JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Fugitive Methane from Biogas and Compressed Biogas Plants: A Critical Review of Measured Losses, Quantification Methods and the Evidence Gap in Emerging Economies

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Abstract

Biogas and biomethane are promoted as low carbon substitutes for fossil gas, yet their climate case rests on a quantity that is rarely measured: the share of produced methane that escapes to the atmosphere. Following PRISMA 2020 guidance, we searched OpenAlex for studies published between 2010 and 2026, screened 393 unique records and combined the 93 eligible studies with 31 sources identified by citation searching and from national programmes and crediting methodologies. A random effects synthesis of independent campaigns gives a mean plant level loss of 5.1% of methane produced (95% confidence interval 3.9 to 6.3%), while individual plants range from below 0.1% to above 20%. The distribution is strongly skewed: in the Danish national dataset the top tenth of plants by emission rate released 37% of the methane. Three sources dominate, namely open digestate storage, pressure relief venting and upgrading off gas. Plant size is the most consistent driver, with small plants losing around 8.8% in a 65 plant German survey against 2.9 to 4.3% for larger plants. Production weighted factors are therefore well below plant averages, a distinction routinely blurred in carbon accounting. Snapshot campaigns systematically miss intermittent events. An energy side calculation shows that losses above 3.4% cancel the 20 year combustion advantage of biomethane over fossil gas when no baseline emission is avoided, rising to 13.1% when a tenth of the produced methane would otherwise have escaped. Mandatory leak surveys introduced in Denmark in 2023 had not reduced measured emission factors by 2025. No peer reviewed whole site measurement of an Indian compressed biogas plant was found, although plant size, warm climate, open digestate handling and untreated upgrading off gas all point to losses at the upper end of the measured range. We close with a mitigation hierarchy and a minimum measurement protocol suited to emerging economies.

Keywords: Biogas; Biomethane; Compressed biogas; Fugitive methane; Methane slip; Digestate storage; Emission factors; Carbon credits; PRISMA; India

1. Introduction

Methane is the second largest contributor to anthropogenic warming and has a far larger effect per tonne than carbon dioxide over the first two decades after release. Cutting methane quickly is therefore one of the few levers that can slow near term warming in a measurable way [1]. Biogas plants sit in an unusual position in this debate. They are promoted because they capture methane that would otherwise escape from manure,

wastewater and organic residues, yet they also handle large volumes of the same gas under pressure, beneath flexible membranes, in open storage and through upgrading units that vent a methane bearing off gas. Whether a given plant is a methane sink or a methane source depends on how much of its production leaks.

The question now carries direct policy consequences. The International Energy Agency attributes about 2 Mt of annual methane emissions to modern bioenergy, and its 2025 assessment notes that the limited measurements available suggest biogas plants emit, on average, methane equivalent to roughly 6% of their output [2, 3]. A 2026 survey of 65 German plants went further, estimating that the German biogas sector alone emits 360 to 370 kt of methane each year, about 23% of national methane emissions and more than current inventories assume [4]. Biomethane is being scaled rapidly across Europe, North America and Asia, and India has committed to a national compressed biogas (CBG) programme with associated crediting under its Carbon Credit Trading Scheme [5, 6]. Every one of these instruments assumes a leakage rate, and most assume it rather than measure it.

Earlier reviews and life cycle studies flagged fugitive methane as a decisive and poorly constrained parameter [7, 8, 9, 10], and recent value chain assessments argue that a plant's contribution cannot be judged by its gas output alone [11]. Since then the evidence base has changed in three ways. Standardised whole site methods, particularly tracer gas dispersion and inverse dispersion modelling, have matured and been validated [12, 13, 14, 15]. National and multinational campaigns now cover dozens of plants at a time, including two Danish national programmes, the German survey and a 31 site survey across Germany, Poland and the United Kingdom [4, 16, 17, 18]. And carbon markets have begun to price biogas methane avoidance at scale, which raises the cost of getting the leakage term wrong [19].

This review takes a critical rather than descriptive stance and asks five questions. What whole site losses have been measured, and how do they vary by plant type, size and gas use? Which sources dominate, and how stable is that ranking? How comparable are the methods behind the numbers? How well do default factors in inventories and crediting methodologies match measured reality? And what can, and cannot, be inferred for tropical, small and medium scale CBG plants in India and similar economies, where no measured data exist?

2. Review method

2.1 Search strategy

The review followed the PRISMA 2020 reporting guidance for systematic searches. The primary database was OpenAlex, an open bibliographic index that aggregates Crossref, PubMed and institutional repositories. It was chosen because every search can be rerun by readers without a subscription, which makes the counts reported here reproducible. Four search strings were applied to titles and abstracts of journal articles and reviews published between 1 January 2010 and 9 November 2026, the date of the search. Table 1 lists the strings and the records each returned.

Table 1. Search strings applied to titles and abstracts in OpenAlex (articles and reviews, 2010 to 2026; searched 9 November 2026).

No.	Search string	Records
1	("methane emission" OR "methane emissions" OR "methane loss" OR "methane losses" OR "fugitive methane" OR "methane leakage") AND ("biogas plant" OR "biogas plants" OR "anaerobic digestion plant" OR "anaerobic digestion plants" OR "biogas facility" OR "biogas facilities" OR "biomethane plant" OR "biomethane plants" OR "biogas production")	247
2	"methane slip" AND (biogas OR biomethane OR upgrading)	42

No.	Search string	Records
3	digestate AND storage AND methane AND (emission OR emissions)	111
4	("pressure relief valve" OR "tracer gas dispersion" OR "inverse dispersion" OR "optical gas imaging" OR flare) AND biogas AND methane AND (emission OR emissions OR leakage)	49
	Total before removal of duplicates	449
	Unique records after removal of duplicates	393

The database search was complemented by backward and forward citation searching of the included studies, and by targeted retrieval of national measurement programme reports, IEA assessments, IPCC guidance and carbon crediting methodologies, which are not indexed as journal articles but carry the emission factors that policy actually uses. Studies by the authors relevant to plant monitoring and digestate behaviour were also considered. Unlike the database search, these supplementary sources were not restricted by date.

2.2 Eligibility, screening and data extraction

Studies were eligible if they reported measured or modelled methane emissions from operating anaerobic digestion or biomethane facilities, from digestate storage, from upgrading units or engines, or if they quantified how leakage affects life cycle results or carbon accounting. Studies of landfills, enteric fermentation, natural gas systems or vehicle exhaust were excluded unless they supplied a method or analogue used directly in the argument. Records without a resolvable DOI were excluded from the database stream. Titles and abstracts of all 393 unique records were screened independently by two authors (SK and SJM), and the 95 records that passed were assessed against the full eligibility criteria using the abstract and, where accessible, the full text. Two records were excluded at this stage, one without a DOI and one concerning vehicle exhaust. Disagreements between the two screeners were resolved by jointly rechecking the record and its source data against the eligibility criteria. Every DOI in the final reference list was checked against the doi.org registry.

For each measurement study we extracted the country, number of plants, plant type, measurement method, campaign duration, reported operating state, the denominator used to express loss, and the mean and range of the result. A formal risk of bias score was not applied, because measurement campaigns differ in kind rather than degree. Instead, each study was appraised on four criteria that govern comparability: whether the method captured the whole site, whether intermittent sources were covered, whether the operating state was reported and whether the denominator was stated. Figure 1 summarises the flow of records.

Where campaigns reported a mean plant level loss, the means were pooled with a DerSimonian and Laird random effects model [20], and heterogeneity was expressed with the I^2 statistic [21]. Standard deviations were calculated directly from the published plant level data for the 2025 Danish programme, derived from reported 5th and 95th percentiles for the 2026 European survey, and estimated from the sample size and range for the remaining campaigns [22]. Because the Danish programmes of 2019, 2021 and 2025 partly measured the same plants, the main analysis used one campaign per country and period, and the overlapping campaigns were added in a sensitivity analysis. The concentration of emissions was analysed from the plant level emission rates in the 2025 Danish dataset.

