

UAV METHANE MRV AS A TOOL FOR CIRCULAR ECONOMY MANAGEMENT

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ABSTRACT

Reliable and scalable methane (CH₄) monitoring is essential both for near-term climate mitigation and for supporting circular-economy strategies focused on energy recovery and the reduction of losses along value chains. Unmanned aerial vehicles (UAVs) enable facility-scale measurements with high spatio-temporal resolution. However, most studies rely on point sensors that require repeated flights at different altitudes and interpolation from low-density datasets, leading to potentially high uncertainty under turbulent and variable wind conditions. Open-path optical sensors can increase the effective sampling volume and improve plume representativeness, but practical, field-ready frameworks remain relatively under-developed. This study presents an operationally oriented UAV mass-balance framework for facility-scale CH₄ quantification using a drone-mounted open-path TDLAS sensor. The method is demonstrated across three representative emission contexts in Italy. At an intensive dairy cattle farm, 24 tests were conducted over one year (two per month). UAV-derived model-corrected net enteric emissions ranged from 0.182 to 0.242 kg CH₄ AU⁻¹ day⁻¹ and were broadly consistent with IPCC reference estimates. At a natural gas compression facility, six tests were conducted under two operating configurations, with site-level emissions of 14.3 ± 4.1 and 11.9 ± 2.6 kg CH₄ h⁻¹, showing consistency with an independent Method 21 bottom-up estimate. At a municipal solid-waste landfill, four quantification flights yielded site-scale fluxes ranging from 3.7 to 11.5 g s⁻¹, with uncertainty dominated by meteorology. Overall, the results show that the proposed open-path framework is promising for facility-scale CH₄ assessment across different emission contexts, with performance primarily governed by wind stability. This supports more frequent, management-oriented monitoring in line with circular-economy objectives. However, the approach remains sensitive to meteorological conditions, particularly under non-steady flow and when wind speed is measured at a single near-ground location.

1. INTRODUCTION

Mitigating global warming requires increasingly reliable and scalable emission monitoring tools, particularly for gases with a high global warming potential such as methane (CH₄), whose greenhouse effect is approximately 86 times greater than that of CO₂ over the first two decades following emission (IPCC, 2021). Within the context of the transition towards circular economy models, the accurate quantification of CH₄ emissions represents not only an environmental requirement, but also an operational prerequisite for optimising energy recovery, reducing losses along production chains, and supporting more efficient resource management strategies.

Recent estimates indicate that agricultural and livestock activities contribute approximately 43% of global anthropogenic CH₄ emissions, the energy sector accounts for 37%, and the waste sector—particularly landfills—for the remaining 20% (Saunio et al., 2025). Across all these sectors, the availability of robust and representative emission data is essential not only for achieving international climate targets, but also for supporting targeted mitigation actions and ensuring transparent, verifiable reporting in line with evolving regulatory and sustainability frameworks.

In this context, airborne remote sensing techniques—including satellite observations, crewed aircraft and unmanned aerial vehicles (UAVs)—are playing an increas-



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ingly important role in CH₄ monitoring (Shaw et al., 2021; Morales et al., 2022). Among these platforms, UAVs offer distinct advantages at the facility scale owing to their ability to operate at low altitude, rapid deployment, and high spatio-temporal resolution. These characteristics enable measurements to be carried out close to emission sources at relatively low cost and facilitate integration into monitoring, reporting and verification (MRV) systems consistent with circular economy principles (Allen et al., 2019; Scheutz et al., 2025).

The growing availability of miniaturised, low-cost sensors has further accelerated the adoption of UAVs for environmental monitoring applications (Burgués & Marco, 2023). Most existing studies quantify CH₄ emissions using point sensors mounted on multirotor platforms in combination with mass-balance approaches that require simultaneous measurements of methane concentration and wind fields (Andersen et al., 2023; Vinković et al., 2022; Yong et al., 2024). However, these approaches are constrained by low vertical sampling density and the non-simultaneity of measurements. Plume reconstruction typically requires repeated flights at different altitudes, introducing significant interpolation uncertainties that are further amplified by atmospheric turbulence and short-term wind variability (Allen et al., 2019; Yong et al., 2024). Under typical operating conditions, estimation errors may therefore exceed 100% even in relatively stable wind regimes (Liu et al., 2024; Mohammadloo et al., 2025).

These limitations motivate alternative sensing strategies that increase the effective sampling volume while remaining compatible with rapid, low-altitude UAV surveys.

To address these constraints, increasing attention has turned to UAV deployments using open-path optical sensors, particularly tunable diode laser absorption spectroscopy (TDLAS) systems that provide path-integrated methane observations rather than point measurements (Golston et al., 2018; Yang et al., 2018; Fosco et al., 2025). In principle, open-path sensing can improve plume representativeness because each observation samples a larger air volume and partially relaxes the need for dense point sampling across the downwind cross-section. Unlike point-sensor approaches, the open-path TDLAS measurements provide concentration values integrated along the vertical direction, eliminating the need for vertical interpolation. Spatial interpolation is therefore required only in the horizontal direction. Furthermore, the 10 Hz acquisition frequency provides a higher spatial sampling density than that typically achieved by point sensors (approximately 1 Hz), reducing the distance between consecutive measurements and the associated interpolation uncertainty. This makes the approach attractive for facility-scale applications where rapid deployment and operational simplicity are essential.

