), followed by facilities primarily treating energy crops (n = 14) and biowaste (n = 11). For four AD facilities, information on primary feedstock was not available. Furthermore, manure-based facilities had mainly (76 %) gastight digestate storage, and more than half (57 %) were large in size. In contrast, only 16 % of the WWTPs had gastight digestate storage, and most (84 %) were either small or medium in size. Biogas facilities primarily treating energy crops or biowaste had mostly gastight digestate storage (57 and 73 %) and were mainly of medium size (71 and 64 %), with a few AD facilities categorised as large.

The ANOVA on wastewater-specific CH_4 EF (kg PE^{-1} yr^{-1}) (cf. section 2.5.2) revealed that all *p*-values were higher than the 0.05 significance level. Details on the results and distribution of the data are shown in SI D.

3.1.3. *Methane emission factors of different plant configurations*

Based on the results of our statistical analyses, we report CH_4 EFs (% of CH_4 produced) for different combinations of plant characteristics with a significant impact on CH_4 losses – namely primary feedstock, plant size and digestate technology (cf. section 3.1.2 and SI D).

Table 4 summarises the median, mean, minimum and maximum values of various combinations. Within each feedstock group, large AD facilities with gastight digestate storage consistently had the lowest average CH_4 EFs, ranging from 0.6 % (biowaste) to 2.8 % (WWTP), with individual plants emitting a minimum 0.3 % (biowaste and manure-based), 0.6 % (energy crop-based) and 1.9 % (WWTP). In comparison, within each feedstock group, the largest CH_4 losses were reported for facilities with not-gastight digestate storage, i.e., for small and medium-sized facilities (on average 3.0–6.9 %) as well as large ones (on average 2.4–6.0 %). However, sample sizes for larger facilities were small (n = 1–3 per group), as only a few had not-gastight digestate storage. Individual (small and medium-sized) AD facilities reached maximum CH_4

Table 4
CH_4 emission factors (% of CH_4 produced) for different plant configurations (n = 105). The complete dataset and associated references are provided in an open access repository (cf. data availability section).

Primary feedstock	Plant size	Digestate storage	CH_4 EF [% of CH_4 produced]					
			Median	Mean	SD[a]	Min	Max	n[b]
Biowaste	**All**	**All**	**2.4**	**2.8**	**2.0**	**0.3**	**6.5**	**11**
	Small & medium[c]	Gastight[e]	2.4	2.7	0.8	1.8	3.9	5
		Not-gastight	4.9	4.9	2.1	3.4	6.5	2
	Large[d]	Gastight	0.6	0.6	0.2	0.3	0.8	3
		Not-gastight	5.5	5.5				1
Energy crops	**All**	**All**	**1.7**	**1.9**	**1.2**	**0.4**	**4.0**	**14**
	Small & medium	Gastight	1.4	1.3	0.6	0.4	1.9	5
		Not-gastight	3.0	2.7	1.0	1.4	4.0	5
	Large	Gastight	0.8	1.1	0.7	0.6	1.9	3
		Not-gastight	3.8	3.8				1
Manure	**All**	**All**	**2.5**	**3.7**	**3.6**	**0.3**	**16.2**	**49**
	Small & medium	Gastight	4.4	5.6	3.4	2.1	11.5	10
		Not-gastight	4.7	6.3	5.0	1.5	16.2	11
	Large	Gastight	1.6	1.9	1.6	0.3	8.4	27
		Not-gastight	2.4	2.4				1
Sewage sludge	**All**	**All**	**6.8**	**7.0**	**3.8**	**1.9**	**17.9**	**31**
	Small & medium	Gastight	8.4	7.4	4.6	2.4	11.4	3
		Not-gastight	6.9	7.5	3.9	2.6	17.9	23
	Large	Gastight	2.8	2.8	1.2	1.9	3.7	2
		Not-gastight	6.0	5.3	1.9	3.2	6.8	3

[a] SD: standard deviation.
[b] n: number of AD plants.
[c] Small & medium: CH_4 production $\leq 250\ kg\ h^{-1}$.
[d] Large: CH_4 production $> 250\ kg\ h^{-1}$.
[e] 100 % of digestate storage tanks are gastight covered.

EFs of 4.0 % (energy crop-based), 6.5 % (biowaste), 16.2 % (manure) and 17.9 % (WWTP).