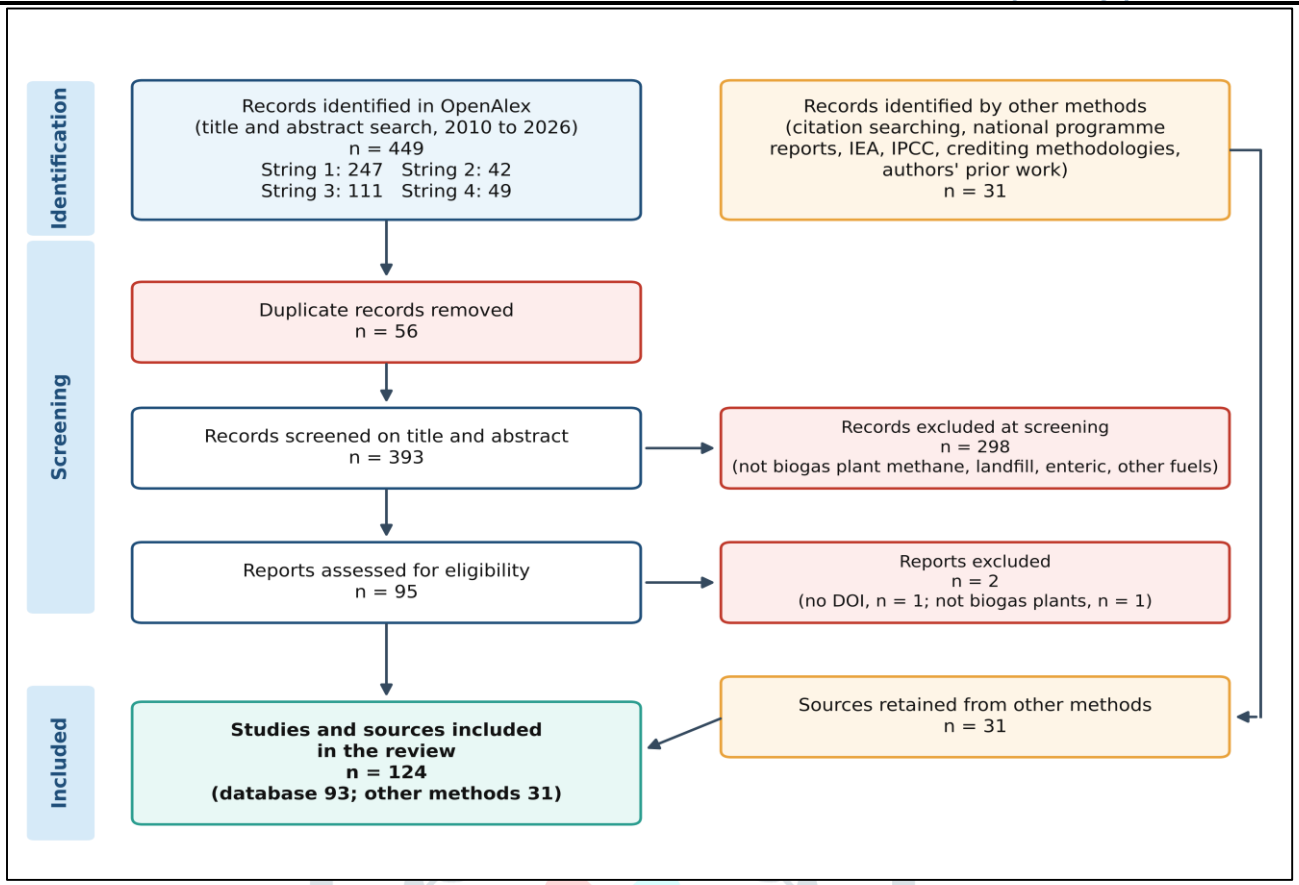

Figure 1. PRISMA 2020 flow diagram of the literature search, screening and inclusion.

Comparing studies also requires care with definitions, because the same word, loss, is used for quantities that differ by a factor of two or more. Table 2 sets out the metrics used in this review. The distinction between a plant average loss and a production weighted emission factor is the most important. In the 2025 Danish programme the former was 6.0% while the latter was 2.8% for the same 80 plants, simply because large plants leak a smaller share of their output [17].

Table 2. Metrics used to express methane losses and how they should be compared.

Metric	Definition	Comparison note
Methane loss (plant level)	Measured emission E divided by total methane formed, E plus registered production P, in kg CH4 per hour	Used by the Danish programmes; adding E to P avoids understating losses at leaky plants [17]
Plant average loss	Arithmetic mean of plant level losses across a sample	Weights small and large plants equally; describes the typical plant
Production weighted emission factor	Sum of emissions divided by sum of production across a sample	Dominated by large plants; suited to national inventories, not to project crediting
Methane intensity	Volume of methane emitted per volume of methane produced	Used by recent European surveys; numerically close to plant level loss [18]
Component emission factor	Emission from one source as a share of plant production	Additive only if all sources are captured without overlap [23]
Methane slip (upgrading)	Methane in off gas as a share of methane fed to, or delivered by, the upgrader	The denominator differs between suppliers and studies and must be stated [24]

3. Where methane escapes

A biogas or CBG plant is a chain of vessels, pipes, valves and process units, and methane can leave at almost any point. Figure 2 maps the emission points reported in measurement studies onto a typical CBG flow sheet. Some are continuous, such as diffusion through membrane roofs, methane in upgrading off gas and emissions from open digestate stores. Others are episodic, such as pressure relief valve (PRV) venting when gas production exceeds consumption, flare outages and maintenance. The episodic sources are the hardest to capture and, as later sections show, often the most consequential. An early German inventory of ten agricultural plants already identified unsealed digestate storage and the cogeneration unit as the two main sources, with improper handling of gas filled equipment causing substantial losses in some cases [25].

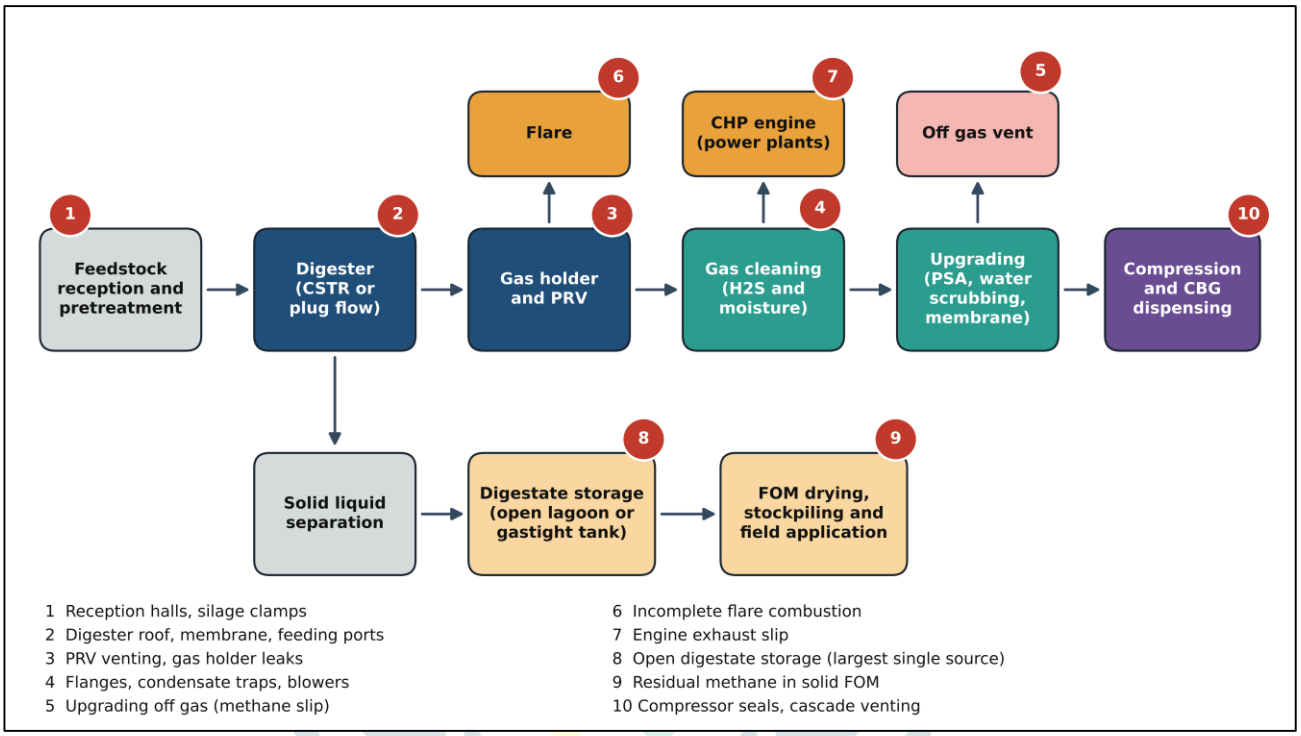

Figure 2. Methane emission points along a typical compressed biogas plant. Numbered markers correspond to the sources discussed in Table 3.