Despite this potential, open-path UAV quantification remains comparatively under-developed and far less widely adopted than point-sensor approaches. The limited diffusion is not primarily due to a lack of sensing capability, but to methodological issues that complicate routine field deployment. These include the interpretation of path-integrated signals within turbulent plumes, their coupling

with wind characterisation, and the definition of robust background-handling procedures and uncertainty budgets that are transparent and reproducible across sites and campaigns (Varon et al., 2018; Mohammadloo et al., 2025; Hasan et al., 2025). As a result, although a small number of studies has demonstrated feasibility under selected conditions (Golston et al., 2018; Yang et al., 2018), there remains a need for practical frameworks that translate this promise into repeatable, operationally deployable quantification.

Against this background, this paper presents a field-oriented UAV mass-balance framework for facility-scale CH₄ quantification using a drone-mounted open-path TDLAS sensor. The focus is on method applicability and transferability rather than platform aerodynamics, and on providing operational steps that can be replicated in practice. The framework combines rapid multi-altitude transects to reconstruct a downwind measurement plane, an explicit background estimation strategy based on the same acquisition configuration, and a formal uncertainty treatment driven by meteorological and instrumental variability. The method is demonstrated across three representative emission contexts in Italy, an intensive dairy cattle farm, a natural gas compression facility and a municipal solid-waste landfill.

From a circular-economy perspective, access to reliable emission estimates that can be obtained at high temporal frequency is a practical enabler for moving from sporadic campaigns to more continuous, management-oriented monitoring. Across the three sectors considered, UAV-based quantification can support optimisation of energy recovery from biogas and natural gas, reduction of losses along processes, and identification of emission hotspots that can be addressed through targeted interventions. In this sense, the proposed method is not merely a measurement tool. It provides an operational approach that helps integrate methane monitoring into environmental management and performance tracking, with direct benefits for efficiency, mitigation actions, and transparent reporting.

2. MATERIALS AND METHODS

2.1 UAV Platform and Instrumentation

The UAV platform used is a commercial quadcopter (Matrice 350 RTK, DJI) equipped with an RTK (Real-Time Kinematic) system for high-precision positioning. In many UAV applications, spatial coordinates are derived from GPS (Global Positioning System) measurements combined with onboard atmospheric pressure. This approach can lead to positioning errors of several tens of centimetres and is therefore insufficient to quantify atmospheric CH₄ fluxes from a UAV with adequate accuracy (Morales R. et al., 2022). The RTK system onboard the DJI M350 provides a positioning accuracy of 1.5 cm (± 1 ppm) in the vertical direction and 1 cm (± 1 ppm) horizontally. To account for site topography during each flight, the system also integrates a radar altimeter (NRA24, Hunan Nanoradar Science and Technology Co., Ltd), a compact and lightweight unit (95 g) operating at 24 GHz, which improves altitude determination to 0.1 m. Compared with relying solely on RTK positioning, the radar measurement provides an independent constraint on the UAV–ground distance and is expected to

improve the determination of the vertical position of the optical path, particularly over uneven terrain. The nominal 0.1 m accuracy of the radar-derived distance provides a quantitative estimate of the additional constraint introduced by the altimeter, although the overall improvement in optical-path determination was not directly quantified through an RTK-only comparison in this study.

The UAV is equipped with an OP-TDLAS (open-path tunable diode laser absorption spectroscopy) sensor, mounted in a nadir-looking configuration. The commercial unit employed (Laser Falcon, Pergam Inc.) measures path-integrated CH_4 along optical paths between 0.5 and 100 m, with a sensitivity of 1 ppm·m over a range of 0-50,000 ppm·m. An onboard computer (SkyHub, UgCS) enables continuous communication with the variable-path OP-TDLAS sensor and provides real-time visualisation at the ground station (remote controller and laptop).

The radar altimeter is originally intended by the manufacturer to be installed at the front of the UAV for constant-altitude “terrain-following” operations. In that configuration, the sensor is tilted relative to the UAV body to measure terrain elevations ahead of the flight path, enabling real-time altitude correction and a trajectory approximately parallel to the ground. In the methodology adopted here, by contrast, the altimeter is used to determine the optical path length corresponding to each OP-TDLAS measurement. Consequently, its mounting position must ensure

that the altimeter and OP-TDLAS reference frames are co-axial. For this reason, a dedicated mounting bracket was designed and fabricated using a 3D printer, allowing the altimeter to be positioned parallel to the OP-TDLAS sensor.

The setup is completed with a meteorological station (WL-21, Scarlet Tech Inc.), which records wind, pressure, and temperature at 0.5 Hz. Wind-speed resolution is 0.1 m s^{-1} (range 0-50 m s^{-1}) and wind-direction resolution is 1° (range 0-360°N), while the temperature and pressure sensors resolve unit changes. The manufacturer-stated accuracy is 2%, which is periodically verified through calibration tests. The station is mounted on a commercial tripod (Bosch Professional BT 250) fitted with spirit levels for horizontal and vertical alignment. Several design features (approximately 4 kg mass, a ballast hook for high-wind conditions, a star-shaped base, and ground-spike feet for improved stability) make the tripod suitable for surveys under varying environmental and site-specific conditions. The station is secured via a dedicated bracket that enables measurements up to 2.70 m above ground level and can be adapted for greater heights. This is relevant both for comparing wind speed at different elevations (supporting validation of vertical-profile reconstruction models) and for improving field operability by selecting the optimal measurement height in the presence of site obstacles. The overall instrumentation setup is shown in Figure 1, and the main technical specifications are summarised in Table 1.

