Assessing the Performance of Continuous Methane Monitoring Systems at Midstream Compressor Stations

Shuting (Lydia) Yang* and Arvind P. Ravikumar

Department of Petroleum and Geosystems Engineering, The University of Texas at Austin, Austin, TX 78712

Energy Emissions Modeling and Data Lab, The University of Texas at Austin, Austin TX 78712

*Corresponding author. E-mail: shuting.yang@austin.utexas.edu

ABSTRACT

Continuous Monitoring Systems (CMS) are a promising technology to detect and quantify intermittent and high-volume methane emissions across the oil and gas supply chain. This is particularly salient at midstream compressor stations where the contribution of short duration emission events to total emissions make survey type technologies less suitable to develop accurate measurement informed inventories. In this work, we report on the first concurrent and long-term test of five CMS technologies to detect, localize, and quantify methane emission from two major types of midstream compressor stations found in the US – a turbine-only station and an engine-only station. We find that CMS technologies can distinguish between different operational states of the compressor only under conditions of low background methane emissions. Combining known events at these facilities with in-situ controlled releases, we observe that all CMS technologies generally struggle in identifying short duration or low-emission rate (relative to baseline) events. Critically, we find that positive event detection, based on analysis of underlying methane signals, frequently did not translate to alerts sent to the operators. Deployment of CMS at midstream compressor stations must proceed with caution based on specific applications, site configuration, and the nature of baseline emissions.

Keywords: Continuous Monitoring Systems, Methane, Midstream, Compressor Station, Oil and Gas, Inventory

1 Introduction

Methane (CH_4), the primary component of natural gas, is a potent greenhouse gas with a global warming potential 80 times that of carbon dioxide over a 20-year period. [1] The Oil and Gas (O&G) sector is a significant source of anthropogenic CH_4 emissions in the U.S. [2, 3] Concerns over the climate impacts of increased global use of natural gas has led to the development of new regulatory actions and voluntary initiatives to reduce CH_4 emissions across the O&G supply chain. [4] They share an important feature: an emphasis on the use of empirical or measurement-based approaches to detect, quantify, and mitigate emissions. This is the direct result of recent studies around the world that conclusively demonstrated that official CH_4 emission inventories underestimate emissions compared to measurements. [5-8]

CH_4 emissions from O&G supply chain including production, midstream, and downstream distribution sectors have been quantified by different detection technologies deployed on platforms including handheld sensors mobile lab vehicles, drones, aircraft, and satellites. [9-17] These multi-scale snapshot measurements have identified key features relevant to the development of accurate emission inventories and to direct mitigation efforts. These features include the contribution of super-emitters to total emissions, the prevalence of high-volume and intermittent emission events, and the identification of abnormal process conditions as a root cause for large unintended emissions.[18-20] Despite progress, these technologies and platforms only provide snapshot estimates of emissions and would require spatial and temporal extrapolation to accurately estimate annual measurement informed inventories.[21, 22] Furthermore, snapshot measurements are challenging in basins where a large fraction of emissions are attributable to short-duration, intermittent emission events. [23, 24]

Continuous Monitoring Systems (CMS) are a promising class of technologies to detect and quantify both routine and abnormal intermittent emissions at O&G facilities. Several CMS technologies are now available commercially and have been deployed at O&G facilities in limited pilot demonstration studies. [25, 26] Recent studies of CMS under controlled conditions demonstrate challenges in emissions localization and quantification even at simple facilities. Bell et al. presented results from single-blind testing of 11 CMS solutions using a standardized protocol at the Methane Emissions Technology Evaluation Center (METEC) test facility. [27] They found significant variability in performance across different technologies, marked by unpredictable detection efficacy and high quantification uncertainty.

Another controlled release study designed to evaluate the performance of CMS solutions in identifying large releases found that although detection was reasonably effective, quantification was significantly underestimated.[28] Such challenges are not limited to controlled tests. Recent work in evaluating CMS at operating O&G production facilities have brought to light challenges in detecting and quantifying emissions. [29] Extracting useful information from CMS deployed at simple production facilities requires extensive scientific modeling that is currently not available from commercial vendors. [9, 30, 31] Notwithstanding variability in real-world performance of CMS technologies, modeling efforts indicate that CMS could reduce the need for higher frequency of snapshot surveys to achieve equivalent emissions reductions or that CMS networks, under optimal design conditions, can detect over 90% of intermittent emission events. [32, 33] Furthermore, there is evidence that the performance of CMS technologies, collectively, are improving rapidly and would therefore require periodic evaluation. [34]

Much of the literature on the testing and deployment of CMS has focused on their performance at simple upstream production facilities. However, midstream O&G facilities such as compressor stations would benefit from effective CMS-based monitoring for several reasons. First, periodic surveys of compressor stations are challenging because of their sparse distribution. Second, large release events at midstream facilities are often intermittent and last only several minutes to a few hours such as blowdowns or seal vents – these would require an impractical number of snapshot surveys to capture accurately in inventory development. Third, technologies that provide top-down, source-level emission estimates have some challenges in accurately detecting and quantifying sources such as compressor exhaust slip. [35, 36] Despite this, no systematic evaluation of the performance of CMS technologies at midstream compressor stations exists.

In this work, we report on the first concurrent test of five CMS technologies to detect, localize, and quantify CH_4 emission from two major types of midstream compressor stations found in the US – a turbine-only station and an engine-only station. These two facility types encompass the range of emission source types and emission rates found in the midstream O&G sector across the US. The turbine site typically has low emissions under normal operating conditions because of low CH_4 slip from the exhaust of the compressor unit. However, the engine site has typically high emissions under normal operating conditions, with a significant fraction attributable to CH_4 slip from exhaust.[37, 38] This allows us to evaluate the performance of CMS technologies under a range of background CH_4 signals. Combining known emission events at these stations with in-situ controlled releases allowed us to identify conditions under which CMS technologies are effective in detecting, localizing, and quantifying midstream CH_4 emissions. Results from this study directly inform the practical deployment and limits of CMS technologies at midstream O&G facilities.