Table 3 summarises what is known about each source. Digestate storage is the largest single source wherever it is not gastight, because digestate leaving the digester still contains degradable organic matter that continues to produce methane, particularly in warm months [26, 27, 28, 29]. Pressure relief events can dominate the annual balance of an otherwise tight plant, and their frequency depends on operational discipline and on whether an automatic flare is available [30, 31]. Upgrading units contribute a steady, technology dependent slip that is often ignored when plant leakage is discussed [24, 32]. Less obvious sources also contribute. Methane permeates through membrane roofs, and replacing polyethylene with polyamide films can cut permeation by a factor of about 40 under digester conditions [33]. Pre storage of manure before digestion emits methane and forfeits gas potential, with losses rising with storage temperature and time [34, 35, 36].

Table 3. Principal methane emission sources at biogas and CBG plants, their character and the strongest evidence for their magnitude.

Source	Character	Reported magnitude or finding	Key controls
Open digestate storage	Continuous, temperature dependent	12% of digester production at an Ontario plant over two years [26]; 2.4% over a full year at a German plant [29]	Gastight cover with gas recovery, shorter storage, post digestion [37, 38]
Pressure relief valves	Episodic	0.06% at one plant in winter, 3.6 to 3.9% at another in summer [30]; 1.8% falling to 0.6% after mitigation [31]	Automatic flare, gas holder level control, event logging
Upgrading off gas	Continuous	Mean 0.81% across nine plants; up to 1.97% for water scrubbing, 0.56% for membranes, 0.04% for amine units [24]	Technology choice, off gas oxidation [39], tail gas recycle
Engine exhaust (CHP)	Continuous	Main source alongside open storage in early German inventories; larger emission share in CHP scenarios [18, 25, 40]	Engine tuning, oxidation catalysts [41]
Membrane roofs	Continuous	Permeation through polyethylene about 40 times higher than through polyamide films [33]	Film selection, double membranes
Leaks (flanges, seals, ports)	Continuous, often hidden	Membrane rupture raised one Danish plant to 21.6% [17]; remote leak quantification demonstrated [42]	Leak detection and repair with optical gas imaging
Flares	Episodic	Enclosed flares oxidised 95.1 to 99.8% of methane at six sewage plants [43]	Enclosed flares, automatic ignition, flow metering
Feedstock pre storage	Continuous	Methane lost before digestion rises with temperature and storage time [34, 35]	Short storage, frequent removal, acidification [36]

Gas cleaning ahead of upgrading deserves a brief note. Hydrogen sulphide removal is usually discussed for its effect on equipment life and gas quality, but the choice of technology also shapes emission pathways. Biological desulphurisation by air dosing in the digester headspace, water based scrubbing and adsorbent beds each introduce their own vents, condensate points and regeneration steps where methane can escape [44, 45, 46]. These points are rarely measured separately and are usually folded into the leak category.

4. Measuring methane loss: methods and their limits

Two broad families of method exist. Source level approaches identify and quantify individual emission points using chambers, hoods, flow and concentration measurement and optical gas imaging, then sum them. Whole site approaches measure the plume downwind of the entire facility and infer the total emission rate, either by releasing a tracer gas at a known rate or by inverting a dispersion model [47, 48]. Table 4 compares the main techniques, which is worth doing carefully because the choice of method shapes the number that ends up in an inventory.

Table 4. Comparison of methane quantification methods applied at biogas plants.

Method	Strengths	Limitations	Typical uncertainty or evidence
Tracer gas dispersion (mobile)	Captures all sources; low uncertainty; separates neighbouring sources	Needs suitable downwind road; short campaigns; skilled teams	Combined uncertainty 16 ± 4% per measurement in the Danish programme [12, 13, 17]
Inverse dispersion modelling	Works with fixed open path lasers; can run for days	Sensitive to source geometry, stability and wind data	Forward and backward Lagrangian models compared across teams [15, 49, 50, 51]
Mobile survey with Gaussian plume	Fast, low cost screening of many sites	Larger uncertainty; depends on stability class and plume height	Used for 65 German plants and an eight year single plant record [4, 52, 53]
Drone flux methods	Reaches elevated and inaccessible sources	Wind measurement on the drone; flight regulations	Error of +33 to −35% in controlled releases [54, 55]
Source level hoods and chambers	Identifies which component leaks; guides repair	Misses unknown or intermittent sources; access to elevated sources is difficult	Harmonised protocol across 33 plants [23, 25]
Optical, laser and hyperspectral imaging	Visualises and maps leaks and storage fluxes	Quantification still developing	Storage tank and plant mapping studies [42, 56, 57]
Continuous monitoring (lidar, sensor networks)	Captures intermittent events and seasonality	Cost; validation against tracer still in progress	Year long storage record [29]; two month trial against 18 tracer campaigns [17]

Interteam comparisons reveal a wide spread. When six teams measured the same Swedish biowaste plant, remote sensing results ranged from 5 to 25 kg CH4 per hour, equivalent to 0.6 to 3.0% of upgraded methane, and source level results from 5 to 17 kg per hour, with the spread driven as much by the plant's operating state as by the method itself [47]. Comparisons at four Danish plants and in Austria reached similar conclusions: methods broadly agree when the plant is stable, but source level surveys miss what they do not know to look for, and short whole site campaigns miss what does not happen while they are on site [48, 58, 59]. Modelling choices add a further layer: forward and backward Lagrangian models fed with the same data can diverge depending on the speed of meteorological measurement and source configuration [15].

This has a direct consequence for interpreting the literature. Almost all published numbers are snapshots of a few hours under normal operation. Pressure relief events, flare failures and maintenance releases are underrepresented by design, and several programmes measured plants with known disturbances on another day or excluded them from emission factor calculations [17, 60]. The resulting factors describe normal operation well, but they are likely to understate annual losses, and annual loss is the quantity that climate and carbon accounting actually need. Long term records remain rare. An eight year dataset from a single German plant shows that stability itself depends on operating practice [52], and the first full year of continuous monitoring at an open digestate store shows emission rates nearly doubling between cold and warm months [29].

5. What the measurements show

5.1 Whole site losses

Figure 3 summarises the main multi plant campaigns that report plant average losses. These fall between 2.0 and 8.0%, with the most recent and representative surveys clustering at 5.4 to 6.0% [17, 18]. The ranges are wide: from 0.02% at the best performing British plant to 40.6% at the worst Danish site in the 2021 programme [16, 53]. Ten Danish and German plants averaged 2.0% [58], 23 Danish plants averaged 4.6% [61], and the 65 plant German survey found emission rates from 0.3 to 255 kg CH4 per hour [4]. Studies in Canada, Australia and Korea extend the evidence beyond Europe, although each covers only one to three plants [62, 63, 64, 65]. Biowaste dry digestion plants show the same pattern of wide variation, with digestate post rotting a major contributor [66].