For the WWTP-specific EF (kg CH_4 PE^{-1} yr^{-1}), we did not report EFs for different plant configurations, as statistical analyses revealed that all *p*-values were larger than the significance level 0.05 (cf. SI D).

3.2. Methane losses during other-than-normal operating conditions

Temporary high emissions during OTNOC were observed at eight of the 19 analysed AD facilities, as well as by previous studies, and can be attributed to active PRV, flare ignition problems, leakages and/or stirring of not-gastight digestate storage tanks – causing either temporary emission peaks or high CH_4 losses on whole measurement days. The

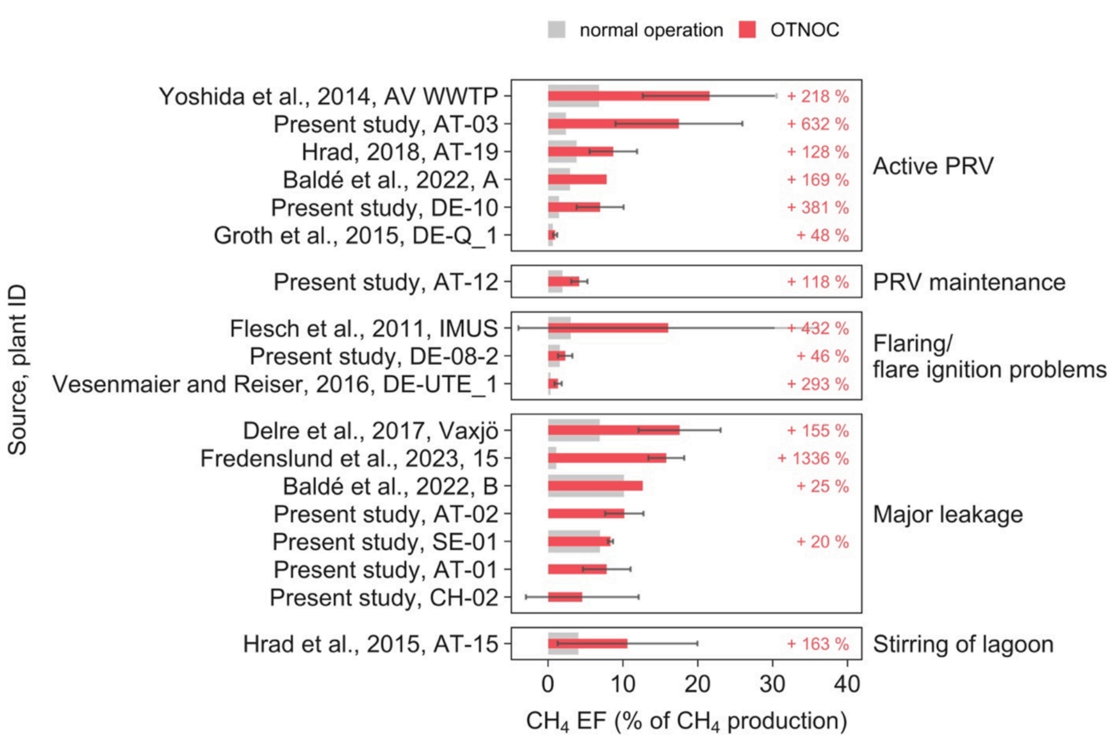

Fig. 3. Whole-site CH_4 emission factors (% of CH_4 produced) during other-than-normal operating conditions (OTNOC) (in red) compared to emission factors during normal operation (in grey). PRV: pressure relief valve. The complete dataset and associated references are provided in an open access repository (cf. data availability section).

following sections 3.2.1 to 3.2.4 present the effect of various OTNOCs on whole-site CH_4 EFs, based on primary and secondary data. A summary of CH_4 EFs during these events is provided in Fig. 3.

