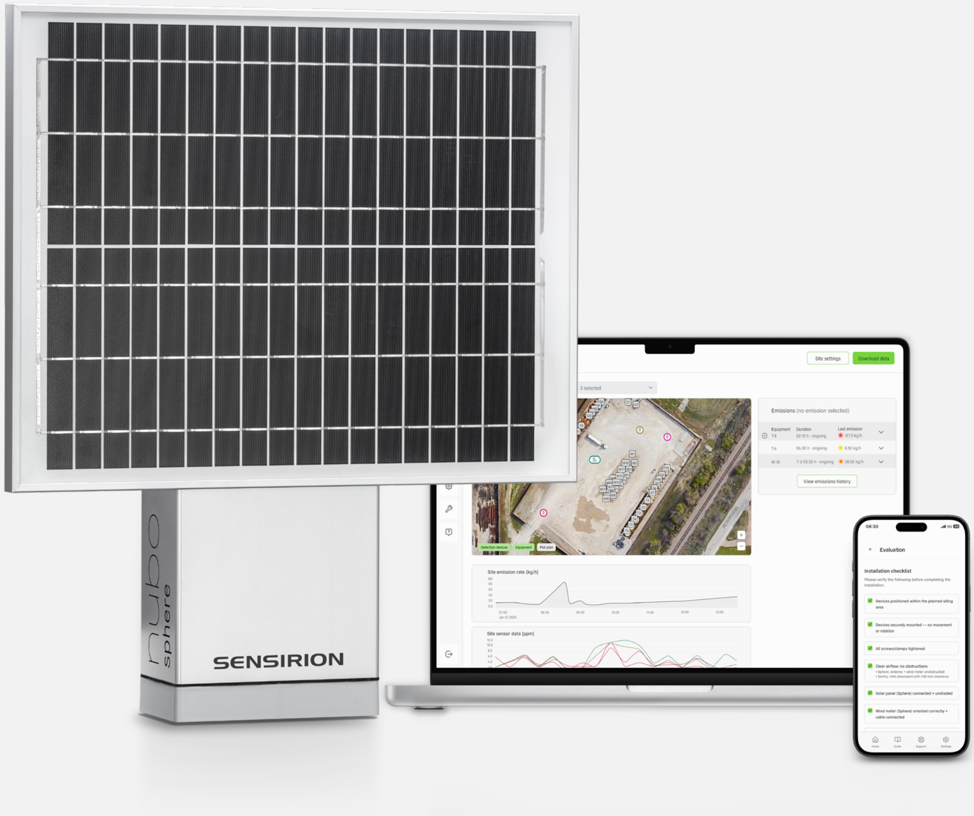

Nubo Sphere
Emissions accounting and event detection performance

Performance evaluation of Nubo Sphere in the 2025 ADED 2.0 controlled release campaign

This technical report evaluates the performance of the Nubo Sphere continuous methane monitoring system using data from the ADED 2.0 controlled release campaign, focusing on its ability to deliver accurate site-level emissions accounting and actionable detection of abnormal emission events.

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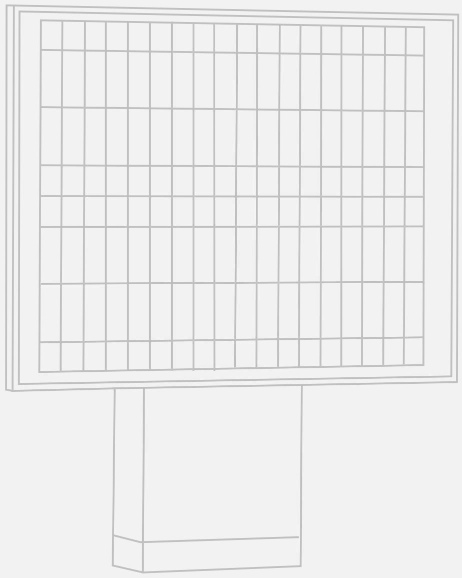


Introduction

Continuous methane monitoring enables operators to quantify total site-level emissions for reporting as well as identify abnormal emission events as they occur for fast mitigation action. Unlike periodic surveys such as aerial or optical gas imaging inspections, continuous monitoring provides time-resolved measurements that capture both sustained emissions and intermittent events. Sensirion Connected Solutions has developed the Nubo Sphere solution, combining proprietary photoacoustic methane sensors with autonomous localization and quantification analytics to support these monitoring objectives.