2 Methodology

2.1 Site and Technology Selection

A three-month field trial was conducted at two select natural gas transmission compressor stations in NY state. Site selection was based on several factors including ease of site access, number and type of compressor units, observed aerial CH_4 emissions, operational constraints, field test requirements, and site configuration. The two sites represent two types of facilities commonly found across NY state and in the US – a turbine-driven only compressor station (*henceforth Turbine site*) and a reciprocating-engine driven only compressor station (*henceforth Engine site*). The Turbine site had one compressor unit at a rated horsepower of 7700 and the Engine site had 5 compressor units, at a total rated horsepower of 18400 (see Supplement Information (SI) section S1).

CMS participants were selected through a rigorous selection process based on past performance in field campaigns, availability of controlled test data, technology readiness level, scalability, and stakeholder interest. Five CMS were deployed contemporaneously at selected sites for technology inter-comparison studies and to monitor CH_4 emissions continuously with a range of temporal resolution (4 s to 15 min). The location and number of sensors installed per site are determined by prevailing wind conditions, the complexity of the facility, the nature of the equipment, and the facility safety guidelines. The layout of two selected facilities and the deployment of sensors of five CMS are shown in SI section S1. The specifications of five selected CMS technologies are shown in Table 1 (also see SI section S2).

Table 1*. Specification of five selected CMS technologies tested in this study. "Sensor type" shows the measurement technique of each system; "CH_4 concentration data reporting logic"*

shows the frequency of CH_4 concentration data to the end users; "Quantification/ Localization capability" columns show the information on whether the system quantifies and reports emission rates, and estimated emission location, respectively; "System type" indicates whether the technology reports an emission rate to end users; "Alert setup" shows whether technologies have an alerting system to the end user; "#Sensor" shows the number of sensors of each system that deployed at the Turbine site and Engine site.

CMS	Sensor type	CH_4 concentration data reporting logic	Capability		System type	Alert setup	#Sensors	
			Quantification	localization			Turbine site	Engine site
Tech A	Metal-oxide	All the sensors report values every 4 s	Alert level	Alert level	Non-emission-rate-based	Y	10	11
Tech B	Metal-oxide	All the sensors report values every 1 min	No	No		N	5	8
Tech C	Tunable diode laser spectroscopy					Y	5	6
Tech D	Metal-oxide	A swinging gate algorithm – only one or two sensors publish data that is changing	Every 1 min (mscf/d)	Alert level	Emission-rate-based	Y	4	4
Tech E	Metal-oxide	Only one sensor reports every 15 min	Every 15 min (kg/hr)	“Wind triangle” algorithm/Alert level		Y	4	5

2.2 Definition of detection

The five CMS technologies are classified into two types of systems: (1) type-1 system is an emission-rate-based system that reports CH_4 concentrations intermittently but quantifies emission rates and monitors emission events in near-real-time. (2) type-2 system is a non-emission-rate-based system that reports real-time high-resolution atmospheric CH_4 concentration measurements with no built-in quantification.

For both types of systems, we need to define "detection", which is a non-continuous variable with possibility states of "yes", "no", and "maybe". For the type 1 system, we combine information from (1) near real-time emission rate estimates and (2) alert reports of CMS - if an event is captured by both (1) and (2) data sources, then the state of "detection" is "yes"; if none of the sources report the detection, the state is "no"; if only one data source reports "detection", we define it as "maybe".

For the type 2 system, we define a metric – "time-averaged detection fraction" which refers to the fraction of concentration data points from downwind sensors that meet or exceed a threshold of CH_4 concentration enhancement above baseline for a pre-determined duration of known emission source. We evaluate the concentration enhancement thresholds of 1 ppm in estimating the time-averaged detection fraction. For a particular emission event, we first determine the upwind and downwind sensors based on the average wind direction during the event period – sensors that are located within ± 90 degrees relative to the wind direction are identified as the upwind sensors and the rest are classified as downwind sensors. Then, the average CH_4 concentration of all the upwind sensors is considered as the baseline CH_4 value for this emission event. We calculate the fraction of data points of downwind sensors that meet the threshold - if the calculated "time-averaged detection fraction" of an emission event is more than 60%, then the detection state is "Yes"; if the calculated "time-averaged detection fraction" is less than 30%, then the detection state is "No"; if the calculated "time-averaged detection fraction" is between 30% and 60%, then the detection state is "Maybe". Tech D and Tech E constitute the type 1 system, and Tech A, Tech B, and Tech C belong to the type 2 system. Tech A and Tech C also have alert systems set up but no quantification function. Tech B has no alert system.

2.3 Operational data

During the three months of deployment from August 1st to October 31st, 2022, there were 25 and 6 routine or maintenance activities reported at the Turbine site and Engine site, respectively (see SI section S4). Major operational activities include blowdown events, blowing drips, non-routine venting, filter changeout, and Lockout/Tagout (LOTO) procedures for the unit. In addition, we collected throughout parameters, leak detection and repair (LDAR) records, and other operational information to evaluate the performance of CMS.

2.4 Controlled release tests

In-situ controlled release tests were conducted at both compressor stations in October 2022. These tests are not designed to extract probability detection curves for the technologies, which require long-term testing at a controlled release facility across a broad range of emission rates.[27] Instead, these releases are used to evaluate the ability of CMS to detect, quantify, and localize intermittent emission sources of similar volumes as seen at a typical midstream compressor station.

In total, 41 controlled releases were conducted over the course of one week at two sites (SI section S3). The duration of the controlled releases varied from 5 minutes to 2 hours, mimicking typical intermittent emissions seen at compressor stations such as blowdown events. Emission rates varied from 5 kg/h to about 100 kg/h, corresponding to observed emissions at compressor stations. CH_4 was sourced from pressurized tanks in a trailer system and was metered using a micro emission flow meter with an accuracy of ±0.1%. A 100 ft long hose was connected to the flow meter through which CH_4 reached a 5 ft or 20 ft high release pipe. A heat transfer system was used to prevent Joule Thompson effect cooling at the release point resulting in a controlled release at ambient temperature and pressure conditions. To allow for effective plume development through the atmosphere and potential sensor delay, each test included a buffer time of 10 minutes between each release. The locations of the controlled releases were based on considerations of facility layout, typical location of emission sources, prevailing wind conditions, and the need to test all sensor solutions installed at the facility. Controlled releases from multiple locations were also used to test the sensitivity of sensor performance to local turbulence. There were 5 release locations at the

Turbine site and 10 locations at the Engine site. For each location, two to three releases with different emission rates, duration, and release heights were conducted to simulate emissions from various equipment on sites (SI section S3). Because these controlled releases happen in identical weather and geographic conditions as the field trials, performance will be more representative of real-world deployment.

