Project Canary is Solution F

Assessing the Performance of Emerging and Existing Continuous Monitoring Solutions under a Single-blind Controlled Testing Protocol

Fancy Cheptonui[1,2], Ethan Emerson[2], Chiemezie Ilonze[2], Rachel Day[2], Ezra Levin[2], Daniel Fleischmann[2], Ryan Brouwer[2], and Daniel J. Zimmerle[2,]*

[1]Department of Systems Engineering, Colorado State University, Fort Collins, CO, 80523, USA

[2] Energy Institute, Colorado State University, Fort Collins, CO, 80524, USA

*Corresponding Author: Daniel Zimmerle (dan.zimmerle@colostate.edu)

Abstract

Continuous Monitoring (CM) solutions have been identified as one method to address methane emissions at oil and gas (O&G) facilities, as these solutions may facilitate faster emission detection and repair than traditional survey methods. This study tested 13 CM solutions over 12 weeks using single-blind controlled testing. Controlled release rates ranged from 0.08 to 6.75 kg CH_4 hr^{-1} and lasted 18 minutes to 8 hours. Six solutions demonstrated 90% detection limits (DLs) within the range of controlled releases, 0.5 [0.3, 0.6] kg CH_4 hr^{-1} to 6.8 [5.9, 8.0] kg CH_4 hr^{-1}. Of the six solutions, 4 had False Positive (FP) rates of 7.8-14%, and four had False Negative rates (FN) of 8-34.1%. Compared with Ilonze et al., these results show retested solutions balancing method sensitivity and FP and FN rates. All scanning/imaging solutions had high localization (≥ 40%) precision and accuracy to the equipment unit. Eleven of 13 solutions were tested for quantification; three had a mean relative quantification error ranging from 33.4 [0.85, 66.0] % to 96.1 [63.4, 128.9] %, 95% CI for leaks between 0.1 – 1 kg CH_4 hr^{-1}. For larger emissions (> 1 kg CH_4 hr^{-1}), nine solutions had a mean relative quantification error ranging from 2.8 [-20.3, 25.9] % to 32.8 [17.2, 48.5] %, 95% CI. Relative to previous studies, uncertainties in quantification estimates decreased, as did FN and FP rates, with improved detection limits for 2 of the four retested solutions. These findings highlight that continuous, rigorous testing enhances solution performance, with notable improvements observed across multiple test programs using the same test protocol.

Synopsis

Regulations have set standards for CM solutions to qualify for emission mitigation; therefore, solutions must be accurate to meet these standards. This study assesses new solutions' performance and tracks existing solutions' performance relative to previous studies.

Keywords

Methane, Detection, Detection Limit, Quantification, Continuous Monitoring, Probability of Detection

Introduction

The production of natural gas (NG) in the US increased by 4%, 5 billion cubic feet per day (Bcf/d), in 2023 compared to the production in 2022 [1]. Natural gas consists of between 70 and 90 % methane (CH_4) [2], one of the major greenhouse gases in the atmosphere. Although CH_4 stays in the atmosphere for a shorter period than CO_2 [3], it has a global warming potential that is 27 - 30 times higher than CO_2 in a 100-year timespan [4], [5], [6]. Methane is emitted from natural sources, such as wetlands, and anthropogenic sources, such as energy production and agricultural activities [7].

Globally, emissions from the energy sector accounted for approximately 130 million tonnes of CH_4 in 2023 [8]. In the US, operations in the oil and gas (O & G) industry are the second largest industrial source of emissions [3]. Federal and state regulations [9], [10] require operators to implement leak detection and repair (LDAR) programs to reduce intentional (vented) and unintentional (fugitive) methane emissions [11] from the O&G industry in the US and Canada.

Although current regulatory-approved methods for LDAR programs, such as EPA method 21 and OGI camera surveys [12], can provide precise component- or equipment unit-level measurements, they can be expensive and labor-intensive when scaled over thousands of O&G facilities. Also, studies have shown that emissions exhibit spatial and temporal variability [13], [14], [15], [16] making it challenging to estimate the size of emissions in a facility accurately from surveys. More studies show that super emitters (emitters greater than 100 kg hr^{-1}: [12]) skew the emissions distribution [16], [17], [18], [19]. Therefore, detecting such emitters is challenging when using traditional methods.

Recent regulations [12], [20], [21], [22] and research efforts have motivated the development and testing of new and existing LDAQ technologies [23], [24], [25], [26], [27], [28], [29], [30], [31]. LDAQ solutions, such as continuous monitors, promise to address some emission measurement concerns by cost-effectively providing temporally resolved monitoring of O&G facilities. The major advantages of CM solutions include the capability to detect large emissions, sustained operational capacity, and provision

of temporal data. Despite these advantages, CM solutions cannot be used for regulatory LDAR programs unless they demonstrate equal or better emissions reduction than existing LDAR survey methods.

The recent EPA's final rule [12] has stipulated the performance CM solutions must meet to be approved as an alternative approach for regulatory LDAR programs. According to subpart OOOOb 40 CFR part 60 by EPA [12], the detection threshold for CM systems must be at least 0.4 kg hr^{-1} of CH_4. While operators are already using CM solutions for internal emissions accounting programs and voluntary methane emissions reduction programs like OGMP 2.0 [32], more rigorous testing is needed to improve confidence in output data (such as 90% DL, quantification accuracy, detection, and localization) and track the trend in solutions' performance over time.

Colorado State University (CSU) developed a standardized, controlled testing protocol as part of the Advancing Development of Emission Detection (ADED) project to assess the performance of CM solutions [33]. Starting in 2022, the protocol has been utilized for an extended CM test from February to April each year. The 2022 testing is documented in Bell et al. [24], the 2023 testing in Ilonze et al. [26] and the 2024 testing in this paper.

The 2022 test showed that CM solutions exhibited quantification uncertainties over ± 60% for single emission estimates. One of the primary metrics assessed for all the CM solutions is the 90% DL, which shows the probability of a solution detecting emitters 90% of the time [24]. In 2023 testing, retested solutions showed a decrease in 90% DL and FP rates but similar wide quantification uncertainties for single emission estimates. The 2023 testing also indicates that solutions with the lowest DL90 (90% DL in the current study) had the lowest FP and FN rates, counter to the expectation that raising detection limits to lower FP and FN rates is necessary.

The current study (2024 testing) tested 13 CM solutions, including four solutions that participated in the 2023 testing [26], and 2 of the four solutions and 1 of the thirteen were also tested in the study by Bell et al. [24]. The solutions were tested at Colorado State University's (CSU's) Methane Emissions

Technology Evaluation Center (METEC), Colorado, US. Solutions were categorized into point sensor networks (PSN) and scanning/imaging solutions. PSN solutions consist of point sensors deployed at/on the facility's equipment to detect the presence of hydrocarbons in the atmosphere [34]. Scanning/imaging solutions deploy scanning lasers and short/mid-infrared cameras that generate 2D images of gas plumes at the deployed locations [24], [26]. Algorithms are used with meteorological data to produce quantification and localization information. Primary performance metrics such as the probability of detection (POD), quantification accuracy, localization accuracy, and precision of a solution are presented in this study and compared to the performance of solutions from 2023 [26] and 2022 [24].

Methodology

Testing Facility

The solutions were tested between February and April 2024 at CSU's METEC facility. The facility is an 8-acre (3 ha) outdoor facility for testing and improving CH_4 emissions LDAQ solutions. The facility consists of 7 wellpads, complete with retired O & G equipment, including, but not limited to, wellheads, separators, and tanks (SI Figure S-1). For this study, wellpads 4 and 5 were used for controlled releases of compressed natural gas. Wellpad 4 consists of 5 wellheads, four horizontal separators, and three tanks, while wellpad 5 consists of 3 wellheads and three vertical separators (SI Figure S-3). The tanks, wellheads, and separators have unique emission points (with unique tag identifiers) and flow meters that control the gas flow.

ADED Continuous Monitoring Protocol R1.0

Overview: The first revision of ADED's continuous monitoring protocol [33] was developed in September 2020 by METEC with contributions from stakeholders in the O & G industry, LDAQ technology developers, regulatory bodies, non-governmental agencies, and state and federal environmental

agencies. The protocol employs single-blind, controlled testing to evaluate the performance of solutions in a rigorous and reproducible manner to allow for inter-solution comparison and year-over-year performance evaluation. In a single-blind test, the test center knows the emission rates and locations, while the performers (solution providers) are unaware of this information. Testing is conducted for extended periods, typically months, to assess the performance of a solution over a wide range of emission rates with varied environmental and meteorological conditions.