In this technical report, we first present results for site inventories focusing on the ability of Nubo Sphere to quantify total site-level emissions over several weeks and months. We specifically demonstrate the high-quality quantification performance can be maintained at lower sensor numbers typical of commercial installations. Further in section 6, we summarize Nubo Sphere's ability to detect and localize abnormal emission events on a shorter timescale of several hours.

Key takeaways

- A new generation of fully automated analytics developed by Sensirion Connected Solutions turns continuous methane monitoring into operator-ready outcomes: trusted emissions site totals for reporting, and actionable alerts.

- The **ADED 2.0 controlled release campaign** is designed to replicate emission profiles from operated facilities: multiple sources, intermittent behavior, and conditions that change from seconds to days—so results translate to operations, not just a lab test.

- Nubo Sphere's emission rate estimates are consistently close to the ground truth: **90% of estimated site totals fall within 1.5× of the true site emissions and 98% within 2x.**

- Over the full controlled release campaign using data from 10 sensors, cumulative emissions show near-zero bias (-2.5%), supporting reliable inventories and helping reduce year-end reconciliation surprises.

- Even with only 6 or 4 strategically placed sensors, as typical for commercial deployments, the reported site total is estimated within **±10% uncertainty** of the ground truth. This is achieved by explicitly accounting for times when wind and geometry limit what the sensors can observe ("gap-filling").

- Breakdowns of site totals by equipment group show where methane is coming from—credible, data-driven input for inventory reconciliation and for prioritizing LDAR follow-up and mitigation spend.

- Emission alerts are highly actionable: reported events capture **99.5% of the methane released** during true events (TP), while keeping false-reported methane at only 0.6% (FP) thus minimizing unnecessary callouts.

- When an emission alert is generated, localization points you to the right place: the dominant **equipment group is identified correctly for 80% of events**.

Accuracy of site totals

Emission rate estimates consistently close to ground truth.

90%

within 1.5× of true emissions

98%

within 2×

Bias

Reliable inventories, no meaningful over/ underestimation.

-2.5%

Reporting

Highly reliable reporting across various sensor setups.

±10%

uncertainty

Detection Performance

Highly actionable alerts

99.5%

of methane captured

0.6%

false positives

Localization

Good accuracy in identifying emission sources.

80%

correct equipment group

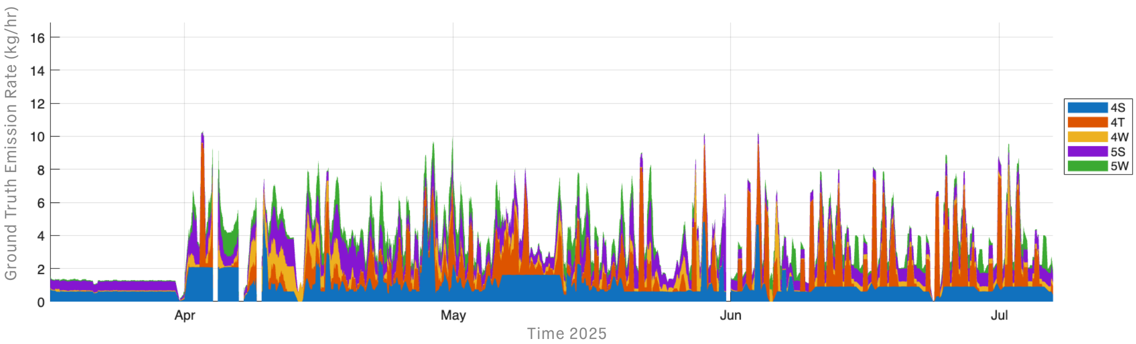
2 Experimental setup

ADED 2.0 is designed to reflect real-world methane emissions complexity: multiple sources can emit asynchronously over timescales of seconds-to-days. Controlled releases were conducted at METEC test site (Colorado, USA). For analysis, the 24 emitting equipment units were aggregated into five equipment groups (labelled 4S, 4T, 4W, 5S, 5W as shown in Figure 1 c). Nubo Sphere photoacoustic point sensors were strategically distributed around the site to locally measure methane concentrations using a coverage-based siting approach taking local wind conditions into account. Emission rate estimates were produced by an inference framework operating on 30-minute averaging intervals. A 2D ultrasonic anemometer provided continuous wind speed and direction data to characterize atmospheric transport and sensor visibility.