2.5 Baseline emissions – CH_4 signals from compressor stations under normal operating conditions

To understand the variability in CMS observations under normal operating conditions of the compressor station, CH_4 concentration signals of constant operating states of the compressor with no intermittent emission events were determined through a screening process. First, based on the operator-supplied daily operating hours of compressors, we define that a compressor is "operating" when its daily operating hours are more than 2 hours, and it is "not operating" when daily operating hours are less than 2 hours. The Turbine site has two operational states (operating and not-operating) with one turbine compressor and the Engine site has six operational states due to their five engine-driven compressors (0 to 5 compressors are in operation). Second, the days on which known routine operational activities or emission events happened are filtered out to refine the CH_4 signals for each unique operational state of the compressors. Non-emission-rate-based systems have one more step – we determine the upwind and downwind sensors of each system based on real-time wind conditions and the location of the sensors. Upwind sensors are those that are positioned within a ±90-degree angle of the direction of the wind, whereas the remaining sensors are categorized as downwind sensors. The maximum CH_4 concentration among all identified downwind sensors is considered as the CH_4 signals from the site.

3 Results and Discussion

3.1 Ability of CMS to distinguish between different operational states of the compressor

The distributions of CH_4 concentrations under normal operating status detected by five CMS for each unique operational state at the Turbine and Engine site are shown in Figure 1 (also see SI section S5). Since compressor drivers (especially reciprocating engines) slip a high fraction of fuel in the exhaust and the combustion slip is a major component of midstream facilities' site-level emissions, [39] we investigate the CMS's ability to detect changes in the operational status of the compressor ('on' and 'off') using a discrimination metric called the operation ratio. The operation ratio is the fraction of the binned probability density of observed CH_4 concentrations in the 'on' state to that of the binned probability density of observed CH_4 concentrations across all operational states. Based on this definition of operation ratio, there are three scenarios: (1) when the operation ratio is 1, the CH_4 concentration signals are detected only when the compressor is operating, (2) when the operation ratio equals 0, the measured CH_4 concentration signals are captured only when the compressor is not operating, (3) when the operation ratio is between 0 and 1, CH_4 concentration signals are seen in both operational and non-operational states. We can then identify "cut-off" values – the transition point in the range of operation ratio as a function of concentration signal where different operational states of the compressors can be unambiguously distinguished. We make several observations.

First, at the Turbine site, regardless of whether the turbine-driven compressor was in operation, there is no significant difference in the probability density of average CH_4 concentrations (CH_4 signals varied between 0.1 and 1.1 ppm between idle and operational states detected by five CMS) indicating that the five CMS technologies tested here cannot distinguish operational and non-operational states of the compressor. This is expected as compressor exhaust from a centrifugal turbine is not expected to be a significant contributor to total site emissions. Technology B and C detected ambient-level CH_4 (~2 ppm) most of the time; Technology A, D, and E detected more elevated CH_4 signals. At the Engine site, all the technologies detected higher mean CH_4 values when multiple engine-driven compressors were operating (CH_4 signals varied between 2 and 8.4 ppm between idle and operational (4 engines) states detected by five CMS), indicating an ability to distinguish different operational states of the compressor station. This arises because exhaust slip is a significant contributor to total CH_4 emissions at this site, and site-level emissions are proportional to the number of operating compressor units.[38]

Second, the distributions of CH_4 concentrations under normal operating status across all five CMS technologies show long tails at both sites (also see Figure S3 in SI). At the Turbine site, except Tech D, CMS technologies detect no "cut-off" value which can be used to identify the "on" and "off" states of the compressor. The "cut-off" value detected by Tech D is around 100 ppm and CH_4 concentrations above the “cut-off” value are only detected when the turbine-driven compressor is operating (operation ratio equals 1). At the Engine site, all five CMS observe similar “cut-off” values of around 10 ppm above which CH_4 concentration levels are only detected when there is at least one compressor unit in operation.