3.2.1. Active pressure relief valves

Active PRVs caused notable temporary emission peaks, with whole-site CH_4 EFs increasing up to 7.3-fold compared to normal operation (Fig. 3). These safety valves were triggered due to process disturbances, (unexpected) external events and during normal plant operation. For example, the highest relative CH_4 EF increase was observed at facility AT-03 in the present study, where foam in the digesters blocked pipes leading to gas storage and utilisation, thereby increasing CH_4 losses from 2.4 % of CH_4 produced (number of measurements = 61) to 17.5 % (n = 6). Foaming problems were also reported by Yoshida et al. (2014) for a WWTP, where excess pressure in the digesters triggered the PRV on four out of nine measurement days. During these events, the CH_4 EF increased 3.2-fold from 6.8 % (n = 37) to 21.6 % (n = 33). In addition, Baldé et al. (2022) reported active PRVs and flaring at biogas facility A when CH_4 production exceeded the capacity of either the combined heat and power (CHP) unit (rapid increase in gas production due to frequently changing co-feedstock) or the electricity grid (automatic disconnection of the CHP unit from the grid). During these events, the CH_4 EF increased from 2.9 % (n = 2,070, 45 measurement days) to 7.8 % (n = 3,159, 66 days). A rare cause for PRV activation was observed by Hrad (2018) at AD facility AT-19, where a power failure across the whole village led to a 2.3-fold increase in overall CH_4 losses, from 3.8 % (n = 57) to 8.7 % (n = 7). Furthermore, PRV maintenance (exchanging the water seal with an anti-frost liquid) at facility AT-12 in the present study increased overall CH_4 emissions 2.2-fold, from 1.9 % (n = 56) to 4.2 % (n = 29). PRVs were triggered during periods without any known process disturbances, as reported at facility DE-10 of the present study, with the CH_4 EF increasing 4.8-fold from 1.4 % (n = 61) to 6.9 % (n = 2), and by Groth et al. (2015) at facility DE-Q_1 with CH_4 losses slightly rising from 0.6 % (n = 33) to 0.9 % (n = 3).

3.2.2. Flare ignition problems

Flare ignition problems were observed at facility DE-08–2 in the present study, increasing the CH_4 EF 1.5-fold, from 1.6 % (n = 21) to 2.3 % (n = 13). Furthermore, the most pronounced effect of this OTNOC on CH_4 losses was shown by Flesch et al. (2011), with measurements covering various flaring periods over different seasons. CH_4 losses increased 5.3-fold, from 3.0 % (n = 444) to 16.1 % (n = 102), due to flare ignition problems and flare efficiency. In addition, Vesenmaier & Reiser (2016) observed an almost 4-fold increase in CH_4 losses, from 0.3 % (n = 48) to 1.3 % (n = 6), during maintenance of a CHP unit at facility DE-UTE_1.

3.2.3. Leakages

Within the present study, major leakages were identified at the AD facilities AT-01, AT-02, CH-02 and SE-01 – with leaks repaired at facilities AT-01 and SE-01 between measurement campaigns. However, at facility AT-01, an additional leak (broken flange on the gas bag) was detected during the second campaign, while during the first, leakages were caused by cracks in the concrete walls of two digesters (Wechselberger et al., 2023). Both campaigns showed comparable CH_4 EFs of 7.6 (n = 31) and 8.1 % (n = 13). At facility SE-01 (WWTP), leaks at the gas dryer released 1.2 % of the CH_4 produced (cf. Wechselberger et al., 2023). After repair, we measured a whole-site CH_4 EF of 6.9 % (n = 45) compared to 8.3 % (n = 10). At facility AT-02, part of the total CH_4 losses (10.2 %, n = 26) was caused by leakages at two service boxes on top of concrete digesters, emitting 1.7 % of the CH_4 produced (cf. Wechselberger et al., 2023). At facility CH-02, we measured a CH_4 EF of 4.6 % (n = 275), as a digester's membrane was damaged during both measurement campaigns.

Regarding the collected secondary data, previous studies revealed a considerable reduction of whole-site CH_4 losses after repairing leakages. For example, Delre et al. (2017) measured EF = 17.6 % (n = 10) at the Vaxjö WWTP before a leak at a digester was repaired and 6.9 % (n = 71) afterwards. Fredenslund et al. (2023) reported an even more pronounced effect at a newly constructed AD facility no. 15, where installed soft covers on the digesters had not tested during initial measurements. CH_4 losses decreased from 15.8 % (n = 17) to 1.1 % (n = 33). In addition, Baldé et al. (2022) found that replacing the digester membrane at biogas facility B reduced the CH_4 EF from 12.7 to 10.1 %.