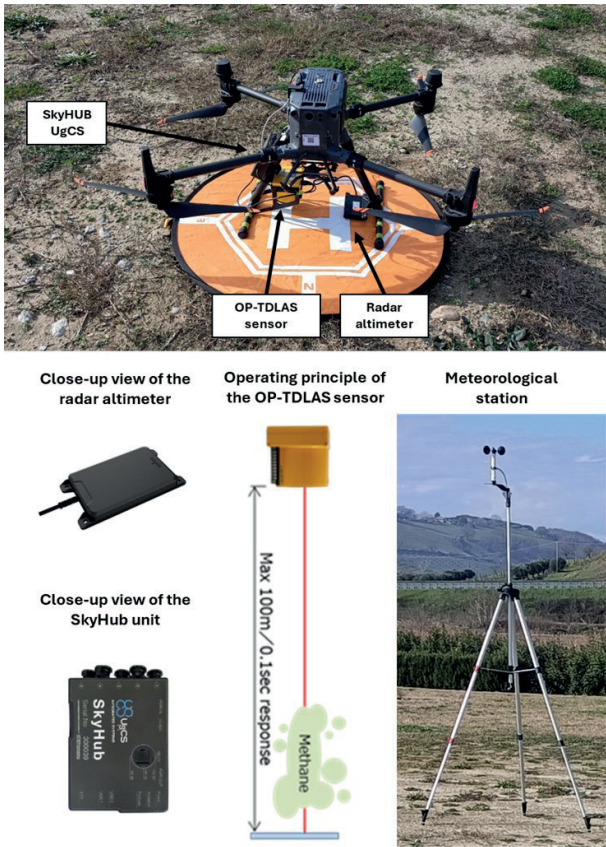


FIGURE 1: Instrumentation for UAV-based methane measurements. Top: DJI Matrice 350 RTK equipped with a OP-TDLAS sensor, a radar altimeter, and a SkyHub (UgCS) unit. Bottom: close-ups of the radar altimeter and SkyHub (left), schematic of the OP-TDLAS operating principle (centre), and the tripod-mounted meteorological station (right).

TABLE 1: Main technical specifications of the instrumentation.

Component	Model	Key specifications
UAV platform	Matrice 350 RTK / DJI	RTK accuracy: 1.5 cm vertical (± 1 ppm) 1 cm horizontal (± 1 ppm)
Radar altimeter	NRA24 / Hunan Nanoradar Science and Technology Co., Ltd	95 g; 24 GHz altitude precision 0.1 m
CH ₄ sensor (OP-TDLAS)	Laser Falcon / Pergam Inc.	Optical path 0.5–100 m sensitivity 1 ppm·m range 0–50,000 ppm·m
Onboard computer	SkyHub / UgCS	Continuous sensor interfacing real-time display at ground station
Meteorological station	WL-21 / Scarlet Tech Inc.	0.5 Hz; wind speed resolution 0.1 m s ⁻¹ (0–50 m s ⁻¹) wind direction resolution 1° (0–360°N) stated accuracy 2%
Tripod	BT 250 / Bosch Professional	Levelled mounting; ~4 kg measurement height up to 2.70 m (extendable)

2.2 Mass-balance framework

The CH₄ emission rate is quantified using a mass-balance method by sampling a vertical measurement plane positioned downwind of the emitting source with the UAV survey flight pattern (Figure 2).

The procedure uses methane measurements integrated along the optical path (derived from the sensor output in ppm·m), acquired through consecutive scans at different altitudes to reconstruct the signal distribution across the plane. For each vertical scan i , the flux F_i (g s⁻¹) is computed as:

$$F_i = \int_0^H v_{z,i} \sin \theta (\bar{\rho}_{CH_4,d,z,i} - \bar{\rho}_{CH_4,b,z,i}) dz \quad (1)$$

where $v_{z,i}$ is the wind speed (m s⁻¹) at height z (m), θ is the angle between the wind direction and the optical-path geometry, and $(\bar{\rho}_{CH_4,d,z,i} - \bar{\rho}_{CH_4,b,z,i})$ is the increment in column-integrated density (g m²) relative to background. Starting from these measurements, it is possible to estimate the concentration of CH₄ between two heights H_1 and H_2 . The final emission rate F (g s⁻¹) is obtained by summing the

contributions from the windows between two successive transects during a single flight (Equation 2):

$$F = \sum_{i=1}^n (F_{H_{i+1}} - F_{H_i}) \quad (2)$$

where F_{H_i} and $F_{H_{i+1}}$ are two successive measurement altitudes defining each vertical window, and n is the number of windows considered in the flight. Each contribution is calculated from the measurements associated with the corresponding vertical window, while repeated scans are used to account for instantaneous variability in the concentration traces.

Importantly, to avoid double counting of the vertical dimension, the vertical column-integrated TDLAS measurements are differenced between consecutive flight altitudes, so that each increment represents the concentration enhancement associated with the corresponding horizontal section of the vertical plane, following the approach described by Fosco et al. (2024).