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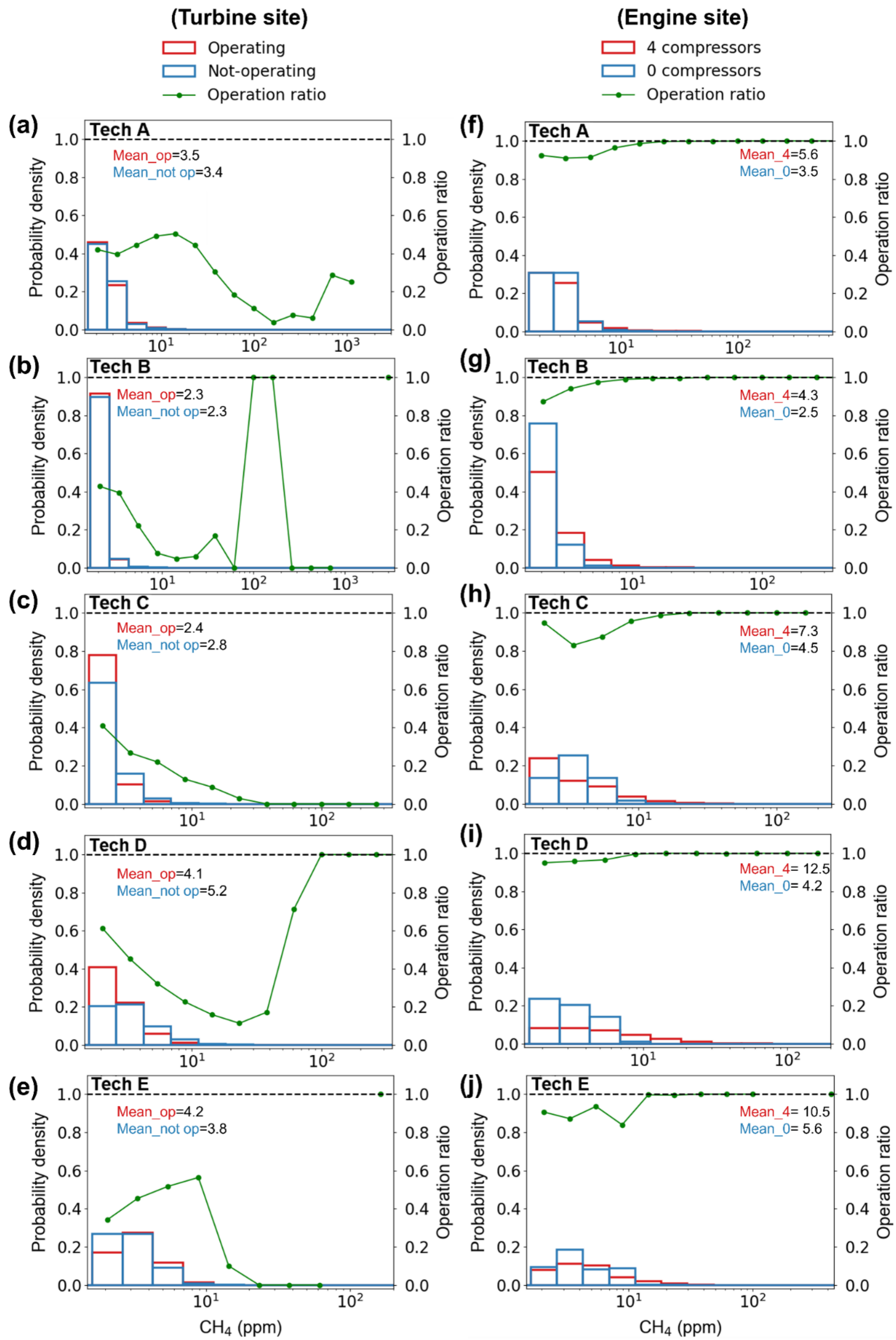

(Turbine site)
Operating
Not-operating
Operation ratio
(Engine site)
4 compressors
0 compressors
Operation ratio
(a)
Tech A
Mean_op=3.5
Mean_not op=3.4
(b)
Tech B
Mean_op=2.3
Mean_not op=2.3
(c)
Tech C
Mean_op=2.4
Mean_not op=2.8
(d)
Tech D
Mean_op=4.1
Mean_not op=5.2
(e)
Tech E
Mean_op=4.2
Mean_not op=3.8
(f)
Tech A
Mean_4=5.6
Mean_0=3.5
(g)
Tech B
Mean_4=4.3
Mean_0=2.5
(h)
Tech C
Mean_4=7.3
Mean_0=4.5
(i)
Tech D
Mean_4= 12.5
Mean_0= 4.2
(j)
Tech E
Mean_4= 10.5
Mean_0= 5.6
Probability density
Operation ratio
CH4 (ppm)

Figure 1. *Distribution of baseline CH_4 concentrations detected by five CMS ((A) – (E)) for different operational states of "operating" and "not-operating" of the turbine-driven compressor at the Turbine site ((a)-(e)) and "4 compressors" and "0 compressors" are operating at the Engine site ((f)-(j)). The green line with markers is the calculated operation ratio. The average CH_4 concentrations of each state are noted in the plots.*

3.2 Ability of CMS to detect, quantify, and localize known emission events

We use two datasets of known emission events to evaluate the performance of CMS, including recorded operational activities and controlled release tests. In total, 38 and 34 known emission events happened during the survey period at the Turbine site and the Engine site, respectively.

Probability of detection. As described in the Methods section, we use two different principles to define the "detection", one for the emission-rate-based system (Tech D and Tech E) and one for the non-emission-rate-based system (Tech A, Tech B, and Tech E). Figure 2 shows the fractions of emission events under different detection states detected by CMS. Detailed numbers of events used to evaluate CMS detection capability are provided in SI section S7.

Given that the operation of engines emitted considerably more engine exhaust CH_4 than turbines [37] – "background" emissions from the Turbine site are lower and the CH_4 signals from emission events should exhibit higher concentration enhancements at the sensor, depending on favorable atmospheric conditions. Yet, our results show that most CMS technologies (excluding Tech A) exhibit better performance at the Engine site with relatively higher detection probabilities. This may be partly due to the different composition of the emission events data we collected at the two sites. At the Turbine site, among 38 known emission events, 25 events are operational activities and 13 are controlled releases. At the Engine site, 34 emission events comprise 6 operational activities and 28 controlled releases. Generally, controlled releases are more likely to be detected due to constant flow rates, and longer durations compared to operational activities. Thus, CMS technologies perform better at the Engine site with more controlled release data. This suggests complex temporal profiles of known intermittent emission sources at compressor stations such as blowdown events may be challenging to detect in real-time for CMS technologies. Furthermore, Tech E detected notably higher probabilities of "maybe" states at both sites which indicates that the sensors did capture high CH_4 signals that didn't pass the thresholds of its alert system. Thus, evaluating CMS for its ability to detect intermittent emissions should focus on two interrelated challenges: one, accurate readings of CH_4 concentration enhancements, and two, analytics to convert concentration readings to emission event alerts to operators. Both challenges need to be addressed for CMS systems to translate to effective mitigation.