According to the protocol, a solution consists of one or more natural gas (NG) or methane sensors, data analytics that convert raw sensor readings to quantification and localization data, and a data management system to report detections, localizations, and applicable quantification data. The analytics may infer the presence or absence of an emission, the source emission rate, and the location of an emission.

Experimental Process

Compressed NG consisting of 84.2% CH_4, 13.3% C_2H_6, 2% C_3H_8, and a trace amount of C_4+ was released from storage gas cylinders. Gas was released at rates ranging from 0.08 to 6.75 kg CH_4 hr^{-1}. Gas flow through the emission points on Pads 4 and 5 was controlled by flow meters assigned to each equipment group in the wellpads. Testing involved a series of experiments with the number of emission points ranging from 1 to 5 per experiment (SI Figure S9). The emission points were located on different equipment units for experiments with multiple emission points. The duration of each experiment ranged from 18 minutes to 8 hours.

Experiments ran 24 hours a day for 5 to 7 days per week. The controlled releases started and ended simultaneously for experiments with multiple emission points. Multiple controlled releases are designed to test the capability of a solution to attribute an emission to a particular location. Individual experiments were separated from the preceding experiment by a no-emission period lasting from 30 min

to 4 hours (SI Figure S-9) to enable solutions to potentially identify the start and end of experiments when the concentration levels were reduced to the original background concentration levels.

The test facility assigned an experiment ID to an experiment and recorded the start and end time, the duration, the metered flow rate, the uncertainty of the metered flow rate, the gas composition as measured using gas chromatography, and the meteorological conditions. Regularly, the team processed the detection reports of various solutions to determine the emission rates and durations that had not been covered while testing (small, large, and longer-duration releases).

Reporting: Solution performers submitted detection reports to METEC's email reporting system for evaluation using the protocol's performance metrics [33]. Detection reports notify the test center of identified individual emission events, the start time, the location, and the emission rate of a source. Each report should be attributed to a single emission or controlled release for proper detection classification. Mandatory information in the detection report includes the *DetectionReportID*, *DetectionReportDateTime*, *EmissionStartDateTime*, *EmissionSourceID*, *Gas* (the species monitored by the solution), and *Equipment Unit* (SI Section S5). The protocol allows performers to update a detection by sending new reports referencing the same *EmissionSourceID* from a previous report. This provision enables performers to change data such as the estimated emission rate, the timing of a controlled release, and the GPS coordinates to reflect the best solution estimates. More details on the protocol, including definitions of these and other terms, are included in the protocol [33], SI, and Ilonze et al [26].

In addition to the detection reports, performers submit offline reports whenever their solution is not operating during testing. The offline reports state the offline start and end time, allowing the exclusion of offline data during analysis. Additionally, the test center records all maintenance events at the site, such as gas house filling and fixing faulty equipment. All the detection reports sent during maintenance events are excluded from the analysis.

Performance Metrics: Controlled releases within the testing period are paired with detections from the detection reports (SI Section S8) to evaluate the performance of the solutions. The detection reports are classified as true positives (TP) or false positives (FP). According to the protocol, a TP occurs when a solution's detection report is attributed to the correct and coinciding controlled release. A false positive occurs when a detection report incorrectly attributes a controlled release within the test facility. During the second implementation of the protocol [26] FPs were further classified into 2: FP—no controlled release or FP- excess. A false positive (no controlled release) occurs when a detection report identifies an emission with no controlled release at the test facility. A false positive (Excess) occurs when a detection report identifies a controlled release already paired with a different detection report.

A controlled release is classified as a false negative (FN) when there is no detection report to pair with it. The current study used the primary performance metrics, including the probability of detection (POD), localization accuracy and precision, quantification accuracy, and detection time for classification. More details about the metrics can be found in the protocol [33] and the SI.

Before classification, specific data were removed from the analysis, including 1) data when the performer reported their system was offline, 2) data that occurred outside the testing window, 3) data that the performer stated the equipment unit as being off facility, i.e., outside the test facility's fence line, and 4) data that occurred during maintenance events as shown in the maintenance log sheet.

As stipulated in the protocol [33] and as shown by Ilonze et al. [26], the classification process was as follows:

1.) All the controlled releases conducted within the test facility were sorted by equipment unit identifier and then by the flow rate if reported by the performer, in descending order.
2.) From the first step above, the remaining controlled releases were sorted by equipment group identifier and then by flow rate, if reported by a solution, in descending order.

3.) Finally, the remaining controlled releases were sorted by flow rate, if reported by a solution, in descending order. After this step, all the controlled releases and unpaired detections were classified as FN and FP detections, respectively.

In steps 1, 2, and 3 above, all the detections identifying the sorted equipment unit, group, or facility as the emission source were selected, respectively. The selected detections whose emission start time was between the controlled release start and end time were filtered and sorted by flow rate, if reported by a solution, in descending order. Finally, the uppermost detection was paired with a controlled release as a TP detection with correct unit, group, or facility-level localization precision for steps 1, 2, and 3, respectively. After each step above, a matched pair was removed from further classification.

ADED Participating Solutions: Spring 2024

Participants were recruited through an open invitation on the METEC facility's website and by contacting solution developers identified during protocol development. Thirteen performers deployed their solutions at wellpads 4 and 5 before the start of controlled testing. Some solutions monitored a subset of equipment groups, while others deployed their sensors in all the equipment groups in wellpads 4 and 5 (SI Figure S-3). After deployment, solution providers operated their solutions remotely except when their hardware malfunctioned; in this case, the solution providers' team would fix their hardware during 'no release' periods.

In alphabetical order, the participating solutions were Blue-Rock, ChampionX, Earthview, Honeywell, Oiler-Equation, Project-Canary, Sensirion, Sensit, Shepherd-Safety, and SLB. Table 1 shows all the solutions deployed during testing identified with a unique solution ID. Three solutions tested in the current study were scanning/imaging solutions, while 10 were PSNs. While a PSN records concentration readings, scanning/imaging solutions generate gas plume images. Solution providers use various algorithms to convert the concentration readings or images to interpretable data, illustrating the

presence/absence of an emission. As shown in Table 1, 4 solutions that were tested in 2023 [26] were retested in the current study, i.e., solutions N, F, D, and P. Solutions D and F in the current study were also tested in the study by Bell et al. [24]. Solution C was tested by Bell et al. [24] and subsequently tested in the current study. All the solutions were deployed across Pads 4 and 5 except solution U, which was only deployed on the tanks in Pad 4.

Table 1. Participating solutions in the current study (2024), solutions from 2023 [26], and solutions from 2022 [24], in alphabetical order of the solution ID.

		Sensor Count				
		2024	2023	2022		
Solution ID	Sensor Type	(this study)	(Ilonze et al.)	(Bell et al.)	Detection	Quantification
C	PSN	12	-	6	✓	✓
D	PSN	8	8	8	✓	✓
F	PSN	9	10	8	✓	✓
I	Scanning/Imaging	1	-	-	✓	✓
M	Scanning/Imaging	7	-	-	✓	✓
N	PSN	50	18	-	✓	✓
P	PSN	14	6	-	✓	×
R	PSN	11	-	-	✓	✓
S	PSN	12	-	-	✓	✓
T	PSN	7	-	-	✓	✓
U	PSN	3	-	-	✓	×
V	Scanning/Imaging	1	-	-	✓	✓
W	PSN	35	-	-	✓	✓

The table shows two different types of solutions that were tested: the PSNs and scanning/imaging solutions. The current study tested 13 solutions, with 4 of the 13 tested in Ilonze et al. [26], 2 of the 4, and 1 of the 13 tested in Bell et al. [24].
✓ means the solution reported the data necessary for detection or quantification.
× means the solution did not report the data necessary for detection or quantification.

Data Analysis

As with the study by Ilonze et al. [26], this study used power functions with the intercept set to zero to estimate the POD and generate the POD curves for each solution. The POD curve is calculated as a function of the source emission rate, duration, and wind speed. Data used to generate the POD curve for each solution had a quantile ranging from 30 to 50 data points per bin. The number of points was determined using quantile-based discretization, which produced the highest *goodness of fit* (R^2) for a solution. In quantile-based discretization, equal-sized data bins were generated for various test conditions and used to fit the POD curve. More information on the analysis can be found in the SI section S7 and sections S10.1 and S10.2.

A 5-minute buffer time was applied on the maintenance end time to account for any residual emissions in the atmosphere that solutions may detect and to avoid assigning a FP detection to such reports. Additionally, 20-minute buffer times were applied to the start and end times of the experiments to maintain consistency with previous studies and to effectively track the performance of solutions that have been retested.