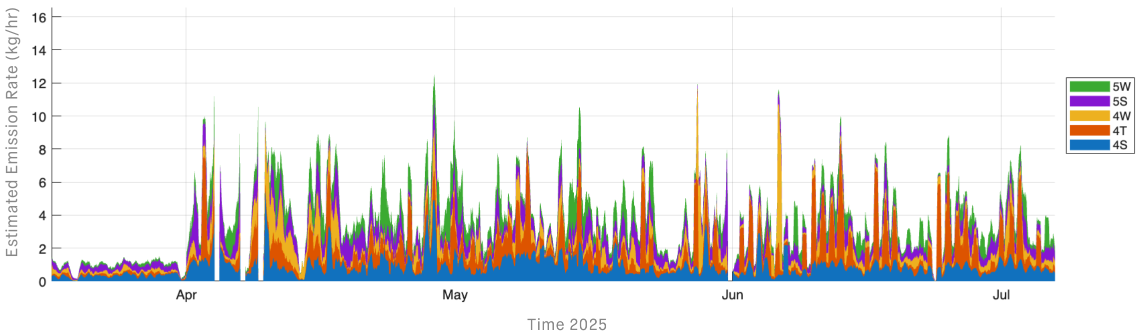
To evaluate commercially relevant sensor densities, we analyzed 10-, 6-, and 4-sensor configurations derived from the same layout. For reduced-density cases, inference analytics were rerun using only the selected subset, mirroring typical commercial deployments. Reduced sensor density introduces intervals with no spatial coverage of certain equipment units or groups called "gaps" (i.e., when plumes are not observed by any active sensor). We treat such intervals with a statistical gap-filling procedure to compute site-level and equipment-group emissions (Daniels et al., 2024).

Real-world sites can exhibit highly dynamic emission behavior, with multiple sources active simultaneously and start/stop times spanning seconds to days. These characteristics are modelled by the emissions profile for the 2025 ADED 2.0 campaign as shown in Figure 1 a) with stacked contributions from the five equipment groups. The Nubo Sphere emissions estimates can capture these complex emissions profiles well as shown in Figure 1 b).

1 a) Ground truth



1 b) Nubo Sphere estimated emissions rate



1 c) METEC site layout

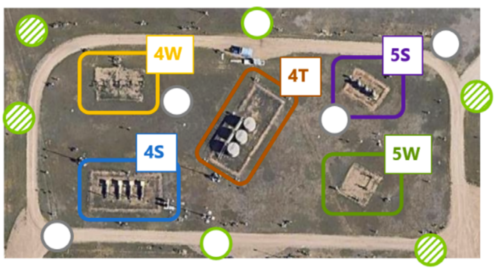


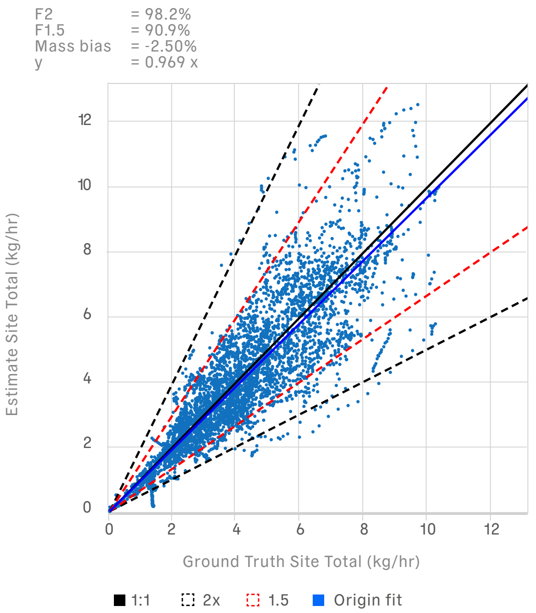
Figure 1
Overview of the 2025 ADED 2.0 campaign.
(1 a) Ground truth emission rates;
(1 b) Nubo Sphere estimates over the full controlled release period (12-hour moving average, 10-sensor configuration);
(1 c) Site layout with equipment group labels and circled sensor locations, including the 6-sensor (hatched and empty green circles) and 4-sensor subsets (hatched green circles).

3 Quantification performance

We evaluate quantification by comparing site total estimates with ground truth for different moving averages windows reported at a 30-minute cadence. With a 12-hour moving average window, 90% of the estimates fall within 1.5x of ground truth and 98% within 2x. The linear fit bias is −2.5%, indicating minimal systematic error across the full dataset (Figure 2 a). These results show strong site-level quantification performance, with scatter dominated by random rather than systematic error—critical for emissions accounting, because random error averages while systematic bias does not.