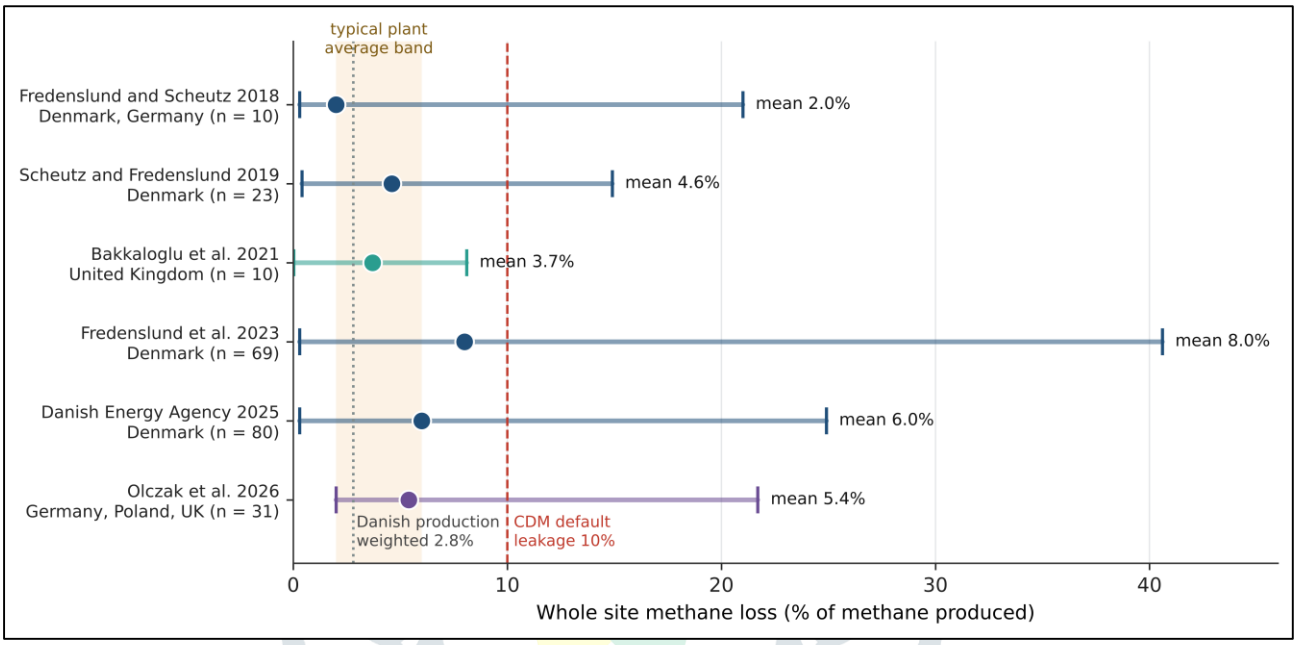

Figure 3. Plant average methane loss (points) and observed range (bars) in the main multi plant measurement campaigns. The shaded band marks the typical plant average range; the dotted line shows the Danish production weighted factor and the dashed line the 10% default leakage assumed in several CDM methodologies.

Table 5. Summary of major whole site measurement campaigns at biogas and biomethane plants.

Study	Country	Plants	Method	Mean loss (%)	Range
Wietzel and Schmidt 2026 [4]	Germany	65	Mobile Gaussian plume	8.8 small; 2.9 to 4.3 larger	0.3 to 255 kg/h
Olczak et al. 2026 [18]	Germany, Poland, UK	31	Source and site level	5.4	2.0 to 21.7%
Danish Energy Agency 2025 [17]	Denmark	80	Tracer dispersion	6.0 (2.8 weighted)	0.3 to 24.9%
Wechselberger et al. 2025 [60]	Europe	109	Inverse dispersion and secondary data	2.2 to 6.2 by group	Not given
Park et al. 2025 [65]	South Korea	1	Field measurement	0.38	Single plant
Fredenslund et al. 2023 [16]	Denmark	69	Tracer dispersion	8.0 (2.5 weighted)	0.3 to 40.6%
Hrad et al. 2022 [48]	Austria	Several	Method comparison	Method dependent	Not pooled
Bakkaloglu et al. 2021 [53]	United Kingdom	10	Mobile Gaussian plume	3.7	0.02 to 8.1%

Study	Country	Plants	Method	Mean loss (%)	Range
Scheutz and Fredenslund 2019 [61]	Denmark	23	Tracer dispersion	4.6	0.4 to 14.9%
Fredenslund et al. 2018 [58]	Denmark, Germany	10	Tracer and source level	2.0	0.3 to 21.0%
Liebetrau et al. 2013 [67]	Germany	10	Source level	Component based	Not pooled

The skew of the distribution is as important as its centre. Across the European supply chain, a meta analysis found that just 5% of emitters were responsible for 62% of total methane emissions, and that the digestate stage generated the most methane overall [68]. The Danish data show the same pattern at plant level: seven of 80 plants lost 1.0% or less, all of them agricultural, while five lost more than 15% [17]. A sector average therefore says little about any individual plant, and a policy that treats all plants as average will over credit the worst and under reward the best. Estimation methods add their own bias: a comparison of officially recorded and recalculated emissions for 33 Iberian biogas plants concluded that current estimation methods understate fugitive methane, partly because recovered methane is left out of the accounting [69].

5.2 Quantitative synthesis

Pooling the three independent campaigns that report plant level means, from Denmark, the United Kingdom and a combined German, Polish and British survey, gives a random effects estimate of 5.1% of methane produced (95% confidence interval 3.9 to 6.3%), with substantial heterogeneity between campaigns (I^2 = 60%). Adding the three earlier Danish campaigns, despite their partial overlap with the 2025 programme, barely changes the result: 5.3% (4.1 to 6.4%), I^2 = 67% (Figure 4a). Because only three independent campaigns report plant level means, and standard deviations for two of them were estimated from reported ranges or percentiles, the pooled value is indicative rather than precise. The estimate should be read as the expected loss at a typical European plant, not as a sector factor, because means of skewed distributions sit above the median. In the 2025 Danish dataset the median plant lost 4.4% against a mean of 6.0%, with an interquartile range of 1.5 to 9.1% [17].

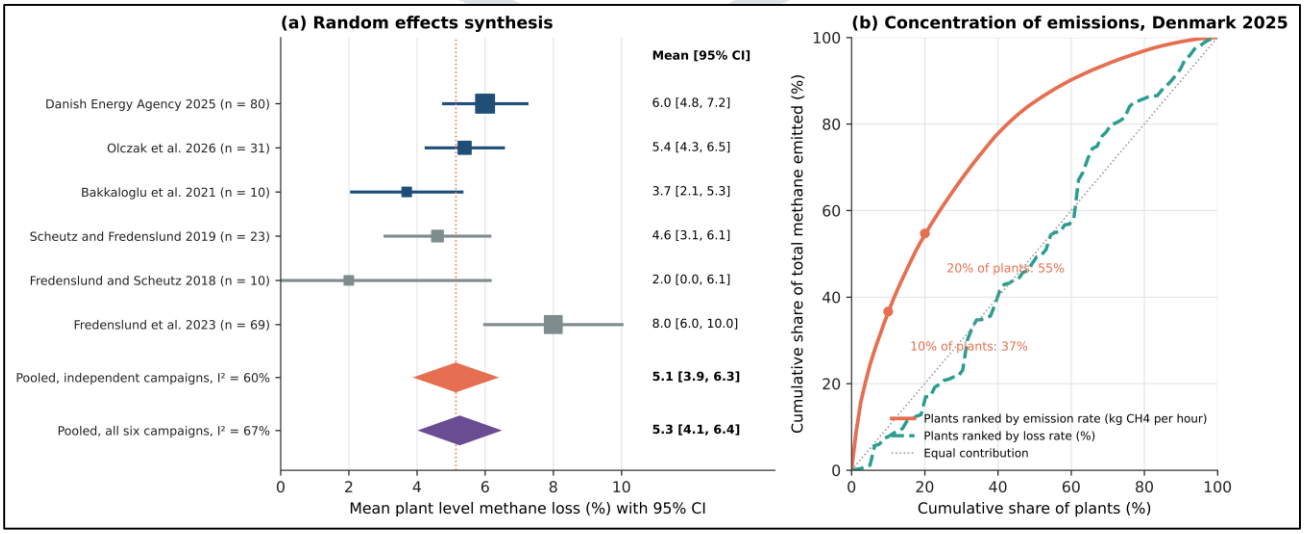

Figure 4. (a) Random effects synthesis of mean plant level methane loss across measurement campaigns; squares are sized by the number of plants, navy marks the independent campaigns in the main analysis and grey the overlapping Danish campaigns added in the sensitivity analysis. (b) Cumulative share of total methane emitted against cumulative share of plants in the 2025 Danish programme under normal operation (n = 79), with plants ranked by absolute emission rate and by percentage loss. Authors' analysis of data from [16, 17, 18, 53, 58, 61].

The concentration analysis adds a point that percentage figures hide. Ranked by absolute emission rate, the top 10% of Danish plants, eight in all, released 37% of the methane emitted by the 79 plants in normal operation, the top 20% released 55%, and half the plants accounted for 86% (Figure 4b); the Gini coefficient of emissions was 0.51. Ranked by percentage loss, however, the leakiest tenth released only 8% of the total, because high loss rates occur mostly at small plants. The implication for policy is direct. Percentage losses identify the plants whose climate case is weakest, but the tonnes are concentrated at large plants with modest percentage losses, so a programme aimed at abating the most methane should start with the largest emitters.