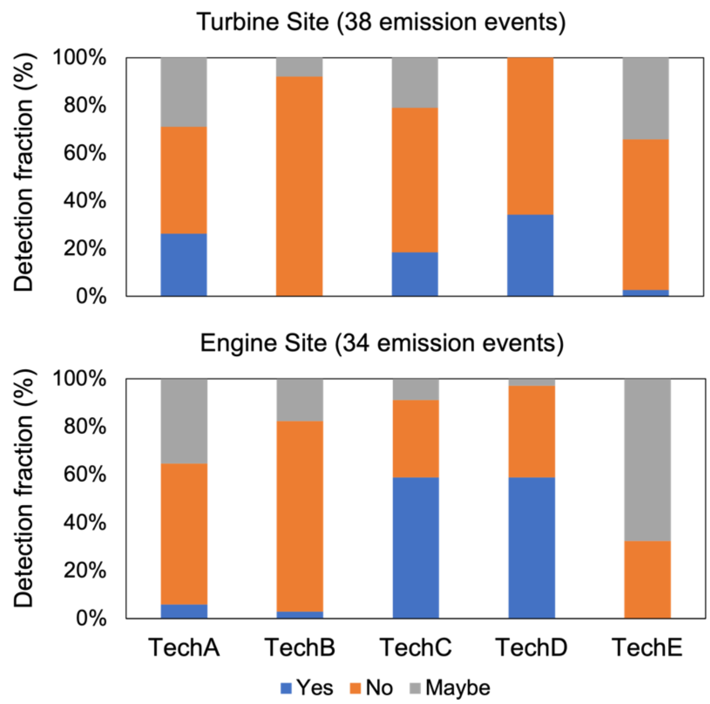

Figure 2. *The fraction of the known events that are under different detection states detected by five CMS ((A) – (E)) at two sites. The blue bar shows the fraction of "Yes", the orange bar is "No", and the gray bar is "Maybe".*

Ability of CMS to quantify and localize emission events. Figure 3 shows the quantification and localization accuracy of CMS that provides quantitative estimates (Tech A, Tech D, and Tech E) for "detected" events. Due to a lack of data on true emission rates from operational activities, only controlled release emissions rates are used to evaluate the quantification capability of Tech A, Tech D, and Tech E. In general, all three technologies tend to underestimate emission rates, among which Tech D has relatively the best performance. However, Tech D also reported a few high estimated emission rates with relative errors of more than 300%. CMSs report site-level emission rates and the background site-level emissions on the controlled release days can be estimated based on prior aerial surveys of these sites reported in the literature.[40] The turbine site was idle during the controlled test days and the Engine site had 4 compressors in operation during the controlled test days. The estimated site-level emissions from aerial measurements were less than 5 kg/h and 87 kg/h for the Turbine site and Engine site, respectively, under the same operational status as that of the controlled test days. The controlled release rates (5 to 100 kg/h) are less than or comparable to the background site-level emissions at the Engine site and thus, the total emission from the Engine site on the controlled release days should be higher than the controlled release rates. If we add the site-level emissions of 87 kg/h from aerial measurements to the emission rates of controlled releases conducted at the Engine site, the average relative quantification error of Tech A, Tech D, and Tech E will change from -75.4%, 18.8%, and -30.8% to -97.7%, -84.7%, and -88.7%, respectively, providing further evidence for potential significant underestimation of emissions.

For all the emission events detected by Tech A, Tech D, and Tech E, we evaluate their localization capability by comparing the emission equipment identified by CMS with known source locations/equipment. If the estimated equipment is the true equipment that emits CH_4, we consider the localization results as "accurate" and calculate the fraction of emission events with accurate localization results over all the detected emission events as shown in Figure 3(b). Tech A and Tech E have higher localization accuracy at the Turbine site compared to the Engine site. Given that the Turbine site is smaller with only one compressor unit compared to the Engine site with 5 compressor units, localization is expected to be more accurate at the Turbine site compared to the Engine site. The performance of Tech D in localizing emission sources at two sites is similar, but the overall localization accuracy (~35%) is lower compared to Tech A and Tech E (SI section S8).

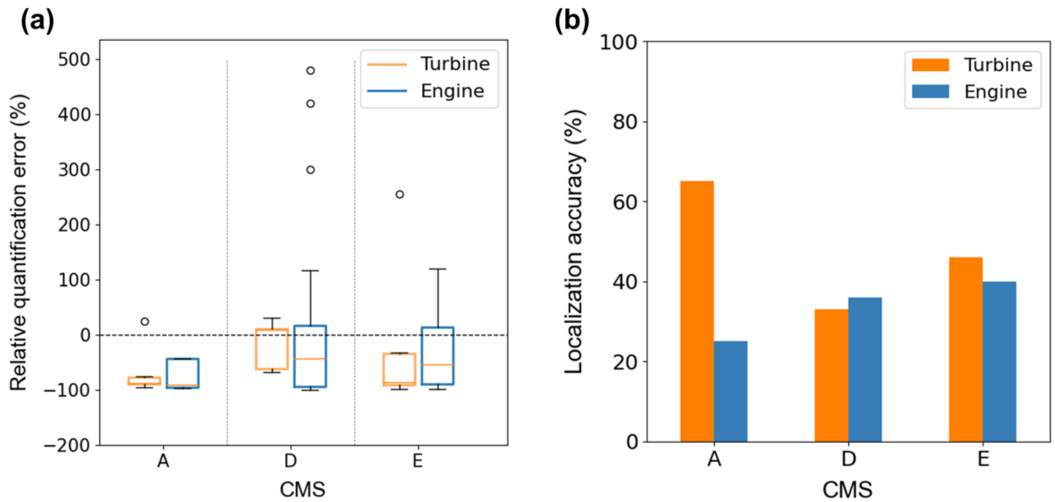

Figure 3. *(a) Relative quantification error (%) between CMS estimates and the controlled release emission rates at the Turbine site (red box) and the Engine site (blue box) for Tech A, Tech D, and Tech E. The red segment inside the box is the median. The top and bottom of the box are the 75th and 25th percentile. Whiskers extend to the largest/smallest value within 1.5 times the interquartile range from the hinge. Jittered points are also shown as circles. (b) Localization accuracy (%) of detected emission events by Tech A, Tech D, and Tech E, at the Turbine site (orange bar) and the Engine site (blue bar)*

Sensor up-time. Since each sensor of five CMS technologies reports data periodically (Table 1), we calculate the uptime fraction of a sensor that is operational during the three-month deployment period. Figure 4 shows the up-time fraction of all five CMS technologies. The metal-oxide sensors of Tech A, Tech B, Tech D, and Tech E are operational for over 90% of the test period. However, the up-time of Tech C's laser-based sensors varied at both sites – at the Turbine site, the up-time fraction ranged between 76% and 90%; at the Engine site, one sensor of Tech C was offline for nearly 30% - 40% of the survey period, and the overall up-time fraction varied between 60% and 91%. This is relevant in the context of the recently finalized US EPA methane rule that requires CMS to have an operational uptime of over 90% on a rolling 12-month average period.[41]