Protocol Constraints

The performance of the tested solutions is only representative of the test conditions used; therefore, the results cannot be extrapolated for untested conditions. Additionally, emission rates ranging from 0.08 to 6.75 kg CH_4 hr^{-1} were used; however, for most production facilities, there can be larger emission rates not tested in the study due to safety reasons. Also, some CM solutions rely on the accuracy of measurements from emissions that run for extended periods. Therefore, since the controlled releases in this study ran for up to a maximum of 8 hrs, the results may not cover the full range of capabilities for such solutions. The implementation of the protocol is such that the solution is tested for component emission detection and quantification; however, some solutions operate as full facility monitors and may

provide facility-level emission rates rather than emission detection at the component level. Testing in this study involved steady-state emission rates; however, this may not be the case in production facilities. The detection reports in this study are human-influenced in that the protocol requires the solution providers to infer the presence/absence of emission based on sensor readings rather than sending the sensor readings directly to the test center.

Results

Overview of the Results

Results of a multivariate logistic regression model showed that the emission rate significantly ($p<0.05$) affected the probability of all solutions to detect emissions except for solution T (SI Table S4). Therefore, POD curves were generated as functions of the emission rate. Other variables tested for their impact on the POD of a solution include the controlled release duration, ambient temperature, wind speed, wind direction, and distance to the closest sensor (Table S5-S9). In the plots below, the 90% DL represents the emission rate at which results indicate the solution could detect emissions in 90% of cases, regardless of the prevailing meteorological conditions [24]. Regulatory agencies consider the 90% DL when approving CM solutions for emissions monitoring at production facilities [12]. Figure 1 compares the POD curves for solutions retested in this study relative to Ilonze et al. [26]; Figures 2 and 3 show the POD curves for the newly tested solutions. Each plot's release rate in the x-axis was divided into different quantiles with an equal number of data points per bin, ranging from 30 to 50 (SI Section S7). The mean, minimum, and maximum points per bin are shown. The red and blue markers represent the fraction of controlled releases in a bin classified as TPs. The faded curves were derived from bootstrapping the data points to obtain the uncertainty of the POD curve (SI Section S10.1).

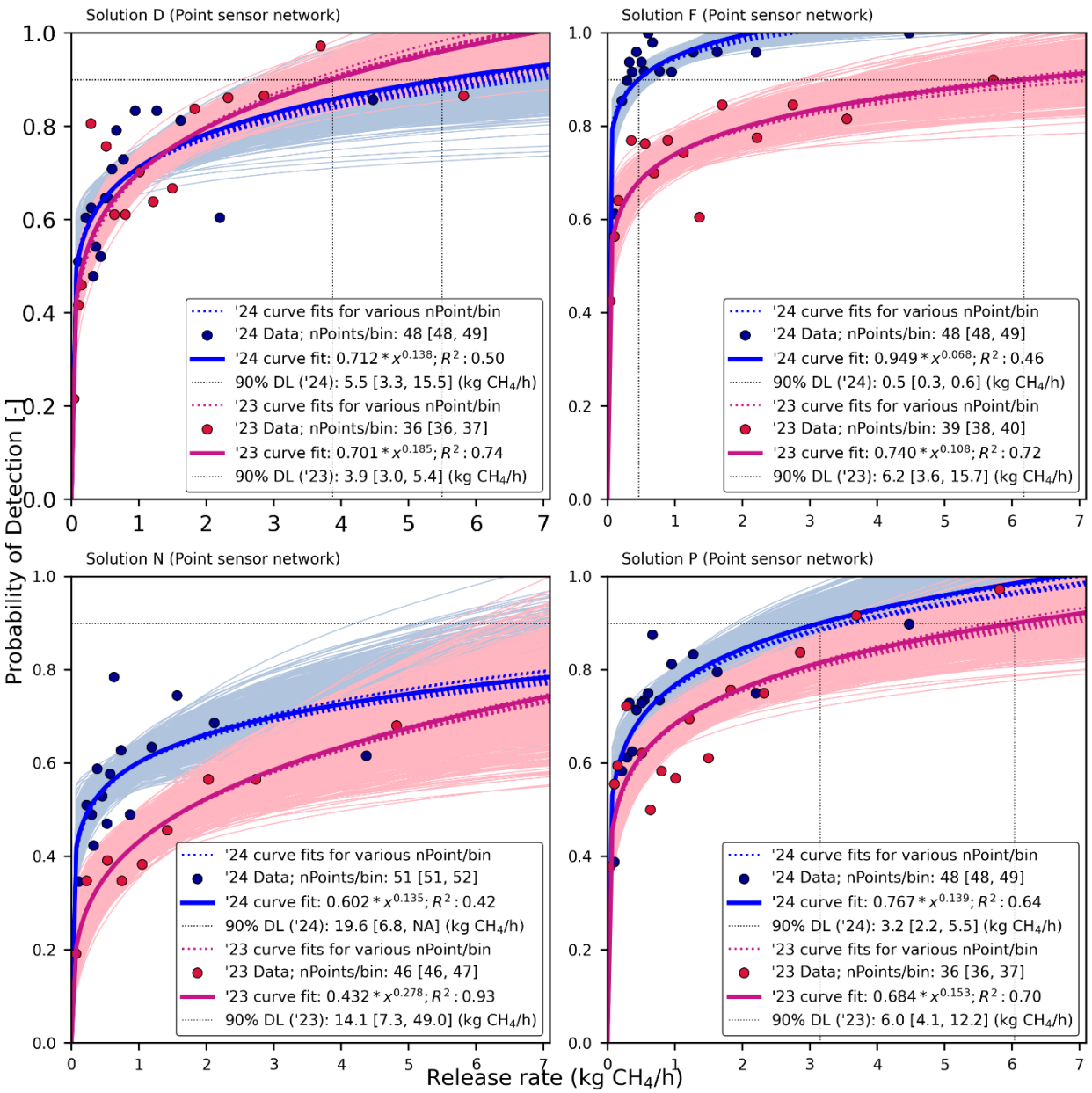

Figure 1. The probability of detection against the controlled release rate for PSNs tested in the current study and in the study by Ilonze et al. [26] The plots also show the 90% DLs for these solutions. The figure shows that three of four solutions (Solutions D, F, and P) are within the range of tested release rates. Although solution N's 90% DL is out of the range, the lower bound of the 90% DL is within the range.

Probability of Detection: In this section, we discuss the PODs of the solutions in various categories: PODs within the range of tested emission rate, PODs outside the tested emission rate range (> 10 kg hr^{-1} and < 10 kg hr^{-1}), and PODs which could not be estimated. Additionally, we perform an inter-solution comparison of the PODs (PSN versus scanning/imaging solutions).

Generally, figures 1, 2, and 3 show that 10 out of 13 solutions had 90% DLs ranging from 0.5 to 76.5 kg CH_4 hr^{-1}. First, considering the 6 (of 13) solutions with DLs within the range of the controlled release rates, results indicate that these solutions balance method sensitivity and low FP and FN rates (as in Ilonze et al., [26]). Table 2 shows that 5 of the six solutions had the lowest FP rates (8 to 19%), and 4 had the lowest FN rates (8-33%) (SI Section S8.1).

Second, 4 of 13 solutions with 90% DLs outside the controlled release rate range exhibit a mix of high and low FN and FP rates; 2 (of 4) solutions had high FP (>20%), and 3 (of 4) solutions had high FN (>50%) rates. Three solutions have 90% DLs substantially outside the tested emission rates (>10 kg hr^{-1}), N (Figure 1), C (Figure 2), and U (Figure 3). POD for solution C, the solution with the largest 90% DL, is affected by duration, emission rate, distance to the closest sensor, and wind speed. For solution U, the POD was affected by the emission rate and the distance to the closest sensor. The POD for solution N was affected by emission rate, duration, wind speed, temperature, and distance to the closest sensor. For solution M, although the 90% DL was outside the tested emission rate range, the 90% DL did not deviate substantially (< 10 kg hr^{-1}) from the maximum tested emission rate (Figure 2). As for these solutions (N, C, U, and M), their 90% DLs should be used cautiously as they fall outside the range of tested release rates, 0.08 – 6.75 kg CH_4 hr^{-1}. More information about the various tested conditions for the POD can be found in the SI Section S8.2.