The procedure accounts for instantaneous fluctuations in the methane concentration signal induced by the turbu-

UAV survey flight pattern

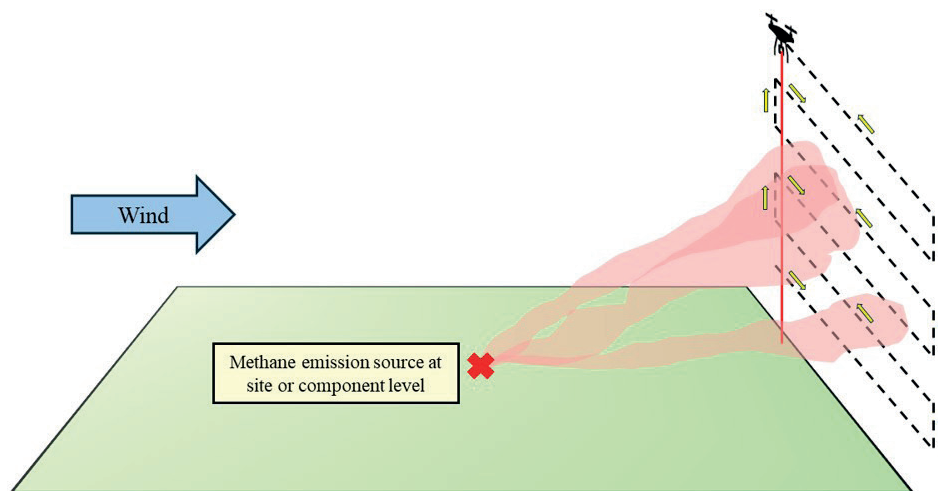


FIGURE 2: Schematic of the UAV survey flight pattern used to quantify methane emissions at site or component level. Yellow arrows indicate the UAV direction of travel, while the red line represents the optical path of the laser beam emitted by the OP-TDLAS sensor.

lent nature of the flow. The characteristic temporal scale of these fluctuations is evaluated from the autocorrelation function of the concentration signal, expressed as:

$$R_{c(\tau)} = \frac{1}{N} \sum_{i=1}^N \frac{[C(t_i) - \bar{C}][C(t_i + \tau) - \bar{C}]}{\sigma_c^2} \quad (3)$$

where $C(t_i)$ is the measured CH_4 concentration at time t_i , $\bar{C}$ is the mean concentration, σ_c^2 is the variance of the concentration signal, and τ is the time lag. The autocorrelation time τ_c is determined from the decay of the autocorrelation function according to a predefined threshold, such that $R_{c(\tau_c)} = k$, where k is a dimensionless threshold parameter. This characteristic time scale is then used to account for short-term fluctuations in the concentration signal during each scan. The sensor output in ppm-m is converted to an integrated concentration (g m^{-2}) assuming ideal-gas behaviour:

$$\bar{p}_{\text{CH}_4, d, z, i} = \left[\frac{P * 16.04 * (1 - H_2O)}{RT} \right] * \frac{(\text{ppm} - m)_{d, z, i}}{10^6} \quad (4)$$

where P , T and R are atmospheric pressure, temperature, and the universal gas constant, respectively; H_2O is estimated from temperature and relative humidity. When humidity is not measured, the $(1 - H_2O)$ term may be neglected, with an expected impact of $<1\%$ (Morales et al., 2022).

The background, $\text{CH}_{4, b}$, is derived from an upwind flight performed immediately before each flux-quantification flight, using the same measurement configuration. The upwind measurement was used to characterise the atmospheric CH_4 concentration representative of the area and meteorological conditions at the time of the quantification flight. Measurements are first screened to remove false positives using a dedicated algorithm (De Molfetta et al., 2025), then normalised by the optical-path length and averaged to obtain a background value in ppmv.

Assuming the background is approximately uniform across the plane, the integrated background component $\bar{p}_{\text{CH}_4, d, z, i}$ is computed as the product of this value and the optical-path length. This approach reduces the risk of over-estimating the background when a substantial fraction of optical paths intersects the plume during scanning. Overall uncertainty is quantified via error propagation applied to Equation 5:

$$\delta Q_{\text{CH}_4} = \sqrt{\left(\frac{\delta Q_{\text{CH}_4}}{\delta \bar{v}}\right)^2 + \left(\frac{\delta Q_{\text{CH}_4}}{\delta \bar{\theta}}\right)^2 + \left(\frac{\delta Q_{\text{CH}_4}}{\delta \bar{p} - \bar{m}}\right)^2 + \left(\frac{\delta Q_{\text{CH}_4}}{\delta \bar{p}}\right)^2} \quad (5)$$

with:

$$\delta \bar{v}, \delta \bar{\theta} = \sqrt{(\text{measurement uncertainty}_{v, \theta})^2 + (\text{temporal variation}_{v, \theta})^2} \quad (6)$$

$$\delta \bar{p} - \bar{m}, \delta \bar{p} = \text{measurement uncertainty}_{\delta \bar{p} - \bar{m}, \delta \bar{p}} \quad (7)$$

where, for v and θ , instrumental uncertainty is combined with temporal variability (1σ), whereas for integrated concentration and positioning only the instrumental component is considered. The mass-balance formulation assumes that the wind field measured at the meteorological station is representative of the sampling plane.

To minimise spatial differences between the measured wind field and the conditions prevailing across the sampling plane, the meteorological station was positioned in close proximity to the measurement plane. This reduces the potential error associated with spatial variability in wind conditions. The vertical wind reconstruction model used in the present approach was also experimentally validated under near-field conditions. Nevertheless, increasing the distance between the meteorological station and the measurement plane may result in differences between the measured wind conditions and those actually affecting the sampling plane. Such differences may introduce errors into the reconstructed wind profile and, consequently, affect the estimated CH_4 flux.

Uncertainty associated with background estimation was considered negligible and was therefore not included in the propagated uncertainty budget, given the rapid acquisition time, which limits the observable variation in background concentration during the survey.