5.3 Plant size, type and gas use

The most consistent driver in the measured data is plant size. Figure 5a plots every plant in the 2025 Danish programme. Relative losses fall steadily as methane production rises, from a typical 10 to 20% at small wastewater sludge digesters producing under 50 kg CH4 per hour to around 1% at large agricultural plants producing more than 1,500 kg per hour. Wastewater plants recorded the highest mean loss, 11.2%, mostly because sludge stores still lack gas collection, followed by agricultural plants without upgrading at 6.1%, agricultural plants with upgrading at 3.8% and industrial plants at 2.9% [17]. Peer reviewed studies from other countries confirm the size effect. In Germany, small plants averaged about 8.8% while medium and large plants and upgrading facilities lost a more consistent 2.9 to 4.3% [4], and across 109 European facilities small and medium plants averaged 5.6% against 2.2% for larger plants, a gap attributed mainly to the absence of gastight digestate storage [60].

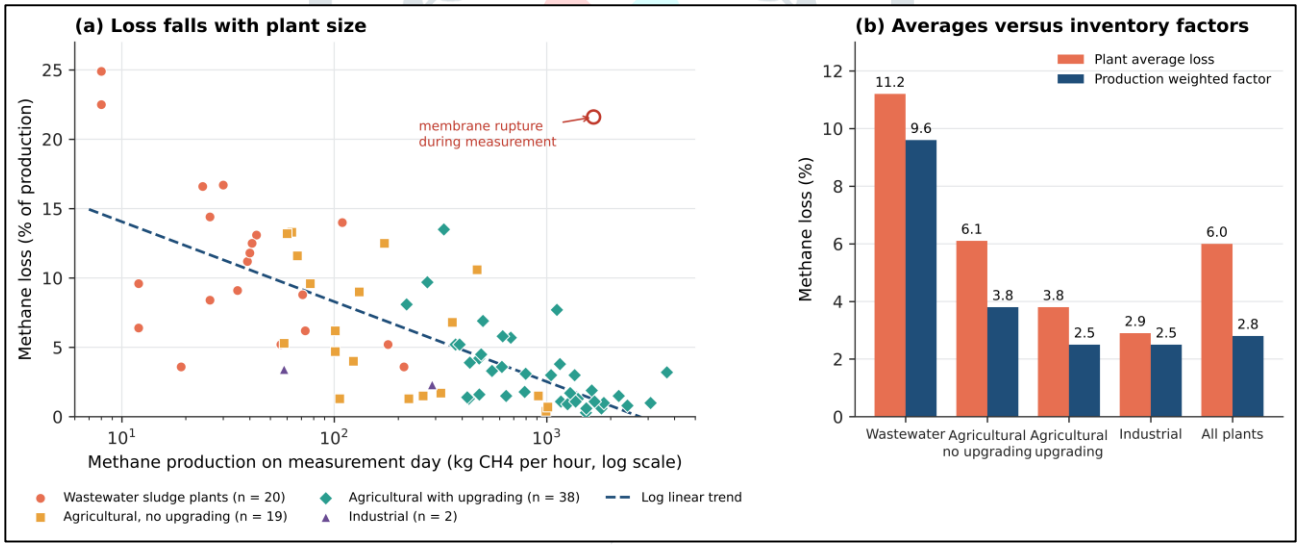

Figure 5. (a) Methane loss against methane production for the 79 plants in the 2025 Danish national programme measured under normal operation, plus one plant measured during a membrane rupture (open circle). (b) Plant average losses compared with production weighted emission factors by plant type. Data from the Danish Energy Agency programme [17].

Gas use also shapes the result. The 2026 European study found that methane made up 47% of total supply chain greenhouse gas emissions for plants burning biogas in combined heat and power engines, compared with 30% for plants injecting biomethane, because engine exhaust slip adds a continuous source that upgrading plants with off gas treatment avoid [18]. Analyses of German agricultural plants likewise show how the specific emissions of power production are distributed across storage, engine slip and leaks [40]. In Denmark, agricultural plants without upgrading, most of which generate electricity on site, carry a production weighted factor of 3.8% against 2.5% for upgrading plants; this production weighted 3.8% is a different metric from the 3.8% plant average for upgrading plants given above [17]. Component level work across Austria, Germany, Sweden and Switzerland found that IPCC defaults tend to underestimate emissions from biogas utilisation while overestimating the contribution of leaks at well maintained European plants [23].

5.4 Has regulation worked?

Denmark offers the only natural experiment so far. After a 2021 voluntary programme found a national factor of 2.5%, the Danish Energy Agency introduced binding requirements from January 2023, including self monitoring, annual third party leak surveys and emission measurements on upgrading units [16]. A mandatory follow up campaign in 2024 and 2025 measured 80 plants representing 73% of national production. Figure 6a compares the two surveys. None of the category factors fell; the national factor moved from 2.5 to 2.8%, and the wastewater factor from 7.7 to 9.6%, though neither change is statistically significant given the uncertainties [17].

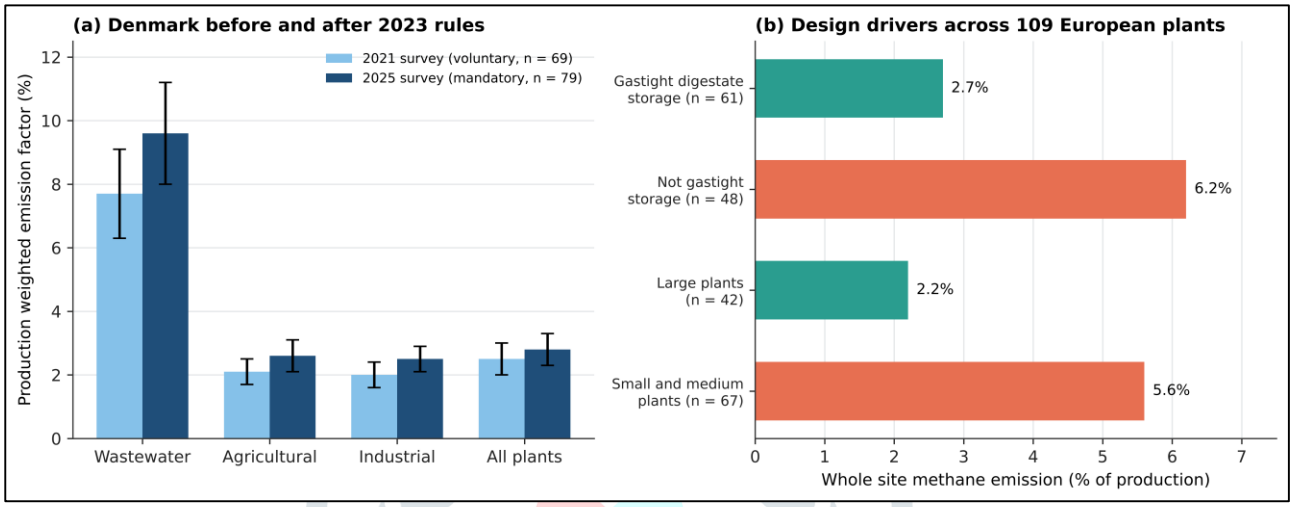

Figure 6. (a) Danish production weighted emission factors before (2021, voluntary participation) and after (2025, mandatory participation) the 2023 regulations; error bars show reported uncertainty [16, 17]. (b) Effect of digestate storage design and plant size on whole site emissions across 109 European facilities [60].

The result has two possible explanations, each with its own lesson. The first is selection bias: participation was voluntary in 2021, so the earlier sample may have favoured better plants and masked a real improvement. The second is that leak detection and repair, while necessary, does not touch the largest sources. Open sludge stores and residual methane in digestate are structural problems that need capital works, not maintenance [17]. Figure 6b makes the point from the European data: gastight digestate storage alone separates plants averaging 2.7% from those averaging 6.2% [60]. Regulation that targets leaks without targeting storage design should not be expected to move the national number quickly.

6. Source level evidence

Whole site numbers tell us how much is lost; source level studies tell us where, and therefore what to fix. Figure 7 places the best documented source magnitudes on a common logarithmic scale, drawing only on peer reviewed measurements. The spread covers more than two orders of magnitude, which is itself the main finding: the same source can be negligible at one plant and dominant at another.