Longer averaging further reduces short-time-scale variability resulting in 100% of the emissions quantified with 1.5x of the ground truth at 72-hour moving averages (Figure 2b). T his demonstrates the main advantage of continuous monitoring for the purpose of emissions accounting: frequent measurements allow random errors and short-term variability to average down, producing reliable totals over the monitored reporting period.

2 a) Site total 12 hr moving average



2 b) Quantification accuracy vs averaging time

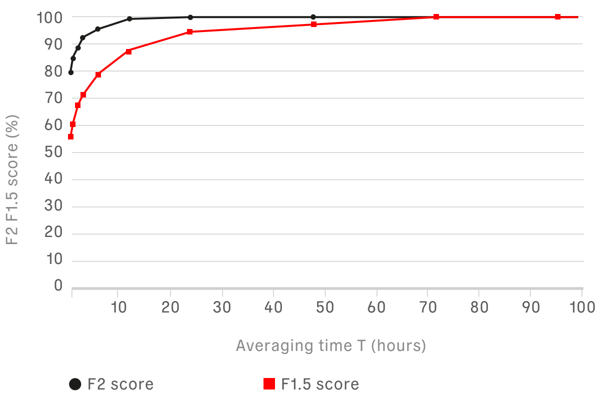


Figure 2
(2 a) 12-hour moving average site totals. The blue line shows a linear fit demonstrating a low bias of -2.5%. The red and black dashed lines are boundaries indicating estimates within 1.5x (red, F1.5 score) and 2x (black, F2 score) of the ground truth with F2 = 98% and F1.5 = 90.9% within 1.5x.
(2 b) F1.5 and F2 scores for different averaging times.

Even on very short time scales of 30min >80% of the emissions are estimated within 2x of the ground truth demonstrating reliable quantification also for short emissions episodes. We assessed emissions inventory performance using cumulative site-level emissions over the controlled release campaign. For the full 10-sensor configuration, cumulative estimates closely track ground truth, indicating low bias with no systematic drift over time (Figure 4 a).

To reflect commercial deployments, we also evaluated 6- and 4-sensor configurations using a coverage-aware emissions accounting approach that explicitly handles intervals with limited observability ("gaps"). We exclude emission estimates

of equipment groups during intervals with no spatial coverage (i.e., when plumes are not observed by any sensor) or when inference confidence is low (see Figure 3). The remaining intervals constitute the observed portions used for direct quantification.

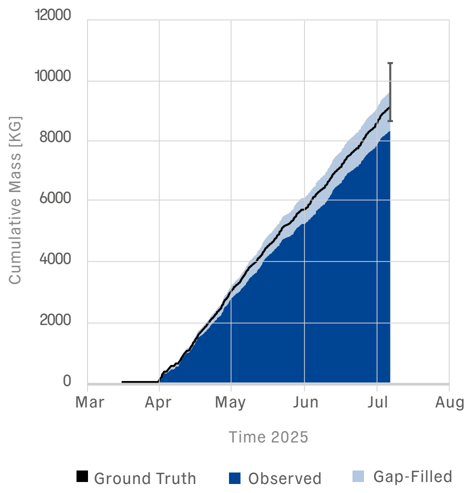
For each equipment group, gaps are filled using the mean emission rate estimated during all that group's observed intervals. The observed and gap-filled contributions are added to form the site-level total used for emissions accounting.

3 a) Source observed 3 b) Source not observed ("gap")

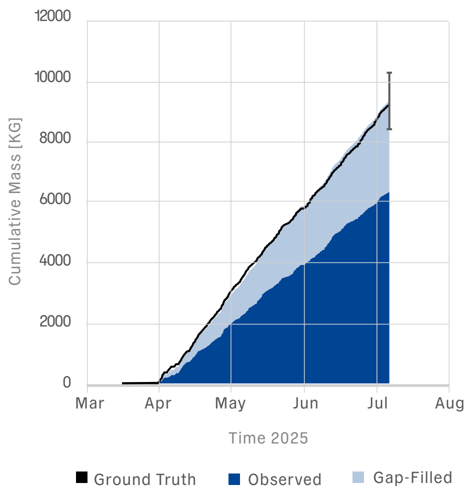
Figure 3
Illustration of coverage concept.
(3 a) Source observed: the plume (shaded blue area) from the emission source in the center (blue circle) is detected by sensor S1 (green triangle).
(3 b) Gap: the plume is not detected by any of the four sensors (S1-S4).