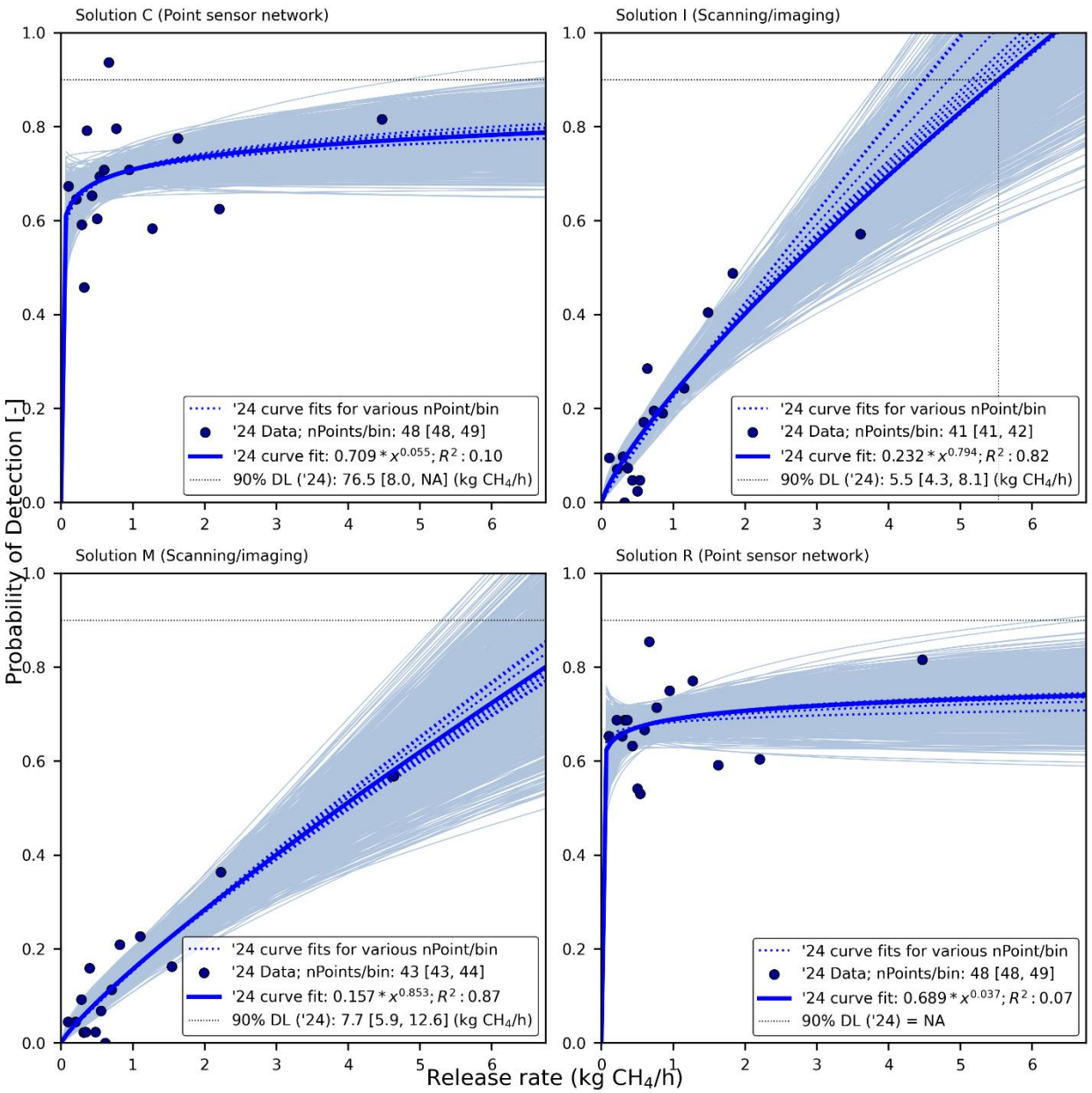

Figure 2. The probability of detection versus the controlled release rate for PSNs (C and R) and scanning/imaging solutions (I and M) that were newly tested in this study. The figure shows that 1 of 4 solutions (Solution I) had a DL within the range of tested release rates. The POD curve could not estimate the 90% DL and the upper bound 90% DL for solutions R and C, respectively; therefore, these are presented as NA.

As for the third category, for the three solutions (R, T, and W) that displayed a minimal trend in POD with emission rate (for the range of tested rates), a 90% DL could not be estimated (Figure 2 and Figure 3). Results show that duration and temperature have a statistically significant impact ($p<0.05$) on the POD for solution T (SI Tables S-6 and S-9). Although the emission rate significantly affects ($p<0.05$) the

POD for solutions W and R, duration, temperature, and wind speed also ($p<0.05$) affects the PODs for these two solutions (SI Tables S-6, S-8, and S-9). For solution R, in addition to the variables above, the distance to the closest sensor significantly ($p<0.05$) affected the POD.

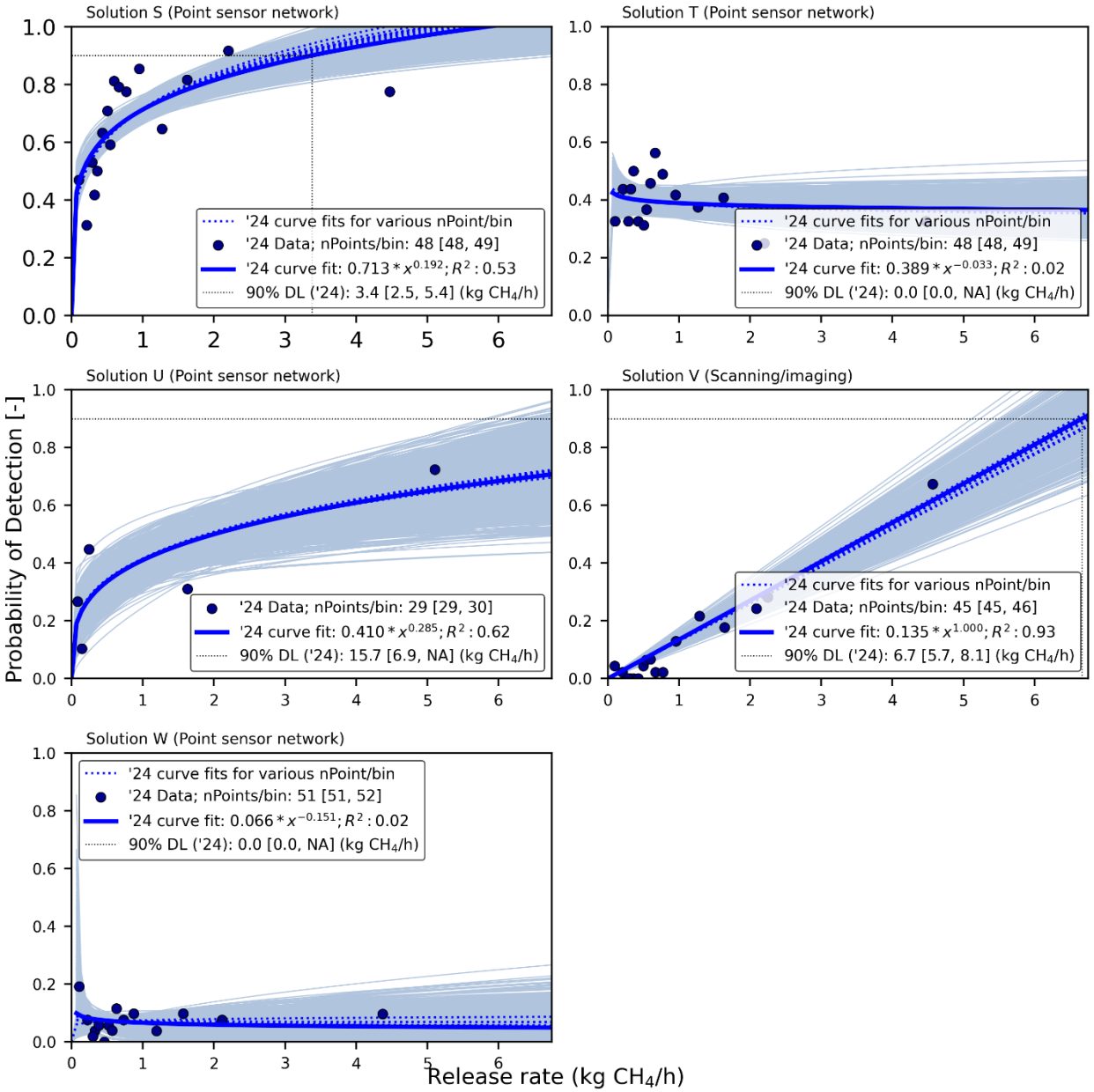

Figure 3. The probability of detection versus the controlled release rate for PSNs (S, T, U, and W) and a scanning/imaging solution (solution V) that were newly tested in this study. The figure shows that the 90% DLs for two solutions (Solutions S and V) are within the range of tested emission rates. The POD for solution U is outside the tested emission rate range, while the POD for the two remaining solutions (T and W) in the figure did not approach 90%.