3.2.4. Agitation of not-gastight covered digestate

Several previous studies have observed increased CH_4 losses during the agitation of digestate in tanks not covered with a gastight cover. Hrad et al. (2015), for instance, reported emission peaks at facility AT-15 on two measurement days, with the CH_4 EF increasing 2.6-fold from 4.0 % (n = 19) to 10.6 % (n = 36). In addition, Hrad et al. (2022) described 6- to 25-fold emission increases during digestate stirring periods at facility no. 2. Bühler et al. (2022), performing continuous IDM measurements at two WWTPs, found that several emission peaks coincided with agitating sludge in storage tanks – in addition to other causes such as high sludge storage tank filling levels and the removal of sludge from the tank.

4. Discussion

4.1. Effect of different plant characteristics on methane losses

CH_4 EFs varied among different plant sizes and configurations required for processing various feedstocks, thereby reflecting differences in emission sources and operational practices. National economic and political frameworks may also influence efforts made by plant operators to minimise emissions.

For instance, plant size emerged as a significant determinant of CH_4 EFs. Larger facilities benefit from economies of scale, leading to more efficient production processes and lower emission intensities. Scheutz & Fredenslund (2019) and Fredenslund et al. (2023), who evaluated part of the presented dataset, stated that larger plants in Denmark often have been constructed more recently and/or have more economic power to (re)invest in new technology and mitigation actions. This is underlined by the fact that most large AD facilities (86 %) in the dataset had gastight digestate storage, while only 37 % of the small and medium-sized plants did so (cf. section 3.1.2). In addition, many large plants (38 %) used low-emission technologies for upgrading biogas (mainly chemical scrubbing) and exhibited low whole-site CH_4 EFs (cf. Table 4), thus indicating good operational practices. Differences in CH_4 EFs, depending on digestate storage and the biogas utilisation technology used, have been recently revealed by Wechselberger et al. (2023), who collected technology-specific EFs from various on-site studies. While not-gastight digestate storage tanks released up to 12.0 % (median = 2.4 %) of the generated CH_4, distinct biogas utilisation technologies had median CH_4 losses between < 0.1 % (biogas upgrading via chemical scrubbing and/or off-gas treatment) and up to 2.7 % of the utilised CH_4 (pilot injection CHP units). However, it is important to note that other factors may also contribute. For instance, emissions from leakages may not be directly proportional to CH_4 production, as leak rates can depend on factors like equipment pressure, rather than solely on the volume of CH_4 produced. As a result, facilities with higher production rates might show lower CH_4 EFs due to these non-proportional emissions.

Furthermore, primary feedstock also played an important role in influencing whole-site CH_4 EFs. Depending on the feedstock applied, AD facilities operate according to distinct objectives and economic circumstances. For example, while agricultural biogas facilities (processing energy crops and/or manure) greatly depend on income from energy production, biowaste processing facilities generate additional revenues from waste treatment. The main purpose of WWTPs is to treat wastewater, with energy production being of secondary importance. Therefore, the economic incentive to minimise CH_4 losses and maximise energy production differs between plant configurations processing various feedstock (Scheutz & Fredenslund, 2019). Furthermore, different feedstocks can imply distinct plant configurations/technologies – and thus different emission sources. For example, at WWTPs, CH_4 emissions not only arise from anaerobic sludge treatment and energy production, but also from the wastewater treatment line and the sewer system from which CH_4 enters the plant via influent (Daelman et al., 2012; Scheutz & Fredenslund, 2019; Tauber et al., 2021, 2023). In addition, the prevalence of not-gastight digestate storage may greatly contribute to higher CH_4 losses from WWTPs. Furthermore, the lower CH_4 EFs from energy crop-based facilities (cf. Table 4) might partly result from negligible CH_4 emissions from substrate storage (Liebetrau et al., 2013). In comparison, higher CH_4 losses can arise from both open manure storage (Kupper et al., 2020; Liebetrau et al., 2013; Wechselberger et al., 2023) and the ways in which diverse feedstocks are handled, such as mixing, processing and storage (Fredenslund et al., 2018; Wechselberger et al., 2023), albeit they typically result in minor emissions (Fredenslund et al., 2018; Liebetrau et al., 2013; Reinelt et al., 2017; Wechselberger et al., 2023). Regarding the feedstock and plant size combined, most large AD facilities in the dataset (76 %) utilised agricultural feedstock (manure and/or energy crops), while WWTPs had the largest share (39 %) of small and medium-sized facilities.