2.3 Case-study sites

To evaluate the proposed UAV mass-balance framework under operational conditions, measurement campaigns were carried out at three representative facilities in Italy, namely an intensive dairy cattle farm, a natural gas compression facility within the Oil & Gas sector, and a municipal solid-waste landfill. The three sites were selected to span distinct methane emission settings, including predominantly diffuse surface emissions at the landfill, a confined area with clustered sources associated with dairy housing and handling activities, and potentially localised fugitive emissions from heterogeneous equipment distributed at different elevations at the compression facility.

All surveys followed the acquisition protocol described in Section 2.2, with the vertical measurement plane positioned downwind of the facility and typically located 25-30 m from the site boundary. Quantification flights were organised as discrete tests, each comprising multiple downwind transects used to reconstruct a vertical plane at several heights above ground level, and upwind checks were used to exclude non-site contributions. At the dairy farm, emission estimates were expressed on a functional unit basis to ensure comparability across test days with differing herd structures, and the net enteric component was derived by accounting for the manure-related contribution.

3. RESULTS AND DISCUSSION

3.1 Dairy cattle farm

Figure 3 summarises the results of all UAV tests carried out at an intensive dairy farm, reporting enteric methane emission rates in $\text{kg CH}_4 \text{ AU}^{-1} \text{ day}^{-1}$. To obtain a robust reference for the UAV-derived estimates, measured emissions were compared against the IPCC model, using both Tier 1 and Tier 2 calculations (with their typical uncertainty ranges of $\pm 50\%$ and $\pm 20\%$, respectively).

In order to make emission estimates comparable across test days despite differences in herd structure, animals were standardised to a single functional unit (AU,

Methane emission rate – Dairy Cattle Farm

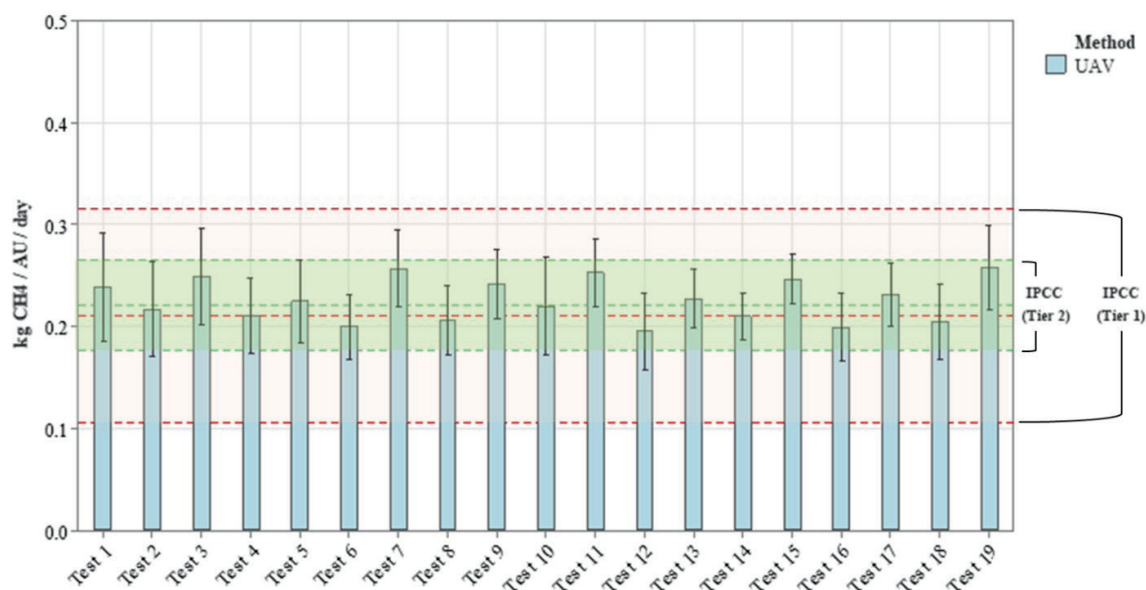


FIGURE 3: UAV-based enteric CH₄ emission rates in an intensive dairy farm compared with IPCC Tier 1 and Tier 2 estimates. The red band represents the Tier 1 uncertainty (±50%), while the green band indicates the Tier 2 uncertainty range (±20%).

equal to 500 kg live weight) by converting non-lactating categories into lactating-cow equivalents. Dry cows were assumed to emit 39% less CH₄ than lactating cows (ISPRA, R398/2024), while heifers/young stock (6-24 months) were assumed to emit 75% less (Vinković et al., 2022). Because the UAV quantifies the total CH₄ flux through the down-wind sampling plane (enteric plus manure-related contributions), the manure component was estimated using the IPCC Tier 2 approach and subtracted, so that the values reported represent net enteric emissions.

Across the campaign, UAV-derived enteric emissions ranged from 0.182 to 0.242 kg CH₄ AU⁻¹ day⁻¹, showing consistency with the IPCC reference estimates. Given the uncertainty associated with the IPCC inventory approaches, this comparison is intended to demonstrate consistency between the UAV-derived estimates and the reference values rather than to provide direct validation of the proposed methodology. The maximum relative deviation from Tier 1 was 0.54%, and the mean relative deviation from Tier 2 was 4.32%, remaining consistent with expected Tier 2 uncertainty and indicating that the UAV approach yields estimate comparable to inventory-based modelling under operational conditions.