Finally, the 4 PSNs with 90% DLs within the tested emission rate range had 90% DLs of 0.5 to 5.5 kg CH_4 hr^{-1}, somewhat better than the scanning/imaging solutions' 90% DL of 5.5 to 7.7 kg CH_4 h^{-1} (2 of the 3 had 90% DLs within tested rates). However, overall, the remaining 5 PSNs (all newly tested PSNs) had much higher 90% DLs, outside the tested range, or did not produce data that reflected enough trend to estimate a POD curve and 90% DL.

Table 2. Summary of the solutions' 90% DL, the true positive rate (TP), the false negative rate (FN), and the false positive rate (FP) (SI Section S8).

Solution ID and Type	90 % DL (kg CH_4 hr^{-1})	DL Within Tested Rates	FP (%)			TP (%)	FN (%)
			Overall	No Controlled Release	Excess Reports		
F (PSN)	0.5 [0.3, 0.6]	Yes	14	8	92	92	8
P (PSN)	3.2 [2.2, 5.6]	Yes	8	6	94	72	28
C[a] (PSN)	76.5 [7.2, NA]	No	24	28	72	69	31
R[a] (PSN)	POD could not be calculated	NA	34	3	97	68	32
D (PSN)	5.5 [3.3, 16.0]	Yes	8	16	84	67	33
S (PSN)	3.4 [2.5, 5.2]	Yes	19	5	95	66	34
N[a] (PSN)	19.6 [7.1, NA]	No	4	94	6	57	43
T[a] (PSN)	POD could not be calculated	NA	41	33	67	40	61
U (PSN)	15.7 [6.6, 131.2]	No	34	79	21	38	63
I (Imaging)	6.2 [4.7, 9.6]	Yes	23	35	65	19	81
M (Imaging)	7.7 [5.9, 12.9]	No	5	20	80	14	86
V (Imaging)	6.8 [5.9, 8.0]	Yes	13	50	50	11	89
W[a] (PSN)	POD could not be calculated	NA	5	100	0	7	93

The table is presented in decreasing order of the TP rate. Overall, FP in the table represents the fraction of the detection reports classified as false positives. The FP detection reports were further classified as a no-controlled release or an extra report. For the FP no-controlled release, this is a detection report sent in when the test center was not releasing gas. The FP extra report is when a solution sends multiple detection reports linked to an already TP-classified detection report.

[a]Solutions with no observable POD trend with emission rates or whose 90% DL is significantly outside the range of tested rates. These POD curves and DLs should be used with caution. The POD for solutions T and W did not

exceed 60% and 20% in any bin, respectively.

Comparing the Performance in the Current Study to the two Previous Studies

In the study by Bell et al. [24], logistics regression models were used to generate the POD curve and, hence, used to calculate the Method Detection Limits, referred to as the 90% DL in the current study and the DL90 in Ilonze et al. [26]. The controlled releases in the studies by Bell et al. [24] and Ilonze et al. [26] ranged from 0.4 to 6.4 kg CH_4 h^{-1} and 0.006 to 7.1 kg CH_4 h^{-1}, respectively. In the two previous studies, the 90% DL ranged from 2.7 to 30.1 kg CH_4 h^{-1} in Bell et al. [24] and 3.9 to 18.2 kg CH_4 h^{-1} in Ilonze et al [26]. Six of 11 and Four of 9 solutions had a 90% DL within the range of controlled release rates in Bell et al. [24] and Ilonze et al. [26], respectively.

Ilonze et al. relative to this study: The 90% DLs for the four solutions tested in Ilonze et al. [26] and subsequently the current study showed substantial improvements, though with increased variability, in Ilonze et al. [26], 90% DLs for these solutions ranged from 3.9 to 14.1 kg CH_4 hr^{-1}. By the current study, these limits improved, ranging from 0.5 to 19.6 kg CH_4 hr^{-1}, with notable gains for solutions F and P. Solution F's 90% DL improved from 6.2 [3.6, 17.4] kg CH_4 hr^{-1} in Ilonze et al. [26] to 0.5 [0.3, 0.6] kg CH_4 hr^{-1} in the current study, while solution P improved from 6.0 [4.1, 11.8] kg CH_4 hr^{-1} to 3.2 [2.2, 5.7] kg CH_4 hr^{-1} in the current study. Solution F in the current study had a 90% DL that was above EPA's detection threshold (0.4 kg h^{-1}: [12]) for continuous monitoring systems by 0.1 kg CH_4 h^{-1}. The EPA regulation requires detecting a fugitive emission of 0.4 kg CH_4 hr^{-1} in the presence of baseline emissions: routine emissions common to most O&G sites. However, the current testing has no baseline emissions.

Bell et al. relative to this study: The 90% DL for solutions tested in the current study relative to Bell et al. [24] partially improved. Three solutions, C, D, and F, were also tested by Bell et al. [24]. The 90% DL remained at 5.5 [3.2, 16.1] kg CH_4 h^{-1} for solution D and decreased from 3.4 [2.4, 5.4] kg CH_4 h^{-1} to 0.5 [0.3, 0.6] kg CH_4 h^{-1} for solution F. Although the 90% DL for solution D remained constant, the upper and lower bounds have a wider range than Bell et al. [24]. The 90% DL for solution C relative to Bell et al.

increased from 5.5 to 76.5 kg CH_4 hr^{-1}. This highlights the importance of rigorously and continuously testing solutions to ascertain performance.

Localization Precision and Accuracy

The protocol required the performers to submit the equipment unit to which the solution detected an emission. As a primary metric, the localization precision at the equipment unit level is identified for each TP detection (SI S9.2). As for the localization accuracy at the equipment unit, this was calculated as a ratio of the number of TP detections at the unit level to the total number of reported detections for each solution (SI S9.2). We define sensor density as the ratio of the surface area (in hectares) of the test center, i.e., pads 4 and 5, to the number of sensors deployed by a performer.

Generally, all scanning/imaging solutions indicate higher precision (> 50%) and accuracy (> 40%) at the unit level relative to the PSNs (Table 3; SI Figure S-21). The scanning/imaging solutions, I, M, and V, had a localization precision ranging from 56 to 84.9% and localization accuracy ranging from 43.2% to 80.6% at the unit level. As shown in Table 3, for the PSNs at the unit level, 4 out of 10 solutions achieved precisions of 50% or greater and accuracies of 40% or greater. Results show that scanning/imaging solutions better localize emission sources than PSNs. Overall, most solutions (7) presented high precision (> 50%) at the unit level.

Table 3. Summary of the localization precision and accuracies to the unit, group, and facility levels.

			Localization (Equipment Unit)					
			Localization precision (%)			Localization Accuracy (%)		
Solution ID	Solution Type	Sensor Density (ha/sensor)	unit	group	facility	unit	group	facility
U	PSN	0.28	96.3	3.7	N/A	63.4	65.9	65.9
W	PSN	0.02	89.3	5.4	5.4	84.7	89.8	94.9
M	Imaging	0.12	84.9	10.8	4.3	80.6	90.8	94.9
V	Imaging	0.85	59.8	29.3	11	52.1	77.7	87.2
I	Imaging	0.85	56	34.4	9.6	43.2	69.8	77.2
N	PSN	0.02	55.7	41.2	1.1	55.5	95.2	96.3
F	PSN	0.09	50.4	48.4	1.3	43.3	84.9	86.0
S	PSN	0.07	29.2	49.9	20.9	23.7	64.1	81.1
P	PSN	0.06	25.5	65	9.5	23.5	83.3	92
D	PSN	0.11	24.6	64.2	11.2	22.6	81.8	92.2
R	PSN	0.08	23.2	33	43.8	15.3	37.1	66.0
T	PSN	0.12	22.9	35	42.2	13.6	34.4	59.5
C	PSN	0.07	22	54.5	23.5	16.7	58.2	76.0
Results from Ilonze et al. for the solutions that were retested in the current study								
D	PSN	0.11	27.2	68.8	4.0	25.3	89.3	93.1
F	PSN	0.08	40.8	53.9	5.3	36.5	84.7	89.4
N	PSN	0.05	51.6	41.8	6.6	42.2	76.2	81.6
P	PSN	0.14	27.0	56.9	16.1	23.4	72.8	86.8
Results from Bell et al. for the solutions that were retested in the current study								
C	PSN	0.14	1.0	0.5	98.5	0.8	1.2	79.3
D	PSN	0.11	0.0	52.8	47.2	0.0	47.3	89.6
F	PSN	0.11	24.8	50.2	25.0	19.2	58.1	77.5

The table is organized in decreasing order of the localization precision at the equipment unit level. Precision at the unit level refers to a TP detection that identified the correct equipment unit, precision at the group level refers to a TP detection that identified the correct equipment group, and precision at the facility level refers to a TP detection that identified an emission from the test center.