Finally, plant size, primary feedstock and technology used can be country- specific, in which case CH_4 losses are thus the consequence of different framework conditions such as national regulations (enforcing, e.g., gastight digestate storage for new-build plants and/or plants with certain feedstock – cf. Austrian regulation on waste treatment obligations (BGBl. II no. 102/2017), German technical guidelines on air quality control (GMBl 2021, no. 48–54, p. 1050)), national infrastructure and strategies regarding biogas utilisation or voluntary systems for emission reduction. The latter are implemented, for example, in Denmark and Sweden and entail regular monitoring (leak detection and emission quantification) as well as emission reduction targets (Danish Gas Technology Centre, 2016; Swedish Waste Management, 2019). In Denmark, the voluntary monitoring programme was replaced in January 2023 by a mandatory system including an annual plant review and leak detection, each carried out by a third party approved by the Danish Energy Agency (Danish Energy Agency, 2023). Most AD facilities included in the dataset were Danish, representing 81 % of large plants and 54 % of small and medium-sized plants, typically utilising manure or sewage sludge as primary feedstock.

The importance of distinguishing CH_4 losses across different plant configurations becomes apparent when considering the required GHG savings defined by the RED III (Directive (EU) 2023/2413 of the European Parliament and Council, 2023) for AD facilities of a certain size. Depending on the start date and years of operation, minimum GHG savings need to be 50–65 % compared to fossil fuels, if facilities produce biomethane for the transport sector, and up to 70–80 % if they provide electricity and heat. Liebetrau et al. (2017) found that in the case of electricity and heat production, AD facilities based on energy crops can achieve GHG savings of 70 %, but only if CH_4 losses are less than 1–2 % of the CH_4 supplied to the CHP unit, as energy crops have a GHG burden from crop cultivation. In comparison, biowaste treatment facilities need to emit less than 3.5–5.5 %, while manure-based AD facilities can even release 7 % and still have a negative GHG balance (considering credits from avoiding GHG emissions from open manure storage) (ebd.). Depending on the plant configuration, achieving GHG savings may require gastight covered digestate storage, off-gas treatment after biogas upgrading and/or altering the feedstock.

4.2. *Effect of OTNOCs on methane losses*

Common to all OTNOCs described in section 3.2 is limited information on their frequency and contribution to overall average CH_4 losses. Regarding periodically occurring safety-related OTNOCs such as active PRVs and flaring, to the authors' best knowledge, the only continuous monitoring of CH_4 losses from one plant's PRVs was done by Reinelt & Liebetrau (2020), reporting that CH_4 emissions varied greatly during the two-year on-site investigation. Individual events released up to 11.7 % of the generated CH_4, while annual average CH_4 losses could be reduced from EF = 1.8 % in the first year to 0.6 % in the second, due to various emission reduction measures. Although the causes of some triggering events observed by Reinelt & Liebetrau (2020) were comparable to the ones collected within this study, including, for example, power reduction and the shutting down of CHP units (cf. section 3.2.1), transferring the determined average CH_4 EFs and frequency of events is limited, as PRV activation depended greatly on the mode of plant operation (e.g., targeted biogas filling level of gasholders, regulation of CHP operation) and technical infrastructure (e.g., manually operated biogas flare, insufficient gas exchange between gasholders and flares) (Reinelt & Liebetrau, 2020). Present state-of-the-art safety procedures require that automatic flaring or other secondary gas utilisation prevent uncontrolled biogas release via PRVs (e.g., German technical guideline on air quality control (GMBl 2021, no. 48–54, p. 1050) and the Austrian technical basis for assessing biogas facilities (Austrian Federal Ministry of Labour and Economy, 2022).