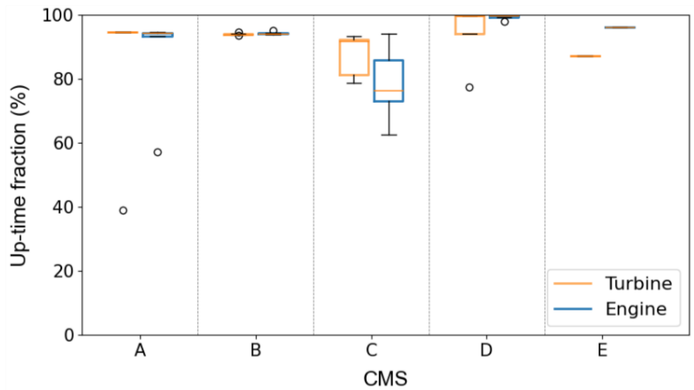

Figure 4. *The fraction of time that sensors are in operation (up-time fraction) during the three months of deployment of Tech A, Tech B, Tech C, Tech D, and Tech E.*

3.3 Ability of CMS to estimate event duration at compressor stations

Three technologies (Tech A, Tech C, and Tech D) have the capability to estimate the duration of detected emission events through alert reports. Figure 5 shows the distribution of duration of intermittent events as detected by Tech A, Tech C, and Tech D at both compressor stations. In addition, we also show the duration distribution of known emission events, including controlled release tests and operational emission events provided by the operator. Known operational emission events include blowdowns, blowing drips, filter changeout, and Lockout/Tagout (LOTO) procedures for the unit.

First, Tech A estimated longer durations (>5 h) of emissions at both sites. Tech C and D estimated most emission events to be between 30 and 100 minutes. Based on information about known operational activities and controlled release tests, we estimate that known events have an average emission duration of about 30 minutes. By comparing this distribution with those estimated by the CMS technologies, we evaluate the effectiveness of these systems in accurately estimating emissions duration. In general, the emission duration estimated by Tech C and Tech D is distributed around 30 min, reasonably well matched with the distribution of the duration of known events. Second, all three CMS tend to overestimate the duration of emission events, among which Tech A identified some long-duration events that are over 5 hours at both sites – conversation with site managers suggested no such long-duration emission event occurred at either site and thus Tech A's reading were either wrong or misattributed a continuous source to an intermittent event. Recently, the U.S. EPA finalized updates to subpart W reporting that requires accurate estimates of the duration of large release events. Our results indicate that significant improvements are needed to attribute and estimate the duration of intermittent emission events.

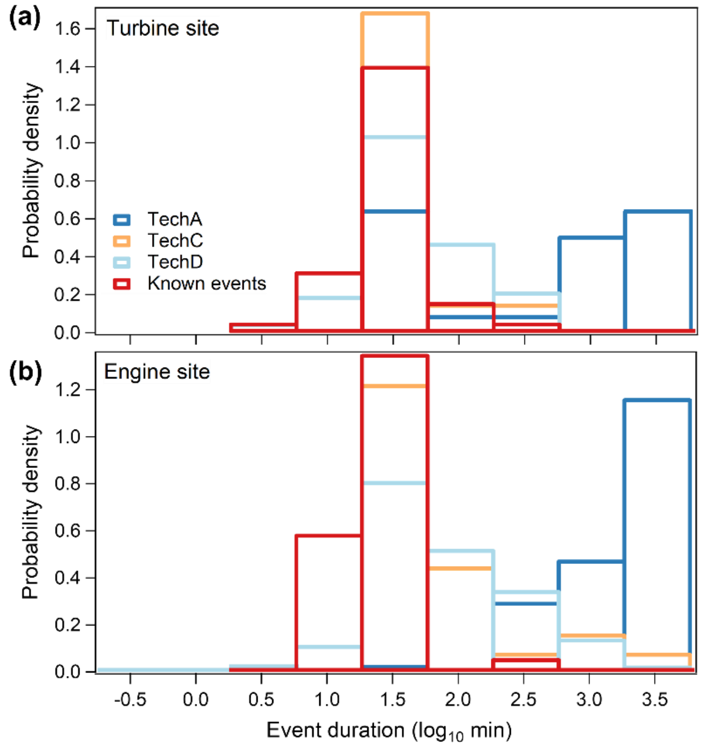

Figure 5. *Distribution of the duration of intermittent emission events detected at (a) the Turbine site and (b) the Engine site by Tech A (blue bar), Tech C (orange bar), and Tech D (blue bar).*

3.4 Performance evaluation of non-emission-rate-based CMS under different control variables

The protocol for controlled release tests encompasses several variables, including duration, emission rate, release height, and release location. We investigate the probability of detection using the time-averaged detection fraction metric as a function of emission rate and event duration as shown in Figure 6. Intuitively, the time-averaged detection fraction of an emission event by CMS can be improved as the emission rate and duration of the emission event increase.

At the Turbine site, for the events with the same emission duration, higher emission rates events have higher probabilities of detection as shown by the increasing trend in time-averaged detection fraction. Whereas there is no obvious correlation (Pearson's correlation coefficient = 0.02) between the time-averaged detection fraction and the emission rate at the Engine site. Compared to the estimated site-level emissions from an aerial survey with the same operational states of compressors at two sites,[38] we find that controlled releases conducted at the Turbine site are considerably higher than its typical site-level emission (<5 kg/h) which makes it more likely for CMS to distinguish enhancements from the controlled release against the background; most of releases (24 out of 28) conducted at the Engine site are lower than the site-level emissions (~87 kg/h), which is likely to make detection of concentration enhancements against background challenging.

Tech A and Tech C have higher time-averaged detection fractions across all the controlled releases compared to Tech B.