Results are shown in Figure 4 for the 10-sensor, 6-sensor, and 4-sensor configurations. The reported site totals reproduce the ground truth with an estimated ±10% uncertainty, even though the 6-sensor and 4-sensor configurations directly observe only ~66% respectively ~40% of total emissions. These results show that accurate reporting-period emissions estimates can be maintained even at sensor densities representative of commercial deployments, reducing monitoring cost while preserving inventory accuracy.

4 a) Cumulative site level emissions - 10 sensors



4 b) Cumulative site level emissions - 6 sensors



4 c) Cumulative site level emissions - 4 sensors

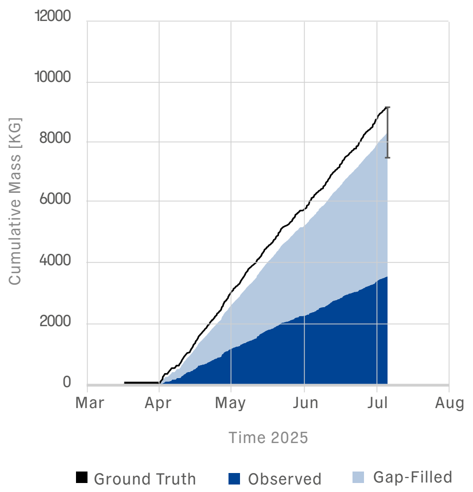


Figure 4
Cumulative site level emissions:
(4 a) 10-sensor configuration;
(4 b) 6-sensor configuration;
(4 c) 4-sensor configuration
showing observed (dark blue) and gap-filled (light blue) contributions and uncertainty. Estimated totals closely follow controlled release ground truth with minimal reporting period bias.

5 Equipment group contributions

Site totals enable annual reporting but are insufficient for guiding reconciliation efforts as required for OGMP 2.0 Level 5 principles. When measurement-informed totals differ from bottom-up inventories, the key question is why. Equipment group contribution shares constrain where discrepancies originate and guide investigation and mitigation to the most relevant categories as shown in Figure 5 for the 6-sensor case. The attribution of emissions to the 5 equipment groups shows a good agreement between the estimates and the ground truth within the estimated uncertainties.

5 Equipment group contribution shares

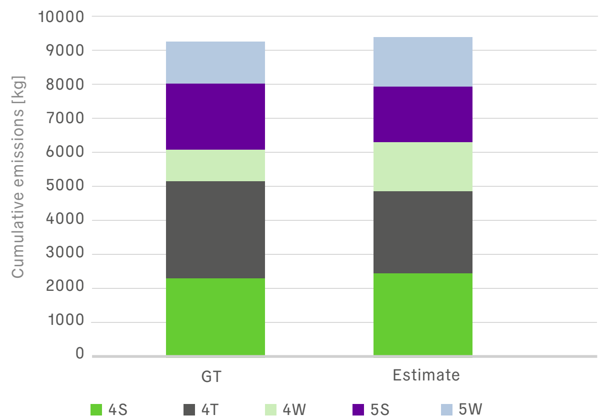


Figure 5
Equipment group contribution shares (left ground truth, right 6-sensor configuration). Stacked bars show each equipment group's fraction of the site total for the 5 equipment groups at METEC.

6 Emission events detection performance

While the previous sections evaluate long-term emissions accounting performance, continuous monitoring also enables rapid identification of abnormal emission events that require operator's attention. For this purpose, other parameters matter such as time-to-detection and localization accuracy.

6.1 Why events?

An operated oil and gas site exhibits continuously varying emissions: the sum of many overlapping intended and unintended emissions with different magnitudes and durations. While Nubo Sphere accurately tracks the aggregate site-level emissions per equipment group, resolving every individual short-lived source does not provide operational value. It rather leads to alert fatigue of the operations teams. Partitioning the continuous time series into "events" and "non-events" thus should be designed to provide actionable insights—prompting operator attention when emissions exceed a context-specific action limit (alert threshold). What counts as "relevant" depends on site equipment, operating conditions, and the operator's mitigation strategy.

6.2 Event evaluation of 2025 ADED 2.0

The initial phase of the 2025 ADED 2.0 campaign (all of March) was used to characterize baseline site emissions (Figure 1). Starting in April, fugitive emission events were introduced on top of the baseline. For the following analysis, we choose an event detection threshold (action limit) of 3 kg/hr, which is approximately equal to the previously determined baseline mean emission rate plus three standard deviations. The intent is to flag anomalies that are clearly above normal operating variability—reducing alert fatigue and focusing attention on events with meaningful mitigation potential. We define emission events as time periods when the ground-truth site emission rate exceeds the action limit (green shaded intervals in Figure 6). Nubo Sphere event detection is based on a 12-hour moving average of the estimated site-level emission rate, which suppresses short-timescale variability and highlights sustained emission increases. As shown in Figure 6, the Nubo Sphere estimates closely track the ground truth and reliably identify these events.