The residual discrepancies are plausibly explained by the intrinsic short-term variability of enteric CH₄ production (e.g., daily dynamics and peaks after feeding; Rodrigues et al., 2024) and by sensitivity to microclimatic and nutritional drivers, since temperature/heat stress can reduce animal activity and emissions (Ngwabie et al., 2011; Saha et al., 2014), and diet composition (particularly higher fibre and lower fat) is generally associated with increased methanogenesis (Benaouda et al., 2019), meaning that snapshot UAV measurements may deviate from model estimates representing averaged conditions.

3.2 Natural gas compression station

The UAV-based method was applied at several facilities within the Oil & Gas sector. This section reports the results of a test carried out at a natural gas compression facility under two different operating configurations (hereafter referred to as A and B). On average, configuration B exhibited higher wind speeds than configuration A (+33%), a condition consistent with improved plume representativeness and a reduced uncertainty in the inferred emission flux.

At the site scale, the UAV-based approach yielded an emission rate of 14.3 kg CH₄ h⁻¹ (uncertainty ±4.1 kg h⁻¹, ~29%) for configuration A and 11.9 kg CH₄ h⁻¹ (±2.6 kg h⁻¹, ~22%) for configuration B (Figure 4).

In parallel, an independent bottom-up assessment based on Method 21 was performed as a reference. At the site level, the bottom-up approach returned 15.8 kg CH₄ h⁻¹ for configuration A and 13.5 kg CH₄ h⁻¹ for configuration B, assuming an overall uncertainty of ±51% (Table 3.2-1). The relative difference between the UAV-based and bottom-up estimates was 9.4% (configuration A) and 11.6% (configuration B), which falls within the maximum tolerance specified by the applicable standard, Regulation (EU) 2024/1787, for comparisons between top-down and bottom-up methodologies (±20%).

The uncertainty analysis for the UAV-based method indicates that wind speed is the dominant contributor to the total variance, whereas wind direction provides a secondary contribution (on the order of a few percentage points). This is consistent with standard error-propagation formulations for mass-balance approaches and with experimental evidence under low-wind conditions.

Under such conditions, the method may underestimate the flux when the plume does not retain sufficient momentum across the measurement plane, or overestimate it

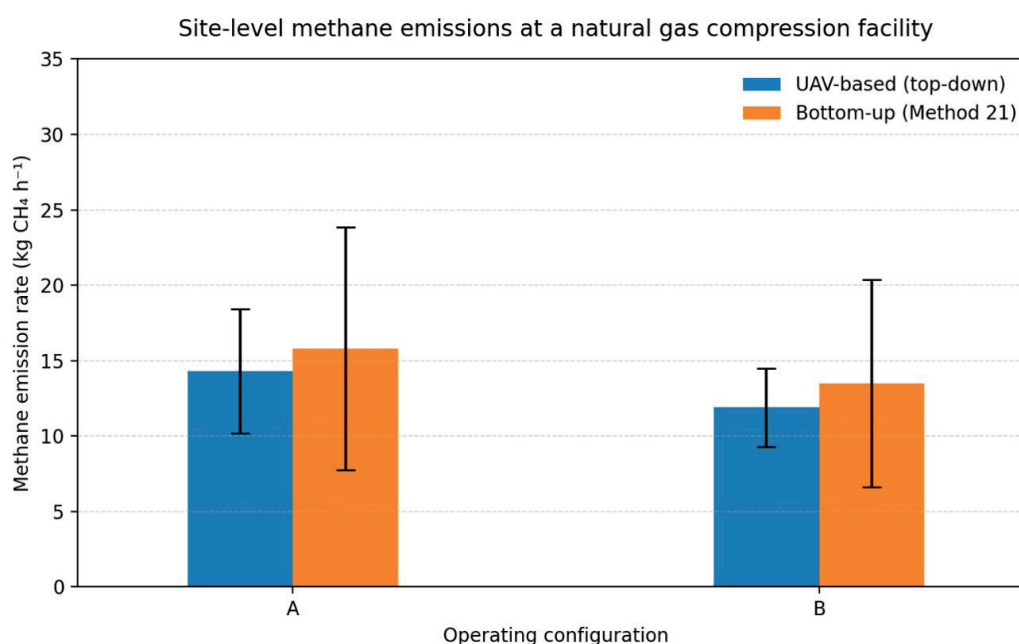


FIGURE 4: Site-level methane emission rates estimated at a natural gas compression facility using the UAV-based approach and the bottom-up Method 21 for two operating configurations (A and B). Error bars indicate the reported uncertainties (UAV-based: ± 4.1 and ± 2.6 kg CH₄ h⁻¹ for A and B, respectively; bottom-up: $\pm 51\%$ of the estimate).

when parts of the plume become quasi-stationary and undergo local recirculation due to turbulence, thereby increasing the observed integrated concentration. Consequently, in future campaigns, reductions in UAV-related uncertainty should be pursued primarily through (i) the selection of meteorological windows characterised by more stable winds and (ii) increased replication of transects within the same window, leveraging rapid data acquisition to improve statistical robustness.

3.3 Municipal solid waste landfill

The UAV method was applied at a municipal solid-waste landfill in Italy (area ≈ 4.2 ha) that had been closed to waste acceptance and was equipped with temporary capping and an active landfill-gas collection system. During two tests conducted between July and September 2024, each comprising two quantification flights, the engine and flare had been switched off approximately two weeks before the measurements as part of the landfill's operating conditions, independently of the UAV measurement campaign. Dedicated upwind flights ruled out any CH₄ contributions not attributable to the site. Fugitive emissions were quantified by reconstructing, downwind, a vertical measurement plane consisting of four horizontal transects at 10, 20, 30 and 40 m above ground level (AGL), extended 30 m beyond the lateral projection of the landfill footprint on both sides to ensure full plume interception. However, the possible extension of portions of the plume beyond the surveyed limits represents a limitation of the measurements.