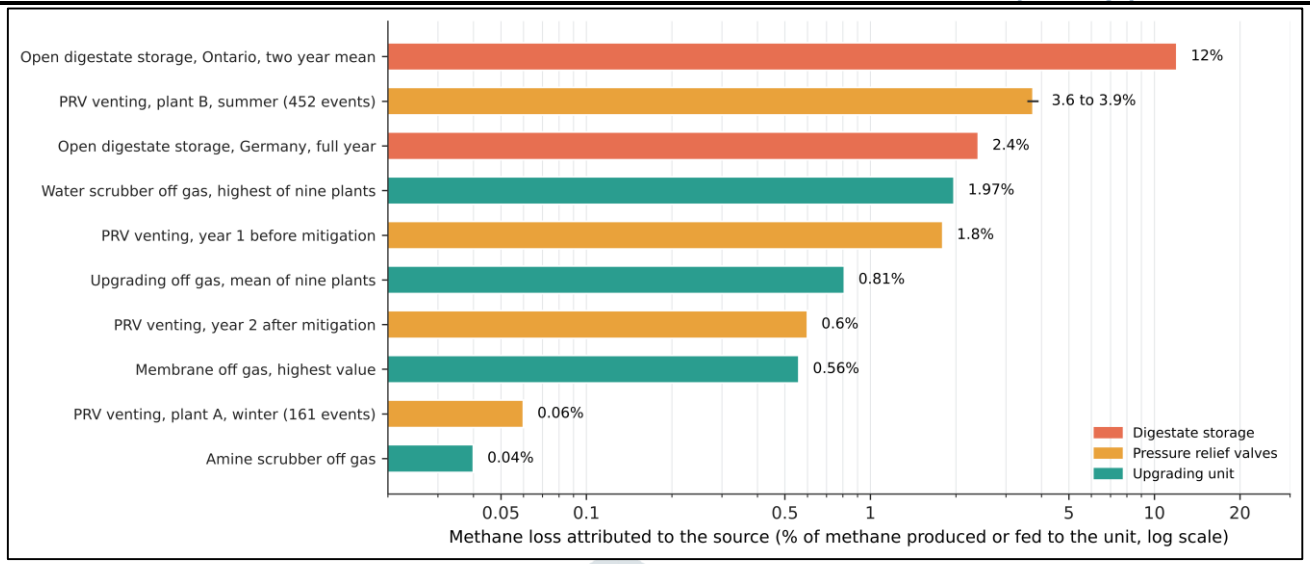

Figure 7. Methane loss attributed to individual sources in peer reviewed source level studies. Digestate storage [26, 29]; pressure relief valves [30, 31]; upgrading off gas as a share of methane fed to the upgrader, nine commercial plants [24].

6.1 Digestate storage

Digestate storage is the clearest example. Two years of measurements at an earthen digestate store in Ontario found annual emissions equal to 12% of the methane produced in the digester, with three quarters released between June and October and a sludge layer holding as much volatile solids as a full year of digester discharge [26]. The first full year of continuous monitoring at an open store on a German manure plant recorded mean digestate temperatures of 14.4 °C in winter and spring against 23.0 °C in summer and autumn, emission rates of 0.12 and 0.22 g CH4 per m³ per hour in those periods, and a cumulative annual loss of 2.4% of production [29]. A second Canadian dairy facility and a Belgian manure plant confirm that methane dominates storage greenhouse gas emissions and that temperature is the controlling variable [27, 28, 70]. Laboratory storage of Italian digestates at 28 °C rather than 18 °C raised greenhouse gas fluxes by 66%, and residual methane emissions pointed to incomplete digestion at short retention times [71].

Digestion still reduces storage emissions compared with raw slurry. A field based synthesis of 98 paired observations found digestate methane emission factors during storage 51% lower than those of raw cattle slurry [72], and Danish scenario analyses attribute much of the climate benefit of biogas to reduced storage emissions [73]. The problem is that the remaining emission is still large enough to weaken the climate case. Separated fractions behave differently: the liquid fraction emits strongly when warm and responds to acidification and post treatment [74, 75], while solid fraction stockpiles also emit methane, which biochar amendment reduced in full scale trials [76]. Emissions at successive stages of digestate management have been documented in Asian conditions as well [77]. Hyperspectral imaging at a Swedish biofertiliser tank confirmed high emissions and showed how hard it is to measure such surfaces without disturbing the flux [56], and year round measurements at ten manure tanks underline that a single summer or winter campaign can misstate the annual mean [78]. Dynamic models now link storage temperature, retention and residual substrate to emissions, offering a route to annual estimates where continuous measurement is impractical [79, 80, 81].

The underlying driver is incomplete degradation. Typically only 40 to 70% of the biomass entering a digester is converted to biogas [38], and full scale studies and residual potential tests confirm that the remaining organic matter keeps producing methane for weeks [82, 83, 84]. Residual potential measured at the German plant ranged from 75 to 135 L CH4 per kg volatile solids across the year [29]. Post digestion in covered tanks recovers part of this gas as product rather than emission [37]. The gap between laboratory

biochemical methane potential and full scale conversion, which reflects short retention, poor mixing and inhibition, is therefore an emissions problem as well as a revenue problem [85].

6.2 Pressure relief and venting events

Pressure relief valves protect gas holders from overpressure and, by design, release raw biogas. Continuous monitoring with explosion proof sensors at two German plants recorded losses of 0.06% at one plant over 106 winter days with 161 triggering events, but 3.6 to 3.9% at another over 66 summer days with 452 events [30]. The emissions depended above all on the operating state, particularly engine outages, and on whether the flare was operated automatically or by hand; even falls in atmospheric pressure affected releases. A two year follow up at one plant cut PRV losses from 1.8% in the first year to 0.6% in the second after mitigation measures were introduced [31]. Household digesters show the same physics at small scale, and venting from over pressurised dome digesters in Kenya and Uganda has now been measured directly [86].

Venting is closely tied to process stability. Feeding surges, foaming and inhibition produce gas faster than downstream units can absorb it, and plants without buffer capacity or automatic flaring vent the excess. Monitoring of gas production, gas holder level and process indicators is therefore an emissions control in its own right, not only a yield tool [87, 88].

6.3 Upgrading, engines and flares

Every upgrading technology rejects some methane with the separated carbon dioxide. Measurements at nine commercially operating plants found an average loss of 0.81% of the methane fed to the upgrader, with water scrubbers reaching 1.97%, membrane units 0.56% and amine units 0.04%; a regenerative thermal oxidiser on the off gas cut methane emissions by 99.5% [24]. Reviews rank the technologies in the same order while stressing that design and operation dominate [32, 45, 46]. Off gas treatment is not trivial, because the stream typically holds only 2 to 3% methane in carbon dioxide with no oxygen, which is why regulators such as Italy's set an off gas limit near 1% and why regenerative catalytic oxidation has been developed for this duty [39]. Multistage membrane designs can approach zero methane emission at a cost in energy and capital [89], while membrane contactors and permeable membranes carry secondary slip mechanisms that show up in life cycle results [90, 91]. Techno economic work shows that the cheapest route to low slip depends on whether a plant chooses a low slip technology or adds oxidation to a cheaper one [92].

Engine exhaust slip is inherent to lean burn gas engines, where the combustion conditions that limit nitrogen oxides leave a fraction of methane unburned. It explains much of the higher emission share of CHP plants in recent European data, and catalysts for oxidising methane in lean exhaust remain under development [18, 41]. Flares are the last line of defence during outages. Measurements of enclosed flares at six Brazilian sewage plants found methane oxidation of 95.1 to 99.8%, and showed that estimates based on literature values or simple temperature readings are a poor substitute for in situ testing [43]. Open flares that ignite late, run at very low load or sit in strong crosswinds are unlikely to perform as well, and no comparable measurements exist for open flares at CBG plants.

7. Climate significance of measured losses

How much leakage is too much? Life cycle studies have long shown that the greenhouse gas balance of biogas and biomethane is highly sensitive to the assumed leakage rate, often more than to any other parameter [8, 93, 94]. The same sensitivity appears in assessments of agricultural, energy crop and industrial biomethane plants across Europe [95, 96, 97, 98, 99], and the choice of climate metric changes the verdict, because methane weighs far more over 20 years than over 100 [100]. Grubert argued that renewable natural gas could become climate intensive at scale if leakage is high and the feedstock methane would not

otherwise have been emitted [101], and a recent comparison with natural gas and hydrogen pathways reached the same conclusion for supply chains with poor methane control [102].