Solution U localized emissions to the unit and group levels because its sensors monitored a specific equipment group, i.e., the tanks on pad 4.

Comparing the Current Study's Localization (Equipment Unit) to Bell et al. and Ilonze et al.

Generally, precision and accuracy for solutions tested in previous studies changed slightly relative to the current study (<15%). Although the results may indicate partial improvement in localization precision and accuracy, these changes could imply an improvement in solutions' algorithms or a change in the sensor density. Relative to Ilonze et al. [26], the localization precision and accuracies increased for 2 of 4 solutions. Relative to Bell et al. [24], the localization precision and accuracies for solutions D and F increased at the unit level (Table 3). The increase in precision and accuracy for 2 of 4 and 2 of 3 solutions relative to Ilonze et al. [26] and Bell et al. [24], respectively, shows that, as a group, the current study's localization precision and accuracy partially improved compared to the two previous studies.

Quantification Accuracy

The quantification accuracy was calculated for solutions that reported the source emission rate. The relative quantification error (in %) was calculated for all TP detections as the relative difference between the reported and metered emission rates. In the current study, 11 solutions reported the source emission rate; 8 solutions had ≥ 50% of their single estimates within a factor of 3 (Table 4). Overall, the percentage of single emission estimates within a factor of 3 for the 11 solutions ranged from 31 to 92% (Table 4). The mean relative error in single emission estimates for controlled releases (CR) between 0.1 and 1 kg CH_4 h^{-1} for two solutions was ≤ 35%. For larger CRs (> 1 kg CH_4 h^{-1}), the mean relative error in single emission estimates for eight solutions ranged from 3% to 33% (Table 4). Small emission rates (between 0.1 and 1 kg CH_4 hr^{-1}), often associated with component leaks, have consistently high uncertainties for most solutions (9). The larger emissions (> 1 kg CH_4 hr^{-1}), often associated with process failures, have lower uncertainties for most solutions (8 solutions); this means that most CM solutions could be well-positioned to mitigate larger emissions (> 1 kg CH_4 hr^{-1}). Section 8.4 and S10.3 of the SI further provide more information on the quantification accuracies for various solutions.

Table 4. The relative quantification error for the 11 solutions that reported the source emission rate.

		Relative quantification error (%)					
		CR [0.1 - 1] (kg CH_4 h^{-1})			CR > 1 (kg CH_4 h^{-1})		
Solution	Percent of Estimates within 3× (%)	Mean Error (%)	Median Error (%)	95% CI	Mean Error (%)	Median Error (%)	95% CI
F	93	35	15	[27, 43]	-12	-22	[-18, -5]
S	74	186	90	[153, 219]	27	8	[12, 41]
D	71	260	124	[213, 308]	33	3	[17, 49]
C	70	96	-2	[63, 129]	10	-40	[-11, 30]
M	67	110	98	[56, 164]	-20	-52	[-45, 6]
N	62	33	-41	[0.9, 66]	3	-51	[-20, 26]
V	57	367	204	[17, 716]	-29	-47	[-46, -12]
W	55	569	394	[319, 820]	4	-14	[-34, 43]
R	40	1326	478	[1003, 1648]	305	111	[205, 406]
T	39	962	383	[775, 1149]	3578	114	[-2832, 9988]
I	31	422	-61	[-279, 1122]	-28	-79	[-63, 8]

The percent of estimates 3× represents the percent of single emission rate estimates within a factor of 3 [33% to 300%] of the CR rate. Also, the table shows the mean, median, and 95% CI for the relative quantification error for control release rates between 0.1 to 1 kg CH_4 h^{-1} and those > 1 kg CH_4 h^{-1}. The table is ranked based on the decreasing order of the percent estimates within a factor of 3.

Comparing the Quantification Accuracy for the Current Study to Ilonze et al.

Figure 4 shows the reported against the actual emission rates for the four retested solutions relative to Ilonze et al. [26]. For these solutions, 3 reported the source emission rate. Between 57 [49, 65] %, 95% CI and 78 [74, 82] %, 95% CI of the single estimates were within a factor of 3 in Ilonze et al. [26]. In the current study, between 61 [57, 67] %, 95% CI and 92 [91, 95] %, 95% CI of the single estimates for the retested solutions were within a factor of 3 (Table 4 and Figure 4). There is an increased percentage of estimates within a factor of 3; however, the 95% CI of these percentages overlaps for solutions D and N.

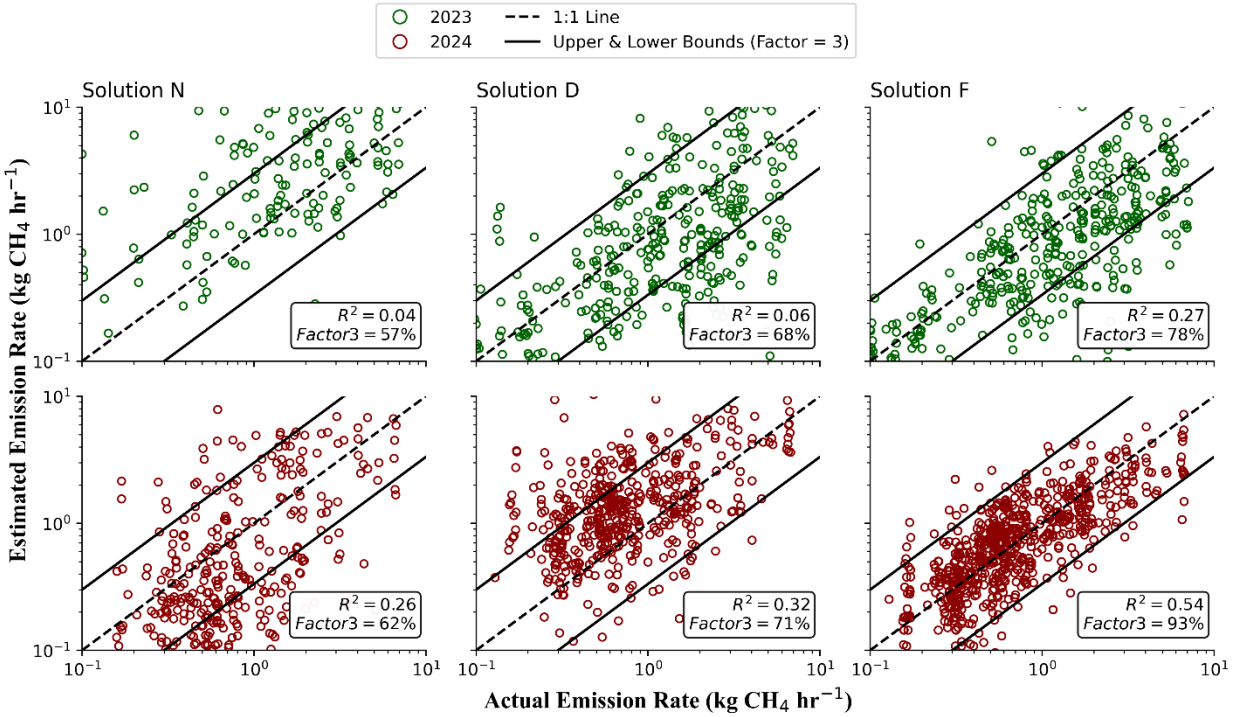

Figure 4. The reported emission rates against the actual (or controlled) emission rate for the three solutions (N, D, and F) that were tested in 2023 by Ilonze et al. [26] and in 2024 (current study). The plots with green points are from 2023 quantification data, while the plots with red points are from quantification data in the current study. The black dotted line represents the 1:1 line; data points along this line illustrate that the reported equals the actual emission rate. The black solid lines highlight the region where the single estimates are within a factor of 3 of the actual emission rates. The R^2 illustrates the correlation between the reported and actual emission rates. Generally, there is a stronger correlation between the reported and actual emission rates relative to Ilonze et al. [26].