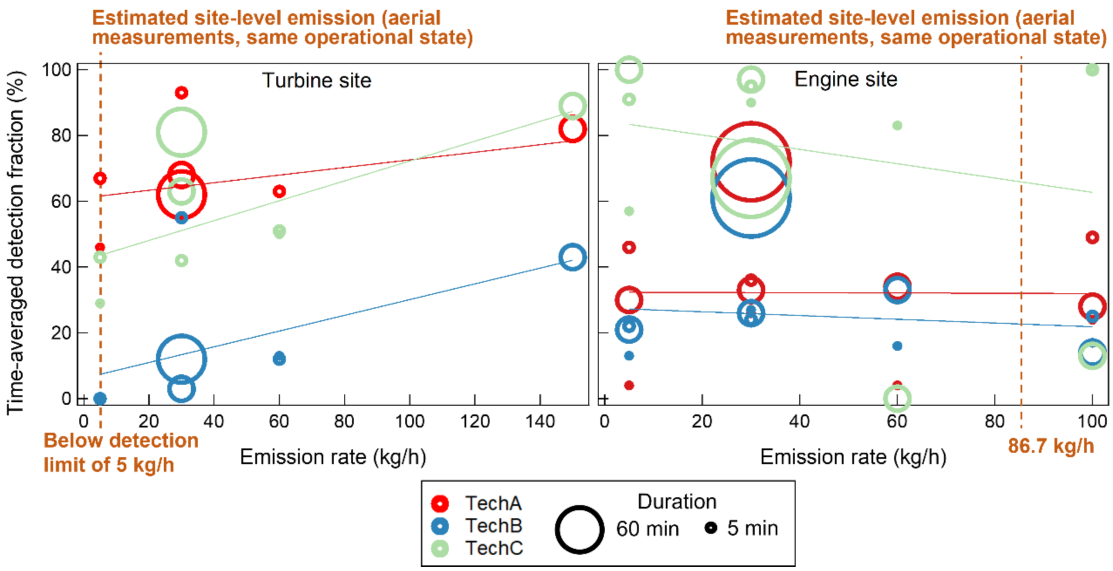

Figure 6. *The calculated mean time-averaged detection fraction (y-axis) of controlled releases detected by Tech A (red circle), Tech B (blue circle), and Tech C (green circle) at the Turbine site and the Engine site as a function of known emission rate (x-axis) with the threshold of 1 ppm enhancement above the baseline. The size of the circle indicates the duration of the emission event. The estimated site-level emissions from aerial measurements are labeled for the two sites.*

The performances of emission-rate-based CMS technologies (Tech D and Tech E) under these controlled variables are also explored and the results are shown in SI section S9. Briefly, on the one hand, no obvious improvement in the detection probabilities and quantification/localization accuracy of Tech D and Tech E are found as a function of increasing emission rate. On the other hand, the detection probabilities and localization accuracy are higher when the duration of the emission event is longer (~ 120 min). Thus, the high temporal resolution of CMS measurements may compensate for the high uncertainty when translating the raw concentration measurements into emission event identification.

3.5 Inter-comparison of CH4 signals detected by co-located sensors

Sensors of different CMS technologies located within 10 m are considered "co-located" sensors and can provide opportunities for cross-validation and performance evaluation of different technologies, eliminating interference from complex atmospheric dynamics. We analyzed the correlation of CH_4 measurements detected by 7 pairs of co-located sensors of Tech A, Tech B, and Tech C at two sites during the three-month field trial. CH_4 concentrations reported by Tech D and Tech E are preprocessed data and are not comparable to the measurements of other technologies. The information on the co-located sensors and the calculated correlation coefficient are shown in SI Figure S1 and Table S6.

Due to the limitation of the non-normally distributed dataset, we calculate the Spearman rank-order correlation coefficient (ρ) for each pair. The interpretation of ρ are as follows (the descriptor applies to both positive and negative relationships)[42], ⩾0.7 – very strong relationship, 0.4-0.69 – strong, 0.3-0.39 – moderate, 0.2-0.29 – weak, and 0.01-0.19 negligible relationship. We calculated the correlation coefficient for raw CH_4 measurements and CH_4 enhancements (background subtracted CH_4 data) of each co-located sensor pair. The CH_4 enhancements are determined by subtracting the minimum CH_4 concentration in each 15-minute interval from the raw data to address variation in baseline readings of different CMS technologies due to factory settings or calibration issues.

Raw CH_4 signals vs. background subtracted CH_4 signals detected by co-located sensors. Figure 7 shows the results for the five co-located pairs of Tech B and Tech C at two sites. We find that the correlation coefficients between the raw CH_4 signals detected by co-located sensors vary from 0.15 to 0.45 (Table S6). Two pairs have strong relationships (ρ >0.4), one pair correlate moderately, and the rest of the pairs have weak or negligible relationships (ρ <0.3). After subtracting the background CH_4 signals to focus on CH_4 enhancement, in general, the correlations between each pair become slightly stronger, increasing, on average, by about 2%. There are no obvious differences between the correlation coefficients in each month.

We also investigated the relative performance of co-located sensors under different operational statuses of the compressors (see Table S6 in SI). Background subtracted CH_4 signals from compressor stations were filtered using a two-step process (as described in section 2.5) to exclude CH_4 enhancement from known operational activities and keep the operational condition constant for different operational statuses. We have two observations. First, correlation coefficients of CH_4 signals after the filtering process for background signals and emission event enhancements are higher than the raw CH_4 signals, and only background subtracted CH_4 was detected by co-located sensors. Second, at the Turbine site, relationships between co-located sensors are comparable regardless of the status of the compressor. At the same time, relationships between co-located sensors at the Engine site are generally stronger when more compressors are operating.

As shown in Figure 7, correlation coefficients of co-located pairs between the same two technologies are independent of the distance between co-located sensors. The larger correlation coefficient (ρ =0.52) indicates a strong relationship between the CH_4 measurements detected by the co-located sensors of pair #1 at the Engine site with a distance of 10 m. Based on the location of the two sensors at the site (see Figure S1 in SI), we find that pair #1 is deployed in an open area of the Engine site that is downwind of major emission sources (e.g., compressors and blowdown silencer) based on prevailing wind direction (southwesterly) during the three-month survey period. Thus, sensors of pair #1 tend to capture more elevated CH_4 signals leading to better correlation.