An energy side calculation makes the stakes concrete (Figure 8). Methane has a lower heating value of about 50 MJ per kg, so each megajoule delivered corresponds to 20 g of methane at zero loss. For a loss fraction L, the leaked methane per megajoule delivered is 20 L divided by (1 minus L) grams. Plants that process manure or other wastes also avoid baseline methane that would have escaped without them, which we express as a fraction B of the methane produced, so that the net burden is 20 (L minus B) divided by (1 minus L) grams. Multiplying by the global warming potential of non fossil methane, 79.7 over 20 years and 27.0 over 100 years [103], and comparing with the 56.1 g CO2 per MJ released when fossil natural gas is burned [104], gives the break even loss at which the methane burden alone equals the combustion emission of the fossil gas it replaces.

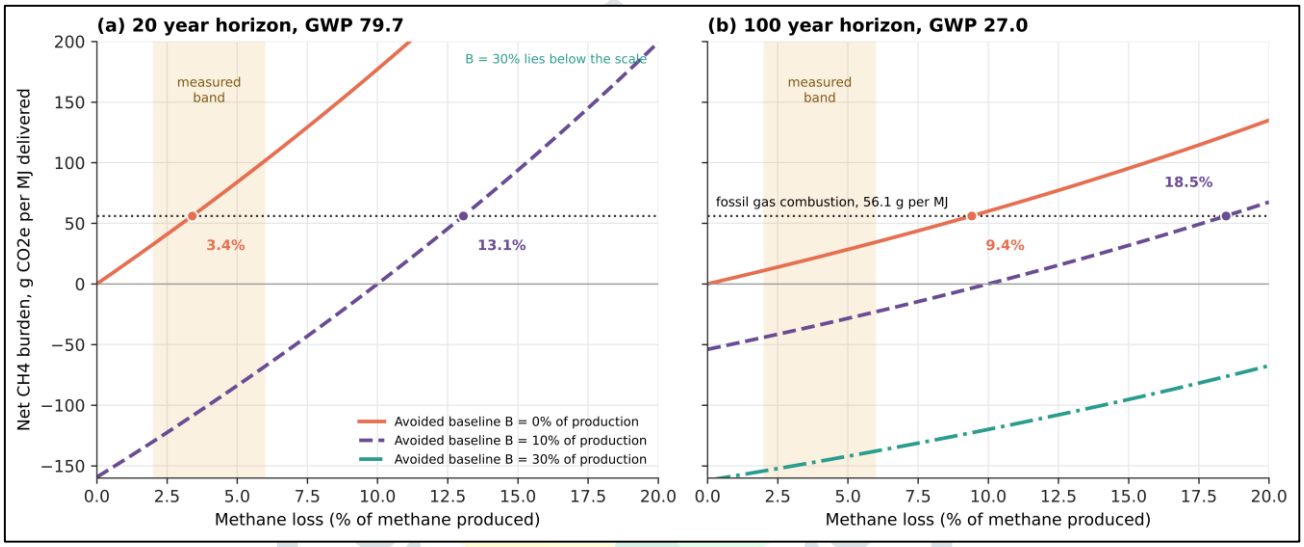

Figure 8. Net methane burden per megajoule of methane delivered as a function of loss rate, for three fractions B of production that would otherwise have been emitted as baseline methane, on (a) 20 year and (b) 100 year horizons. Points mark the loss at which the net burden equals the combustion emission of fossil natural gas (dotted line). Authors' calculation using IPCC AR6 values for non fossil methane; upstream energy and digestate effects are excluded.

With no avoided baseline, as for crop residues that would otherwise be burnt or ploughed in, the break even loss is 3.4% on a 20 year basis and 9.4% on a 100 year basis. When a tenth of the produced methane would otherwise have escaped, the 20 year threshold rises to 13.1% and the 100 year threshold to 18.5%; at 30% avoided baseline, typical of manure or press mud stored or dumped anaerobically in warm climates, it rises above 30% on both horizons. A recent crop residue study for Cameroon found a break even leakage near 4.5% under the local cooking fuel mix, which sits within the same range [105]. Measurements before and after digester installation at a California dairy, and scenario estimates for Indian cattle manure, show how large the avoided baseline can be [106, 107, 108].

For feedstocks with little baseline methane, which includes paddy straw and Napier grass, the measured plant average band of 2 to 6% straddles the short term break even point, and leakage control decides whether the plant helps the climate on its energy merits at all. For manure and press mud, the avoided baseline gives a wide margin, but that margin is precisely the term carbon methodologies estimate rather than measure.

8. Default factors in inventories and carbon crediting

Accounting frameworks handle leakage in three ways: an IPCC style default, a methodology specific default, or a project measurement. Table 6 compares representative values with the measured evidence. Two tensions emerge. First, the CDM default of 10% and the 15% default in AM0073 are higher than the

measured plant average for well run European plants, yet the CDM Methodologies Panel itself noted that leakage may exceed 10% at some digesters unless concrete measures are taken [109, 110]. Second, measured plant level losses vary so widely that any single default is wrong for most individual plants, too generous for the leakiest and too punitive for the best. Site specific factors are relevant on the production side as well: a 22 month study of a covered lagoon treating tapioca wastewater in Indonesia derived a methane yield slightly below the IPCC default, underlining the case for local factors in national inventories [111].

Table 6. Leakage assumptions in accounting frameworks compared with measured evidence.

Framework or source	Leakage value	Comment
CDM small scale methodologies and TOOL14	10% default	Panel noted measured leakage can exceed the default at some digesters [109]
Verra AM0073 (multi site manure)	15% default, or lower if justified	Lower values require documented evidence validated by the verifier [110]
IEA 2025 assessment	About 6% average	Based on limited measurements; flagged as needing confirmation [3]
German survey 2026	8.8% small; 2.9 to 4.3% larger	Measured, 65 plants; sector emissions exceed bottom up inventory estimates [4]
Danish national inventory factor 2025	2.8% (weighted)	Measured, 80 plants, 73% of national production [17]
European plant average 2026	5.4%	Measured, 31 sites in three countries [18]
Korean co digestion plant 2025	0.38%	Single plant; measured values diverged markedly from IPCC 2019 Refinement estimates [65]
India CCTS methodology for CBG	Calculated project emissions	Project boundary covers baseline and project facilities; no measured national factor exists [5]

For project level crediting the implication is clear. A default is defensible only when it is conservative for the plant in question, and the measured distribution shows that no realistic default is conservative for the worst decile of plants. Where digestate is stored openly, where upgrading off gas is vented untreated, or where gas holders vent frequently, crediting on a default risks issuing credits for reductions that did not occur [19]. The growing interest in carbon removal credits from biogenic carbon dioxide captured at upgrading units adds a further reason to measure, since a removal claim made alongside unmeasured methane leakage is unlikely to survive scrutiny.

9. Transferability to India and other emerging economies

No peer reviewed whole site measurement of an Indian CBG plant was identified in this review. The closest literature estimates national biomethane potential and abatement under assumed rather than measured leakage [6], or estimates methane from Indian cattle manure management, which defines the avoided baseline rather than the plant loss [107]. Evidence from other emerging economies is sparse but instructive. Life cycle work on bio CNG from cassava starch wastewater in Thailand, measurements on digestate management in Asian conditions, monitoring of a tapioca wastewater lagoon in Indonesia, tubular digesters in Ecuador and household systems in Vietnam, China, Kenya and Uganda all show that leakage and venting are recognised but rarely measured at industrial scale [77, 86, 111, 112, 113, 114, 115, 116]. The international evidence nonetheless allows a structured judgement about the likely direction of difference, set out in Table 7.

Table 7. Factors affecting methane loss at Indian CBG plants relative to the European evidence base.