Relative to Ilonze et al [26] and Bell et al. [24], the overall emissions quantification has improved over time despite the consistently large uncertainty in single estimates. This is illustrated by an increase in the percentage of single estimates within a factor of 3 in the current study and Ilonze et al. (2024). Additionally, the solutions consistently tested in previous studies had the lowest relative quantification errors for small and large leaks (Table 4).

Detection Time

The detection time was calculated as the time difference between the start time of a controlled release and the time when the email-based reporting system received the solution's detection report. In cases where we received multiple detection report IDs, the time for the first detection report was used for

calculation. Generally, the mean detection time of solutions ranged from 5.1 hrs to 5 days (Figure 5). All solutions except solution D took longer (≥ 8.9 hrs) than the longest duration (8 hrs) of controlled releases in the study. The wide variation in the detection time is due to the manual evaluation of the detection report before submission by the solution provider. In some cases, the automated reporting system may have failed, resulting in delayed processing of the detection reports by the solutions.

The mean detection time of solutions in the current study was larger than the mean detection time in Bell et al. [24] and Ilonze et al. [26]. For the current study, the least mean detection time for 1 of 13 solutions was 5.1 hrs, while for Bell et al. [24] and Ilonze et al. [26], 3 of 11 and 4 of 9 solutions had a mean detection time of ≤ 5 hrs, respectively. The mean detection time increased for 3 of the four solutions tested by Ilonze et al. [26].

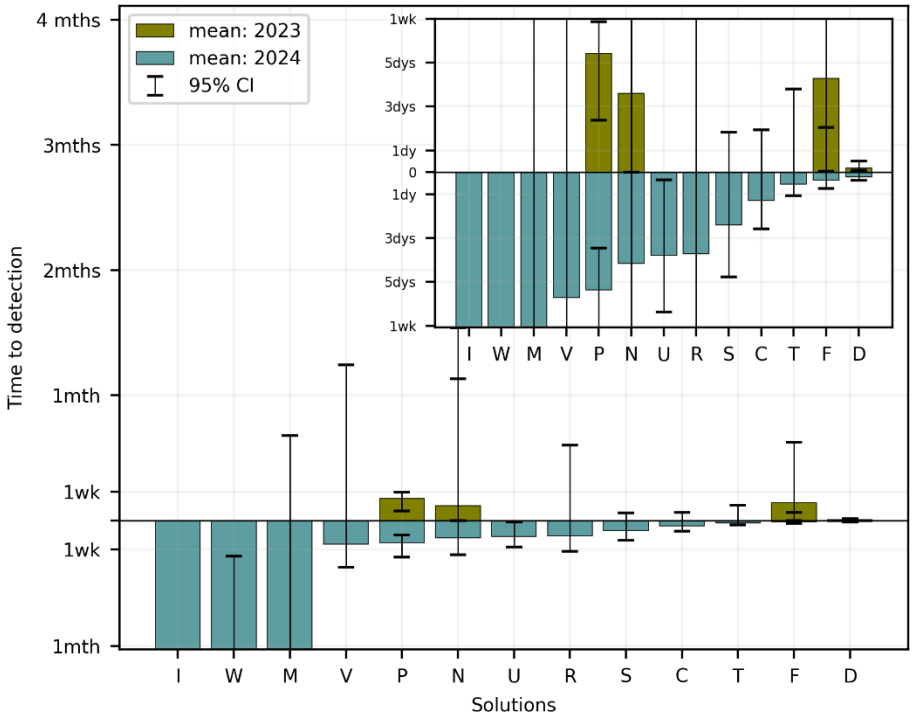

Figure 5. Bar plot showing the mean time to detection for all the solutions tested in the current study (lower half) and those tested in Ilonze et al. (upper half); the bars are organized in descending order of the mean time to detection for solutions tested in 2024. The whiskers represent the 2.5th and 97.5th percentile of the mean detection time for each solution. The inserted plot represents a trimmed y-axis plot of the outer plot. The lower y-axis of the outer plot was trimmed at 1 month; this means that the mean time to detection for solutions I, W, and M is greater than 1 month.

Operation Downtime

Operation downtime is when a solution is not operational during testing, as a performer reports. The operation downtime for 12 of 13 solutions in this study was ≤ 6.4%, meaning that the 12 solutions met EPA's stipulated maximum operation downtime for continuous monitoring systems [12]. The solutions tested in the current study demonstrate the ability of CM solutions to operate for months without malfunctioning.

Implications

This study represents the third implementation of the ADED continuous monitoring protocol. The major findings for the current study are (1) solutions that tested in the two previous studies have improved or held steady in various performance metrics, including lower 90% DL, lower FP and FN rates, and higher localization accuracies at equipment group and facility levels, (2) scanning/imaging solutions offer higher localization precision and accuracy than most PSNs, and (3) solutions have higher quantification accuracies for larger emissions (> 1 kg CH_4 hr^{-1}) than smaller emissions (< 1 kg CH_4 hr^{-1}).

These results highlight the importance of controlled testing in understanding the potential performance of solutions in the field. Although the newly tested solutions performed well on localization precision and accuracy, these solutions struggle with the probability of detection, have large false positive and false negative rates, and generally have long detection times. These results suggest that repeat testing, with concomitant attention to solution evaluation and improvement, positively impacts solution performance. Therefore, providing extended testing windows at low cost will likely benefit the development of next-generation LDAQ solutions.

Additionally, different solutions perform well on different metrics, indicating that they could or may already be tailored towards desirable functionalities or applicable to certain facility types or leak detection and repair programs. Some solutions have 90% DL that qualify for current voluntary and

regulatory leak detection programs. Also, these solutions have sufficiently low FP rates, meaning they should be well-positioned for deployment in those programs.

Finally, as in prior test programs, release rates did not span the range necessary for many solutions to achieve 90% DL within the tested range. Comparing the three release programs to recently approved EPA regulations shows that there is a need for future programs to test above the survey mode requirements listed in EPA's subpart OOOOb [12] of 15 kg/h. Also, field testing [34] indicates a need for future testing to include non-fugitive emission sources during controlled release testing. Revisions of the controlled testing protocol, currently underway, will address these two issues.

Associated Content

Supporting Information

Zip folders containing each solution's report are included. Additional information about the test facility and supplementary results are in PDF form. The final reports on each solution's performance can be found on METEC's ADED Results website.

Author Information

Corresponding Author

Daniel Zimmerle - Energy Institute, Colorado State University, Fort Collins, Colorado 80524; **https://orcid.org/0000-0003-2832-048X**; Email address: **Dan.Zimmerle@colostate.edu**

Authors

Fancy Cheptonui - Department of Systems Engineering, Colorado State University, Fort Collins, Colorado, 80523; https://orcid.org/0009-0003-0001-8649

Ethan Emerson - Energy Institute, Colorado State University, Fort Collins, Colorado 80524; https://orcid.org/0000-0003-0350-3810

Chiemezie Ilonze - Energy Institute, Colorado State University, Fort Collins, Colorado 80524; https://orcid.org/0000-0003-4231-3278

Rachel Day - Energy Institute, Colorado State University, Fort Collins, Colorado 80524; https://orcid.org/0009-0001-9331-1603
Daniel Fleischman - Energy Institute, Colorado State University, Fort Collins, Colorado 80524
Ryan Brouwer - Energy Institute, Colorado State University, Fort Collins, Colorado 80524
Ezra Levin - Energy Institute, Colorado State University, Fort Collins, Colorado 80524; https://orcid.org/0000-0001-7390-4877

Author Declaration

After the testing was concluded and before manuscript submission, Ethan Emerson began working for Sonoma Technology, Inc., headquartered in Petaluma, California. Sonoma Technology, Inc. did not participate financially or otherwise in drafting this manuscript; therefore, the views and opinions expressed do not represent those of Sonoma Technology, Inc.

Acknowledgment

This work was funded by the Department of Energy (DOE): DE-FE0031873, which supported the test protocol development and subsidized the cost of testing for participating solutions at METEC. Industry partners and associations provided matching funds for the DOE contract. The authors acknowledge that the solution vendors paid to participate in the study, and we also recognize their efforts and commitment to the test program. The authors acknowledge the protocol development committee's contributions to the test protocol's development. Finally, the authors wish to thank Ryan Buenger and Wendy Hartzell for their assistance.