In the case of leakages, on-site studies have provided a substantial database on their numbers, and CH_4 losses, from various AD facilities (Clemens et al., 2014; Fredenslund et al., 2018; Liebetrau et al., 2013; Reinelt et al., 2017; Sax et al., 2013; Schreier, 2011; Wechselberger et al., 2023; Westerkamp et al., 2014). However, when summarising the data from existing surveys, Wechselberger et al. (2023) found that the number of leakages per plant varied considerably between 0 and 30 (median = 2.0, total number AD plants = 50), whilst CH_4 losses due to individual leakages (n = 32), mainly caused by material fatigue, construction defects or poor maintenance, ranged from < 0.01 up to 5.04 % of the generated CH_4 (median = 0.08 %) – thereby limiting the transfer of CH_4 EFs from one plant to another. In addition, assessing the contribution to overall average emissions is restricted due to the unknown period between the occurrence of a leakage and its detection and repair. Regarding the whole-site emission data collected within this study (cf. Fig. 3 and section 3.2.3), measurements did not allow for estimating emissions from individual leakages. Even if, for some facilities, CH_4 EFs could be provided for OTNOC (periods with leakages) and normal operation, differences in CH_4 losses might be caused not only by leakages, but also by operational and seasonal variations in whole-site emissions and undetected emission sources (Baldé et al., 2022; Hrad et al., 2022; Reinelt et al., 2017).

Finally, regarding temporary high CH_4 losses during the agitation of not-gastight covered digestate – several studies suggest that the impact of agitation on annual average CH_4 emissions is minimal. Baldé et al. (2016) and VanderZaag et al. (2010, 2014), for instance, observed that after agitation (releasing CH_4 stored in liquid), CH_4 emissions decreased below the level measured before agitation. This suggests that agitation may primarily lead to time-shifted emissions rather than increasing overall CH_4 production.

Although available CH_4 emission data on OTNOC cannot provide estimates of overall average CH_4 EFs, on-site and remote sensing studies provide substantial knowledge on the causes of various OTNOCs and on operational and technical measures to reduce CH_4 losses, respectively. Measures comprise, for example, regular leak detection, the maintenance and replacement of equipment, automated measurements and the adjustment of control variables and can entail minor fixes as well as larger reinvestments (cf. e.g., Fredenslund et al., 2023; Reinelt & Liebetrau, 2020).

5. Conclusions

This study provides valuable insights into methane (CH_4) emission factors (EFs) in relation to various biogas plant characteristics. By utilising a substantial dataset, we established EFs for different plant configurations.

Through ANOVA, we identified primary feedstock (biowaste, energy crops, manure, sewage sludge) and plant size (as CH_4 production $>/\leq 250\ kg\ h^{-1}$) as significant factors influencing whole-site CH_4 EFs, with digestate storage (gastight vs. non-gastight) showing significance when considering CH_4 production as a continuous variable. Wastewater treatment plants (WWPTs) tend to have higher CH_4 losses compared to biogas facilities utilising manure, biowaste and energy crops. Additionally, we observed lower EFs from larger facilities and from plants with gastight digestate storages. We assume that facilities utilising different feedstocks require different configurations/technologies and operate within distinct economic frameworks, which may incentivise varying degrees of emission reduction efforts. The influence of the primary feedstock may also vary depending on the country-specific context (e.g., regulations, voluntary systems). Furthermore, it is important to acknowledge that WWTPs primarily serve the purpose of wastewater treatment rather than energy production. Nevertheless, our findings suggest that larger facilities, with their greater economic power, may have more capacity to implement emission reduction measures (e.g., gastight digestate storage, low-emission technologies for biogas utilisation, regular leak detection and maintenance). Notably, our analysis also identified periods characterised by temporarily or constantly high emission peaks, thereby highlighting the need for targeted mitigation strategies. Future studies could benefit from expanding the provided dataset including additional facilities and a wider range of variables, such as the age of the facility, extent of reinvestments/replacements (state of facility) and mode of operation. A more refined analysis could offer deeper insights into emission patterns and facility performance. Additionally, extending observation periods would help to capture seasonal and temporal variations, enhancing the understanding of long-term emission trends.

CRediT authorship contribution statement

Viktoria Wechselberger: Writing – original draft, Visualization, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Marlies Hrad:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Marcel Bühler:** Writing – review & editing, Investigation. **Thomas Kupper:** Writing – review & editing, Project administration, Funding acquisition. **Bernhard Spangl:** Writing – review & editing, Visualization, Formal analysis. **Anders Michael Fredenslund:** Writing – review & editing, Investigation. **Marion Huber-Humer:** Writing – review & editing, Supervision. **Charlotte Scheutz:** Writing – review & editing, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.11.021.

Data availability

The dataset related to this article can be found at https://doi.org/10.5281/zenodo.14165792, hosted at Zenodo.

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