Factor	Indian context	Likely effect	Evidence basis
Climate	Ambient temperatures of 25 to 40 °C for much of the year	Higher storage losses	Storage emissions rise with temperature [26, 29, 71]
Plant size	Many plants of 3 to 15 tonnes CBG per day, mid sized by European standards	Higher relative losses	Size effect in Denmark, Germany and Europe [4, 17, 60]
Digestate handling	Solid liquid separation with open liquid lagoons and open FOM drying yards	Higher losses	Open storage roughly doubles whole site loss [60]; separated fractions emit [75, 76]
Upgrading technology	PSA and water scrubbing common; off gas oxidation rarely fitted	Higher slip	Water scrubbing up to 1.97% without oxidation [24]
High solids feedstocks	Press mud, paddy straw, Napier grass with variable conversion	Higher residual potential	Residual methane in digestate [38, 82, 85]
Power reliability	Grid outages and compressor trips	More venting events	PRV emissions follow operational disturbance [30]
Monitoring practice	Manual logbooks; limited gas metering at sources	Losses undetected	Monitoring underpins control [87]

Most factors point in the same direction. Indian plants are typically mid sized, operate in a warm climate, store liquid digestate in open lagoons and dry solid fermented organic manure in the open, and rely on PSA or water scrubbing without off gas treatment. Each of these features is associated with higher losses in the measured data, and the German finding that small plants lose roughly twice the share of larger ones is especially relevant [4]. Grid interruptions and compressor trips add venting events that snapshot campaigns would miss even if they were carried out. The cautious conclusion is that typical losses at Indian CBG plants are unlikely to sit below the European plant average and may well sit above it. This is an inference to be tested, not a finding, and it should not be used to assign a number to any individual plant.

There are also reasons for some optimism. Indian plants are mostly new, which in Denmark correlates with lower losses, and the product is compressed gas sold by mass, so lost methane is directly visible as lost revenue. A plant producing 10 tonnes of CBG per day that loses 5% of its methane forfeits roughly half a tonne of saleable gas daily. The commercial and climate incentives are aligned, provided losses are measured.

10. Mitigation hierarchy

The evidence suggests that most methane losses can be avoided with existing technology. The 2026 multi country study estimated that 59% of emissions could be eliminated at no net cost, because the recovered methane pays for the measures [18], and a techno economic assessment of European plants provides cost estimates for individual measures [117]. Evidence from German biowaste plants points the same way [66, 118]. Table 8 ranks the measures by expected effect and by how early in a project they should be decided.

Table 8. Mitigation hierarchy for methane losses at biogas and CBG plants.

Measure	Targets	Expected effect	Design or retrofit
Gastight digestate storage with gas recovery	Largest single source at open storage plants	Very high	Best at design; floating covers as retrofit [60, 119]
Longer retention or post digestion	Residual methane potential	High	Design [37, 38]
Automatic flare with level control	PRV venting during outages	High at affected plants	Low cost retrofit [31, 43]
Off gas thermal or catalytic oxidation	Upgrading slip	Methane in off gas cut by 99.5%	Design or retrofit [24, 39, 92]
Digestate additives and treatment	Storage emissions of liquid and solid fractions	Up to 74% in trials	Operational [74, 76, 120, 121, 122]
Leak detection and repair with optical imaging	Membranes, flanges, seals	Moderate	Operational [16, 42]
Low permeation roof films	Diffusion through membrane roofs	About 40 fold lower permeation	Retrofit at membrane renewal [33]
Engine tuning and exhaust catalysts	CHP slip	Moderate	Operational [41]
Continuous process and gas monitoring	Upsets that trigger venting	Enabling	Operational [87]

The sequence is deliberate. Storage design and retention time are fixed at the detailed design stage and are expensive to change later, yet they address the largest sources. Where storage cannot be enclosed, additives such as a peroxide based treatment cut methane from stored digestate by 74% in trials [120], nutrient recovery reduced storage emissions [122], and methane oxidation in soil layers fed with storage gas has been tested for manure and digestate stores [123]. Dilute methane in building ventilation can also be oxidised, as photoreactor field trials at a biogas plant have shown [124]. Flare automation and off gas oxidation are cheaper than storage works and can be retrofitted. Leak surveys, important as they are, address a smaller share of total losses, which is consistent with the Danish experience. For emerging economies building new capacity now, the cheapest tonne of methane abated is the one designed out before construction.

11. Research agenda and minimum measurement protocol

The evidence gap for emerging economies is not mainly technical; the methods exist and are well validated. The gap is one of programmes, funding and protocols. We propose the minimum protocol in Table 9 as a practical starting point that a national programme, a lender or a carbon registry could adopt.

Table 9. Proposed minimum measurement protocol for CBG plants in emerging economies.

Element	Minimum requirement	Rationale
Whole site measurement	Tracer gas dispersion or validated equivalent at commissioning and every two years, with at least three campaigns covering summer and winter	Captures all sources and seasonal effects [17, 29, 78]
Production metering	Methane metered after the gas holder and before upgrading; loss reported as E divided by (E plus P)	Consistent denominator [17]

Element	Minimum requirement	Rationale
Upgrading off gas	Continuous methane analyser on the off gas vent	Up to 1.97% slip without treatment [24]
Venting events	PRV and flare event logging with duration and estimated volume	Snapshot campaigns miss events [30]
Digestate	Residual methane potential of digestate tested quarterly	Predicts storage emissions [83, 84, 85]
Leak survey	Annual optical gas imaging or drone survey with repair records	Locates repairable leaks [16, 54]
Reporting	Plant average and production weighted values reported separately	Avoids conflation in inventories and credits

Beyond the protocol, four research questions stand out. First, how large are storage emissions from open lagoons and FOM drying yards in tropical climates, and how do they respond to high solids agricultural residue digestates such as press mud, paddy straw and Napier grass? Second, how often do grid related outages trigger venting at CBG plants, and what is their annual contribution? Third, what is the real slip of small PSA and water scrubbing units under Indian operating conditions? Fourth, can low cost continuous monitoring, validated against tracer campaigns, provide credible annual loss estimates for project level crediting? A national programme modelled on Denmark's, starting with a representative sample of 20 to 30 plants, would answer the first three within two years.

12. Limitations of this review

Several limits should be kept in mind when reading these results. The database search used a single index, OpenAlex, chosen because it lets any reader rerun the search; Scopus or Web of Science might have surfaced a few further records, although citation searching was used to narrow that gap. Some records were judged on the abstract alone because the full text could not be accessed. The pooled estimate rests on three independent campaigns, and the standard deviations for two of them were derived rather than reported, so the confidence interval probably understates the true uncertainty. The measured evidence is overwhelmingly European and comes from plants that operate in colder climates, under different regulation and with older fleets than those in India. Finally, the break even analysis compares combustion emissions only and leaves out upstream energy use, transport and digestate effects, all of which would shift the thresholds for an individual project.

13. Conclusions

Measured methane losses from biogas and biomethane plants are real, variable and concentrated. Plant averages cluster between 2 and 6% of production, with a pooled mean of 5.1%; small plants lose the largest share, large plants emit most of the tonnes, and three sources dominate, namely open digestate storage, pressure relief venting and upgrading off gas. A small number of plants also account for a large share of emissions, so sector averages poorly describe individual facilities. Production weighted factors and plant averages answer different questions and should never be used interchangeably. Where little baseline methane is avoided, as with crop residues, the measured band straddles the 3.4% loss at which leakage cancels the short term climate advantage of biomethane over fossil gas.

The Danish experience shows that leak surveys alone do not quickly reduce national emission factors, because the largest sources are structural. Storage design, retention time, automatic flaring and off gas oxidation deliver more and are cheapest when built in from the start. For India and other emerging economies, the absence of measured data is the central finding of this review. The evidence, read carefully,

suggests that losses at typical CBG plants are more likely to sit at the upper end of the measured range than below it. Measuring them, through a national programme and a minimum protocol of the kind proposed here, is the precondition for credible carbon accounting and for a CBG sector that delivers the climate benefit it promises.

Declaration of competing interest

The authors are partners in an engineering consultancy that designs and operates biogas and CBG plants. They declare no other competing interests.

Declaration of generative AI use

During the preparation of this work the authors used Claude (Anthropic) to assist with the literature search, data extraction, drafting and figure preparation. The authors reviewed and edited all content and take full responsibility for the published article.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial or not for profit sectors.

Data availability

All data are drawn from the cited publications and reports. Plant level Danish data in Figure 5 are taken from the published tables of the Danish Energy Agency report. The search strings in Table 1 can be rerun in OpenAlex.

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