References

[1] EIA, "U.S. natural gas production grew by 4% in 2023, similar to 2022 - U.S. Energy Information Administration (EIA)." Accessed: Apr. 24, 2024. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=61646

[2] "Should it be called 'natural gas' or 'methane'?," Yale Program on Climate Change Communication. Accessed: Nov. 14, 2024. [Online]. Available: https://climatecommunication.yale.edu/publications/should-it-be-called-natural-gas-or-methane/

[3] O. US EPA, "Overview of Greenhouse Gases." Accessed: Jul. 21, 2024. [Online]. Available: https://www.epa.gov/ghgemissions/overview-greenhouse-gases

[4] O. US EPA, "Greenhouse Gases." Accessed: May 06, 2024. [Online]. Available: https://www.epa.gov/report-environment/greenhouse-gases

[5] O. US EPA, "Understanding Global Warming Potentials." Accessed: May 06, 2024. [Online]. Available: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

[6] IPCC, *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st ed. Cambridge University Press, 2021. doi: 10.1017/9781009157896.

[7] "Methane | Vital Signs," Climate Change: Vital Signs of the Planet. Accessed: Nov. 14, 2024. [Online]. Available: https://climate.nasa.gov/vital-signs/methane?intent=121

[8] I. E. A. IEA, "Global Methane Tracker 2024 – Analysis," IEA. Accessed: Jul. 21, 2024. [Online]. Available: https://www.iea.org/reports/global-methane-tracker-2024

[9] O. US EPA, "Biden-Harris Administration Announces Final Rule to Cut Methane Emissions, Strengthen and Update Greenhouse Gas Emissions Reporting for the Oil and Gas Sector." Accessed: May 06, 2024. [Online]. Available: https://www.epa.gov/newsreleases/biden-harris-administration-announces-final-rule-cut-methane-emissions-strengthen-and

[10] "5-CCR-1001-9_eff-021424.pdf," Google Docs. Accessed: Jul. 21, 2024. [Online]. Available: https://drive.google.com/file/d/1P6pRmNYx5KwEK6qDReYFL11-K-URI33J/view?usp=sharing&usp=embed_facebook

[11] D. Zimmerle, S. Dileep, and C. Quinn, "Unaddressed Uncertainties When Scaling Regional Aircraft Emission Surveys to Basin Emission Estimates," *Environ. Sci. Technol.*, vol. 58, no. 15, pp. 6575–6585, Apr. 2024, doi: 10.1021/acs.est.3c08972.

[12] "40 CFR Part 60 Subpart OOOOb -- Standards of Performance for Crude Oil and Natural Gas Facilities for Which Construction, Modification or Reconstruction Commenced After December 6, 2022." Accessed: Oct. 27, 2024. [Online]. Available: https://www.ecfr.gov/current/title-40/part-60/subpart-OOOOb

[13] A. R. Brandt *et al.*, "Methane Leaks from North American Natural Gas Systems," *Science*, vol. 343, no. 6172, pp. 733–735, Feb. 2014, doi: 10.1126/science.1247045.

[14] T. N. Lavoie *et al.*, "Spatiotemporal Variability of Methane Emissions at Oil and Natural Gas Operations in the Eagle Ford Basin," *Environ. Sci. Technol.*, vol. 51, no. 14, pp. 8001–8009, Jul. 2017, doi: 10.1021/acs.est.7b00814.

[15] T. L. Vaughn *et al.*, "Temporal variability largely explains top-down/bottom-up difference in methane emission estimates from a natural gas production region," *Proc. Natl. Acad. Sci.*, vol. 115, no. 46, pp. 11712–11717, Nov. 2018, doi: 10.1073/pnas.1805687115.

[16] L. Huang, S. Stokes, Q. Chen, and D. T. Allen, "Uncertainties in the Estimated Methane Emissions in Oil and Gas Production Regions Based on Aircraft Mass Balance Flights," *ACS Sustain. Chem. Eng.*, vol. 12, no. 29, pp. 11024–11032, Jul. 2024, doi: 10.1021/acssuschemeng.4c03945.

[17] W. Collins *et al.*, "Monitoring methane emissions from oil and gas operations ‡," *Opt. Express*, vol. 30, no. 14, p. 24326, Jul. 2022, doi: 10.1364/OE.464421.

[18] B. J. Schuit *et al.*, "Automated detection and monitoring of methane super-emitters using satellite data," *Atmospheric Chem. Phys.*, vol. 23, no. 16, pp. 9071–9098, Sep. 2023, doi: 10.5194/acp-23-9071-2023.
[19] D. Zavala-Araiza *et al.*, "Toward a Functional Definition of Methane Super-Emitters: Application to Natural Gas Production Sites," *Environ. Sci. Technol.*, vol. 49, no. 13, pp. 8167–8174, Jul. 2015, doi: 10.1021/acs.est.5b00133.
[20] O. US EPA, "Methane Emissions Reduction Program." Accessed: Nov. 14, 2024. [Online]. Available: https://www.epa.gov/inflation-reduction-act/methane-emissions-reduction-program
[21] CDPHE, "Oil and gas greenhouse gas intensity program | Department of Public Health & Environment." Accessed: May 06, 2024. [Online]. Available: https://cdphe.colorado.gov/oil-and-gas-greenhouse-gas-intensity-program
[22] E. Parliament, "Reducing methane emissions in the energy sector | Legislative Train Schedule," European Parliament. Accessed: Apr. 24, 2024. [Online]. Available: https://www.europarl.europa.eu/legislative-train/package-fit-for-55/file-reducing-methane-emissions-in-the-energy-sector
[23] C. Bell, T. Vaughn, and D. Zimmerle, "Evaluation of next generation emission measurement technologies under repeatable test protocols," *Elem. Sci. Anthr.*, vol. 8, p. 32, Jan. 2020, doi: 10.1525/elementa.426.
[24] C. Bell, C. Ilonze, A. Duggan, and D. Zimmerle, "Performance of Continuous Emission Monitoring Solutions under a Single-Blind Controlled Testing Protocol," *Environ. Sci. Technol.*, vol. 57, no. 14, pp. 5794–5805, Apr. 2023, doi: 10.1021/acs.est.2c09235.
[25] Z. Chen *et al.*, "Comparing Continuous Methane Monitoring Technologies for High-Volume Emissions: A Single-Blind Controlled Release Study," *ACS EST Air*, Jun. 2024, doi: 10.1021/acsestair.4c00015.
[26] C. Ilonze, E. Emerson, A. Duggan, and D. Zimmerle, "Assessing the Progress of the Performance of Continuous Monitoring Solutions under a Single-Blind Controlled Testing Protocol," *Environ. Sci. Technol.*, vol. 58, no. 25, pp. 10941–10955, Jun. 2024, doi: 10.1021/acs.est.3c08511.
[27] Y. Liu *et al.*, "Assessment of current methane emission quantification techniques for natural gas midstream applications," *Atmospheric Meas. Tech.*, vol. 17, no. 6, pp. 1633–1649, Mar. 2024, doi: 10.5194/amt-17-1633-2024.
[28] MONITOR| Arpa-e, "MONITOR | arpa-e.energy.gov." Accessed: Feb. 23, 2024. [Online]. Available: http://arpa-e.energy.gov/technologies/programs/monitor
[29] A. P. Ravikumar *et al.*, "Single-blind inter-comparison of methane detection technologies – results from the Stanford/EDF Mobile Monitoring Challenge," *Elem. Sci. Anthr.*, vol. 7, p. 37, Jan. 2019, doi: 10.1525/elementa.373.
[30] J. Titchener *et al.*, "Single photon Lidar gas imagers for practical and widespread continuous methane monitoring," *Appl. Energy*, vol. 306, p. 118086, Jan. 2022, doi: 10.1016/j.apenergy.2021.118086.
[31] S. P. Siebenaler, A. M. Janka, D. Lyon, J. P. Edlebeck, and A. E. Nowlan, "Methane Detectors Challenge: Low-Cost Continuous Emissions Monitoring," in *Volume 3: Operations, Monitoring and Maintenance; Materials and Joining*, Calgary, Alberta, Canada: American Society of Mechanical Engineers, Sep. 2016, p. V003T04A013. doi: 10.1115/IPC2016-64670.
[32] "A solution to the methane challenge – OGMP 2.0." Accessed: Nov. 14, 2024. [Online]. Available: https://ogmpartnership.com/a-solution-to-the-methane-challenge/
[33] C. Bell and D. Zimmerle, "METEC controlled test protocol: continuous monitoring emission detection and quantification," Jun. 01, 2022, *Mountain Scholar*. doi: 10.25675/10217/235364.

[34] R. E. Day, E. Emerson, C. Bell, and D. Zimmerle, “Point Sensor Networks Struggle to Detect and Quantify Short Controlled Releases at Oil and Gas Sites,” *Sensors*, vol. 24, no. 8, p. 2419, Apr. 2024, doi: 10.3390/s24082419.