6 Event detection time series

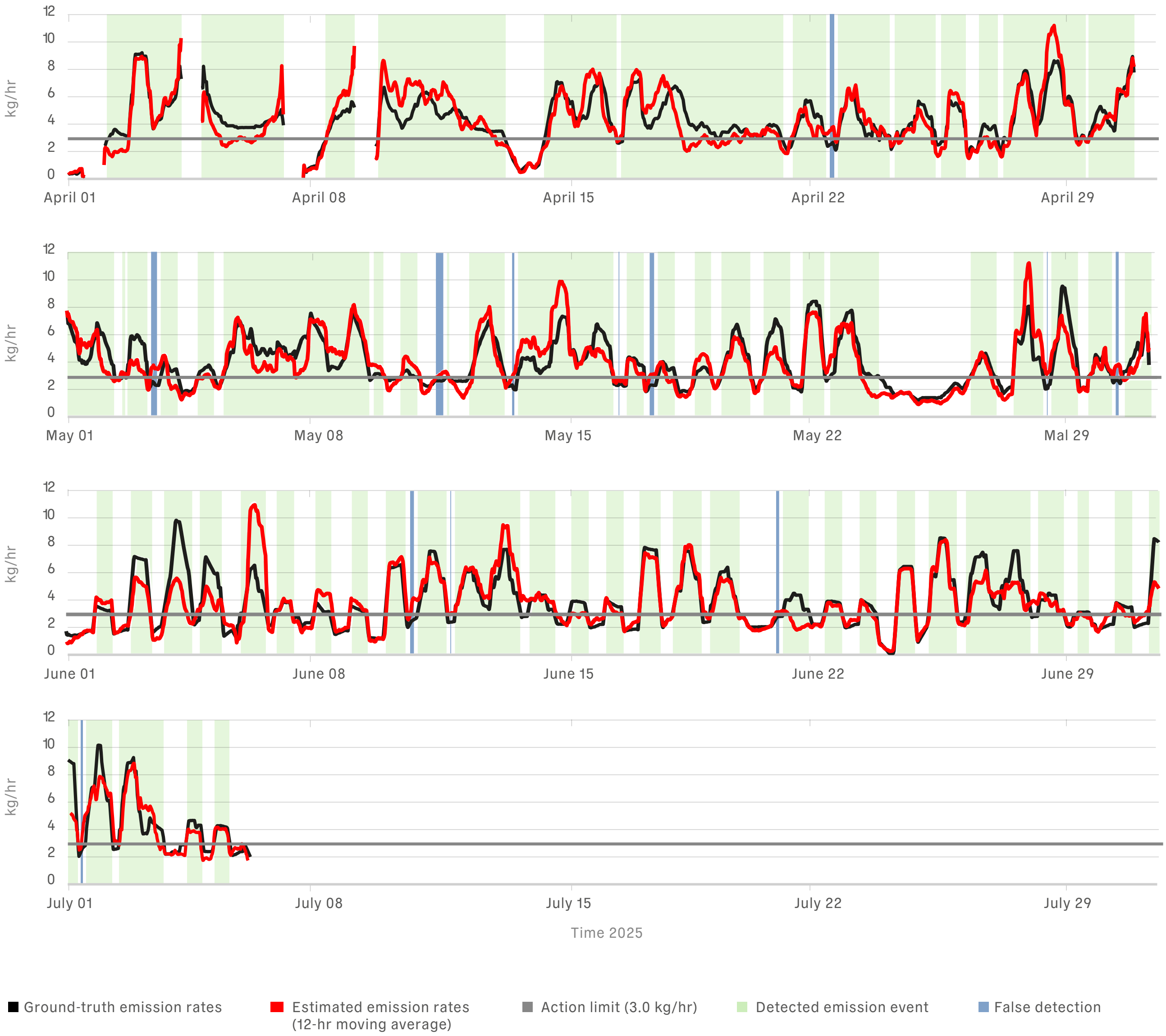


Figure 6
2025 ADED 2.0 total site emissions on a 12-hr moving average with ground truth in black and Nubo Sphere reported emission rates in red. Correctly detected events (green areas) are identified by applying the 3 kg/hr action limit to the ground truth. Rare false detections are shaded in blue.