For Test 1, despite comparable mean wind speeds (4.96 ± 1.15 and 4.77 ± 1.17 m s⁻¹), wind-direction variability differed markedly ($294 \pm 107^\circ$ vs $305 \pm 21^\circ$). The estimated CH₄ fluxes were 11.52 g s⁻¹ and 8.54 g s⁻¹, corresponding to 987 ± 392 and 732 ± 117 mg CH₄ m⁻² h⁻¹ (Table 3), with

total uncertainties of ± 4.57 g s⁻¹ (39.6%) and ± 1.37 g s⁻¹ (16%), respectively. Uncertainty propagation shows that the error budget is dominated by meteorology, with wind speed contributing 60.0–68.7% and wind-direction variability 25.1–34.8%, whereas instrument-related uncertainty is $\sim 6\%$ and positioning contributes $<1\%$, consistent with what is typically reported for airborne mass-balance implementations.

In Test 2, the two flights yielded specific emissions of 320 ± 280 and 578 ± 385 mg CH₄ m⁻² h⁻¹ (Table 3), equivalent to a site-level mass emission rate between 3.7 and 6.7 g s⁻¹.

For an independent comparison at the same case study site, a flux-chamber survey based on 140 points was carried out, with areal integration using the Sinclair approach and the Sichel estimator, resulting in an integrated flux of 2.87 g s⁻¹ (the corresponding specific emission reported in Table 3 is 224 mg CH₄ m⁻² h⁻¹). Relative to Test 2, the flux chambers underestimate the UAV-derived fluxes by $\sim 30\%$ (vs Flight 1) and $\sim 61\%$ (vs Flight 2). This discrepancy is consistent with evidence that chambers, sampling very small surface areas, require substantial spatial upscaling over highly heterogeneous landfill covers and may therefore under-represent hotspots and inaccessible zones.

A tendency towards underestimation has been widely documented (Borjesson et al., 2000; US EPA, 2018) and is exacerbated when sampling density is limited (Babilotte, 2011; Levy et al., 2012; Wong, 2018). In the present case, the sampling density was 18.2 points ha⁻¹, higher than in other Italian chamber studies (Di Bella et al., 2011; Folino et al., 2024), which plausibly explains the good agreement in terms of order of magnitude with the UAV estimates.

Moreover, the chamber–airborne discrepancy is comparable, and often smaller, than that reported in the liter-

ature for faster, higher-altitude airborne platforms. For example, Yeşiller et al. (2022) found flux-chamber estimates to be up to an order of magnitude lower than aerial mass-balance measurements, whereas in this study the estimates remain within the same order of magnitude, consistent with reduced spatio-temporal uncertainty achievable with low-altitude UAV surveys.

Part of the observed differences may also be related to the different measurement durations of the two approaches. The flux chamber survey required approximately two hours to complete, whereas each UAV flight lasted only a few minutes. This difference in sampling duration may result in discrepancies between the two methods because methane emissions can fluctuate during the chamber survey, while the UAV measurement represents a much shorter temporal snapshot of the emission conditions (Table 2).

Finally, comparisons with modelling approaches reported in the literature indicate that models can, in some cases, overestimate emissions relative to measurements (Di Bella et al., 2011; Di Bella et al., 2024), partly because coefficients calibrated under ideal steady-state conditions may overpredict biogas generation (Cossu et al., 1996).

3.4 Implications for the oil & gas, livestock and waste management sectors

In Europe, Regulation (EU) 2024/1787 on methane emission reductions in the energy sector requires companies to measure, monitor, report and verify emissions in line with high monitoring standards. It is also the first legal instrument to explicitly allow the use of drones for site-level monitoring. Operators must submit an annual CH₄ emissions report, subject to independent verification, to the competent authorities of the Member States in which the sites are located. The relatively low cost of UAV-based methods may encourage rapid uptake, provided that

quantification achieves sufficient accuracy and precision. In this respect, drone-mounted open-path laser sensors appear promising, and the error associated with using column-averaged wind data can be substantially reduced, by up to about 50 per cent, when the column is subdivided and averaged across multiple segments. Further momentum is provided by the common framework introduced by Regulations (EU) 2019/945 and (EU) 2019/947, which harmonise drone rules across Member States, although some outstanding issues still require national action. Protocol standardisation also improves the reproducibility of tests across different countries. From an organisational perspective, companies will need to integrate UAV monitoring into environmental management systems, train staff in data interpretation, and align reporting with verification requirements. Beyond compliance, UAV monitoring can enhance transparency, reduce reputational risk, and identify emission hotspots for targeted action, shifting methane monitoring from a regulatory obligation to a management tool.

In the livestock sector, Denmark is considering the introduction of a tax on farm CH₄ emissions from 2030, as part of an agreement aimed at reducing greenhouse gas emissions by 70 per cent relative to 1990. The effectiveness of this measure is debated because reliable and accessible technologies for measuring and mitigating enteric methane at farm scale are still lacking. Conventional methods, including respiration chambers and tracer-gas techniques, remain constrained by cost, complexity and practical applicability. In this context, open-path laser sensors mounted on UAVs could support more accurate farm-scale quantification, with high-frequency measurements and broader spatial coverage. This would be useful both for assessing mitigation measures such as feed additives and for supporting monitoring, reporting and verification systems. From a management perspective, such data can

TABLE 2: Average specific methane emissions from different Italian landfills.