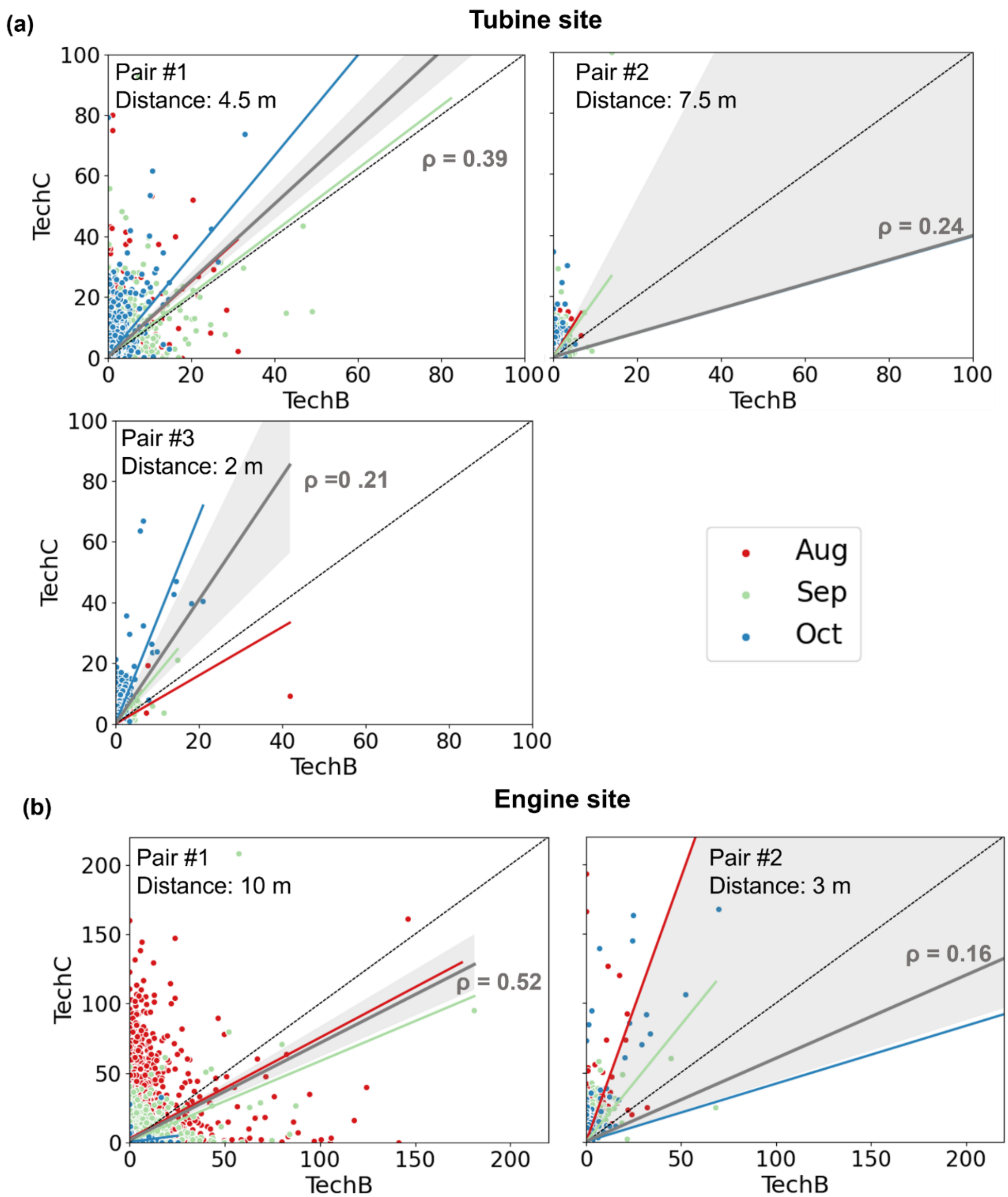

Figure 7. *Scatterplot of the relationship of CH_4 concentration (ppm) detected by five pairs of co-located sensors of Tech B and Tech, at (a) the Turbine site and (b) the Engine site. Red, green, and blue dots indicate the measurements from August, September, and October, respectively. Regression lines that fit the whole dataset and each month are shown by the solid grey line, red line, green line, and blue line respectively. Light grey shaded areas show the 95% confidence interval of the regressions. Black dashed lines are 1:1 line. Correlation coefficients (ρ), pair numbers, and distance between each two co-located sensors are labeled.*

We conducted a comprehensive long-term study of the performance of five CMS technologies at midstream compressor stations. The two types of stations chosen for the study – a turbine site with low exhaust CH_4 slip and an engine site with significant CH_4 emissions from the exhaust – represent the range of emissions observed at midstream facilities across the U.S. By combining known emission events and in-situ controlled releases, we evaluate the performance of CMS technologies in detecting, quantifying, and localizing emission events.

The analysis and results shown in this study indicate that CMS technologies need to be employed cautiously, especially for compact and complex O&G facilities. The findings of this work suggest that emissions from compressor stations can vary substantially over time under different operational statuses. But even as a continuously operating monitoring system, CMS has the potential to miss emission events with low emission rates and/or short durations. A better understanding of the uncertainties of the quantification and localization features of CMS will be useful for these solutions to improve performance. Furthermore, the alert systems of CMS need to be set up with more consideration for the nature of baseline emissions and the location of these sensors to achieve the goal of quickly detecting large emitters. As these technologies rapidly improve, a full understanding of the performance of CMS requires further evaluation before widespread deployment.

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Author contributions

A.P.R. conceived the study. S.Y. conducted the field experiments and analyzed the data. S.Y. and A.P.R. jointly interpreted the results and contributed to the writing of the paper.

Conflicts of Interest Statement

The authors declare the following competing financial interest(s): A.P.R. is currently a member of the Gas Pipeline Advisory Committee of the US Department of Transportation; in this role, he is a Special Government Employee. A.P.R. has current research support from the US Department of Energy, Environmental Defense Fund, and sponsors of the Energy Emissions Modeling and Data Lab (EEMDL).

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