For continuously varying emissions, such as those observed during the 2025 ADED 2.0 campaign and real operating sites, detection metrics such as probability of detection and time to detection provide only a partial view of system performance. The operational objective of continuous monitoring is to mitigate fugitive methane emissions while minimizing unnecessary operator response. We therefore evaluate performance using a proposed metric of "methane mitigation potential", defined as the fraction of methane emitted during true events that occur after the continuous monitoring system detects the onset of the event (defined as the time when the estimated site emission rate exceeds the action limit).

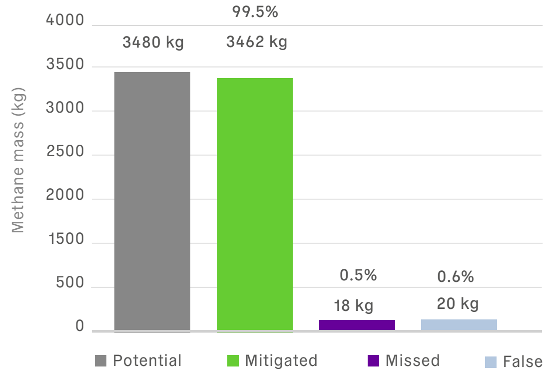
Figure 7 a) summarizes methane mitigation potential from the Nubo Sphere system over the 2025 ADED 2.0 study period. The potential bar represents the total methane emitted above the action limit during ground truth events, while the mitigated bar represents methane emitted after detection of an event by Nubo Sphere. The difference between these quantities is the missed methane. For this dataset, there were no false negatives, so the missed methane reflects only the short delay between actual event onset and Nubo Sphere detection. The methane mitigation potential is 99.5%, with only 18.2 kg (0.5%) emitted prior to detection. The methane associated with false positive detections was also very small, totaling 20 kg (0.6% of the potential methane) and arising from short periods when the estimated rate briefly and barely exceeded the action limit while the ground truth didn't.

Consistent with the methane-mass results above, the event time series in Figure 6, also shows strong binary event performance (traditional way of analyzing performance): all 66 ground-truth events are detected (66 true positives; no false negatives), with 17 false positives. These false positives are brief threshold crossings where the reported emission rate only slightly exceeds the action limit while the ground truth remains just below it—explaining why the total falsely reported methane is small (20 kg). The methane mitigation potential metric presented here complements those metrics by weighing outcomes by methane mass and highlighting the impact on regulatory and operational objectives.

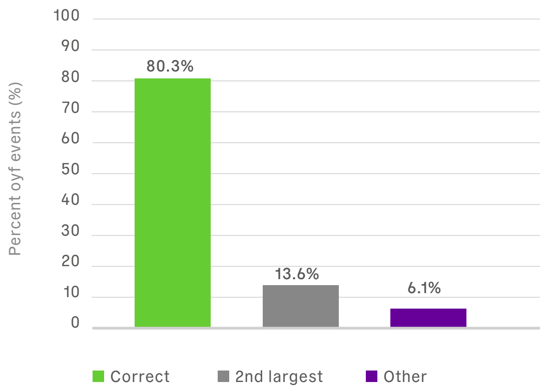
6.3 Event localization

Actionability is enhanced by fast detection and correct localization. Because multiple sources are often active simultaneously in 2025 ADED 2.0 as well as on operated sites, localization is evaluated by comparing the estimated dominantly emitting equipment group during each event versus the ground truth. Figure 7 b) summarizes the results. Nubo Sphere correctly identifies the dominantly emitting equipment group in 80.3% of all events. When the dominant equipment group is not correctly identified, the predicted group corresponds to the second-largest contributor in 13.6% of events, meaning localization errors often still point to a major emission source during the event period.

7 a) Methane Mitigation Potential



7 b) Event localization performance



7 c) Time to detection

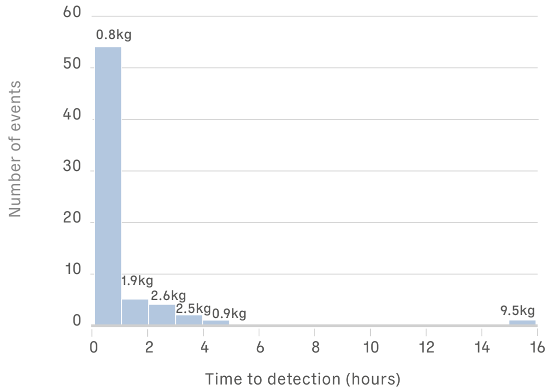


Figure 7
(7 a) Methane mitigation potential for the whole controlled release campaign, showing potential methane to mitigate above the action limit, methane mitigated after detection, methane missed, and methane associated with false positive detections.