Study	Operating conditions	Average specific CH ₄ emission [mg CH ₄ m ⁻² h ⁻¹]	Method
Di Bella et al., (2011) Landfill 1 (Bellolampo)	Active – temporary capping	1368 ± 4104 5123 4840	Flux chamber LandGEM model Erhig model
Brilli et al., (2024) Landfill 1 (Giugliano) Landfill 2 (Case Passerini)	Closed – final capping Closed – final capping	250 ± 238 29 ± 25	Eddy Covariance Eddy Covariance
Folino et al., (2024) Landfill 1 (Fossetto) 2022 2021 2020 2019	Active – temporary capping	720 ± 1086 628 ± 954 403 ± 730 573 ± 1704	Flux chamber
This study Landfill 1 Test 1 Flight #1 Flight #2 Test 2 Flight #1 Flight #2	Closed – temporary capping	 987 ± 392 732 ± 117 320 ± 280 578 ± 385 224	 UAV Mass Balance UAV Mass Balance UAV Mass Balance UAV Mass Balance Flux chamber

inform farm decision-making, support compliance, and improve communication with stakeholders, helping to prioritise cost-effective mitigation options.

For waste management, estimating fugitive CH₄ emissions from landfills remains challenging. Although several techniques exist, there is no internationally recognised reference standard, and application is still limited to a small number of countries. The main difficulties stem from extreme spatial and temporal variability. Fluxes can vary by orders of magnitude over distances of only a few metres, and hotspots can account for more than half of total emissions while occupying a small fraction of the surface. Atmospheric conditions, including pressure and wind, can also influence emissions on hourly and sub-hourly timescales. Accumulation chambers, while widely used, tend to underestimate emissions because they do not adequately represent emission distributions and often miss contributions from wells, vents and inaccessible areas. More advanced methods such as DIAL and tracer approaches can perform well at site scale, but they are costly and difficult to deploy for extended periods. In this setting, UAVs equipped with open-path sensors enable high-frequency surveys over large areas, provide denser spatial coverage, and access hazardous or otherwise unreachable zones. They can support management by delivering timely hotspot information that allows operators to prioritise actions, optimise gas capture and flaring, strengthen compliance and improve transparency.

It is emphasised that CH₄ monitoring is not a circular-economy activity in itself, but can support circular-econ-

omy objectives by identifying resource losses and supporting improved recovery and management of CH₄.

A summary of the key advantages of UAV-based methane monitoring across the three sectors is presented in Figure 5.

4. CONCLUSIONS

This study developed and tested a UAV-based mass-balance framework for quantifying methane emissions using a drone-mounted open-path TDLAS sensor, supported by centimetre-level RTK positioning and radar altimetry to improve geometric accuracy of the optical path. The methodology reconstructs a downwind vertical measurement plane through repeated horizontal transects at multiple heights, applies background correction derived from dedicated no-emission acquisitions, and quantifies uncertainty via formal error propagation that combines instrumental errors with the temporal variability of wind speed and direction.

Field deployments at three representative methane settings in Italy demonstrate that the approach is effective at both site and sector-relevant scales. At the intensive dairy farm, UAV-derived net enteric emissions ranged from 0.182 to 0.242 kg CH₄ AU⁻¹ day⁻¹ and showed close agreement with IPCC references, with a maximum deviation of 0.54% relative to Tier 1 and a mean deviation of 4.32% relative to Tier 2, remaining consistent with the expected Tier 2 uncertainty envelope. At the natural gas compression facility, site-level UAV estimates of 14.3 ± 4.1 kg CH₄ h⁻¹ and 11.9 ± 2.6 kg CH₄ h⁻¹ for two operating configurations were



FIGURE 5: Overview of sector-specific benefits for the Oil & Gas, Livestock and Waste Management sectors, highlighting the potential of drone-mounted open-path laser sensing to deliver cost-effective, high-resolution measurements, improved quantification, and support for monitoring, reporting and verification (MRV).

consistent with an independent Method 21 bottom-up assessment within 9.4–11.6%, which is within the tolerance commonly adopted for top-down versus bottom-up comparisons. At the municipal solid-waste landfill, site-scale fluxes spanned 3.7–11.5 g s⁻¹ across tests and flights, with uncertainty dominated by meteorology. A flux-chamber survey provided the same order of magnitude but underestimated UAV-derived fluxes by approximately 30–61%, consistent with known limitations of point sampling over highly heterogeneous covers and hotspot-driven emission patterns.

Across all case studies, the results highlight that the dominant limitation of UAV mass-balance quantification is meteorological sensitivity, particularly under low-wind or highly variable wind-direction conditions. Wind speed was consistently the primary driver of the propagated uncertainty, with wind-direction variability providing a secondary contribution.

These findings indicate that improved quantification can be achieved by prioritising measurement windows characterised by relatively stable atmospheric conditions and wind speeds between 1 and 6 m s⁻¹, while avoiding periods of atmospheric instability. In addition, increasing transect replication and ensuring an appropriate measurement-plane design can strengthen the statistical robustness and reliability of the estimates. Overall, the results indicate the potential of the UAV-based approach for CH₄ emission assessment, while further testing and validation are required to assess its broader applicability.

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