(7 b) Event localization performance based on the dominant emission source group. Bars show the fraction of events where the dominant group is correctly identified, where the predicted group corresponds to the second-largest contributor, and where it points to another group.

(7 c) Time to detection for methane emission events (action limit = 3 kg/hr, 12-hour moving average). Numbers above each bar indicate the total methane mass emitted before detection for events within that time-to-detection bin.

6.4 Time-to-detection

Time-to-detection is defined as the time gap between the ground truth emission rate exceeding the action limit and the estimated site-level emission rate exceeding the same action limit.

Figure 7 c) shows the distribution of time-to-detection for emission events during the 2025 ADED 2.0 campaign. Most events are detected within the first hour after the ground truth emission rate exceeds the chosen action limit of 3 kg/hr. Numbers above each bar indicate the total methane emitted prior to detection for events in that time-to-detection bin (totaling to 18.2 kg).

A small number of events have longer detection times, but the associated methane emitted is small because these events occur close to the action limit or increase gradually in magnitude. As shown in Figure 7 c), methane emitted prior to detection represents only a small fraction of methane emitted during events. The time-to-detection distribution therefore provides context for how quickly relevant events are identified, while the methane mitigation potential metric quantifies the impact of those detections with regards to total emissions.

7 Conclusions

In 2025 ADED 2.0, Nubo Sphere produced site totals that stayed close to the controlled-release ground truth (90% of quantified site-level estimated within 1.5x; 98% within 2x; -2.5% bias). Add a sentence before Importantly: Total site emissions are quantified within +/-10% of the ground truth. Importantly, this accuracy doesn't depend on a dense sensor network—results remain strong even with sensor counts typical of commercial deployments, because the analytics explicitly handle times when parts of the site aren't observable.

Just as important, the system is operationally useful: it flags real emission events, keeps false alarms and false-reported methane low, and typically identifies the equipment group most responsible for the event.

Bottom line: Nubo Sphere supports both reporting-quality emissions accounting and day-to-day mitigation response, enabled by advances in sensor technology and analytics.

References

Daniels, W.; Waggoner, P.; Hammerling, D., 2024, Response to Request for Information on "Use of Advanced and Emerging Technologies for Quantification of Annual Facility Methane Emissions Under the Greenhouse Gas Reporting Program", link.

8 Appendix - Probability of Detection

Traditional event-based metrics (e.g., probability of detection and confusion matrices) are most informative for binary detection technologies or protocols with discrete, isolated releases (e.g., ADED 2024 campaign and prior). Using ADED 2024 data, Nubo Sphere's fitted 90% probability of detection (PoD) is 0.09 kg/hr, as shown in Figure 8. As such, Nubo Sphere is approved by the US EPA as an alternative technology for periodic surveys and offers the lowest approved detection limit among point-sensor networks to date: 1 kg/hr (vs. 5 kg/hr for other approved systems).

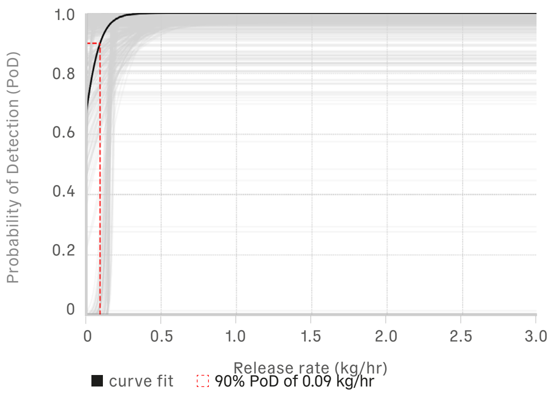


Figure 8
Nubo Sphere PoD based on ADED 2024 data demonstrating a 90% PoD of 0.09 kg/hr.

About Sensirion Connected Solutions

Sensirion Connected Solutions specializes in advanced sensor-based IoT solutions for continuous emissions monitoring in the energy sector. Its end-to-end platform combines proprietary methane sensing and optical gas imaging technologies with powerful data analytics, root-cause diagnostics, and expert field support. Designed to simplify methane mitigation, the company's solutions empower operators to reduce emissions efficiently, meet ESG goals, enhance operational safety, and ensure regulatory compliance. With offices in Boston, Midland, Calgary, Chicago, and Switzerland, Sensirion Connected Solutions is a subsidiary of Sensirion Holding AG, a global leader in high-performance digital microsensors for environmental and flow sensing applications.

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