Advancing Development of Emissions Detection: DE-FE0031873 Final Report

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EXECUTIVE SUMMARY

This document is the final report to the U.S. Department of Energy (DOE for contract DE-FE0031873) awarded to Colorado State University (CSU). CSU and partners at Harrisburg University of Science and Technology, University of Texas Arlington, and University of Texas at Austin organized several testing rounds to provide knowledge focused on advancing the detection capabilities of emissions monitoring devices. With this funding opportunity the research group began by establishing the Advancing the Development of Emission Detection (ADED) program, with the goal focused on enhancing the accuracy, reliability, and field applicability of methane detection technologies. This effort aimed to address the critical challenges of identifying and quantifying methane emissions while enabling industry stakeholders to meet regulatory compliance and environmental sustainability goals. The program engaged with industry, government, and technology stakeholders to promote adoption and consensus on testing techniques for methane detection solutions.

Methane, a potent greenhouse gas, contributes significantly to global warming, and the oil and natural gas (O&G) sector is a primary source of methane emissions. Regulatory measures such as leak detection and repair (LDAR) programs have been implemented to address emissions. However, traditional LDAR approaches, reliant on handheld and component-level measurements, are resource-intensive. To address these limitations and move with evolving regulations, advanced methane technologies are emerging. These solutions include ground-based sensors, mobile systems (e.g., drones, vehicles, and aircraft), and satellite-based platforms. They offer innovative capabilities for autonomous monitoring, larger spatial coverage, and emission quantification using methods such as tracer gas techniques and inverse modeling with Gaussian plume analysis.

The ADED program began by creating methane controlled release (CR) testing protocols for continuous monitoring (CM) and survey technologies that detect and monitor methane emissions at O&G facilities. The protocols were then implemented throughout testing of CM and survey devices at CSU's Methane Emissions Technology Evaluation Center (METEC) facility from 2021 through 2024. As apart of the protocol, solutions that tested under the ADED program installed their solutions at METEC, documented their system under test, and provided detection reports to the METEC team for analysis. The METEC team would provide the solutions with analyzed reports of their emissions and ground truth data of the releases conducted during their testing session. Under the ADED program, CMs were also tested at O&G facilities for a six week test run of challenge release (ChR) releases. The findings from the ADED program underscore the critical role of collaborative research and innovation in tackling methane emissions, offering a pathway for the oil and gas sector to achieve significant environmental and economic benefits.

Results from METEC testing saw improvement of performance and accuracy across all solutions over the extent of the ADED experiments. The results also showed a variance in CM solution performance between CRs and ChRs. That variance pushed the team to further analyze the differences between CR testing environments and field conditions. With the drive from regulations and that variance in field conditions, the ADED team began designing a new CR testing protocol and additions to the METEC testing facility.

The METEC team is furthering the progress made through the ADED program with awarded funding from DE-FE0032276. This funding pushes the development of METEC's addition with new equipment, allowing for an updated facility layout. METEC still facilitates for traditional facilities, with a legacy pad, while expanding an new design based on how O&G infrastructure has been changed over the last decade. Throughout the ADED program the team has also been working with international partners to ensure staying in the trend globally. International partners have been essential in moving the new protocol forward to implement into CR testing at the METEC facility in Spring 2025.

Results presented in this report are supported by several supplemental articles which are cited throughout. Results have also been disseminated in the following peer-reviewed publications:

1. Bell et al. [22] – Performance of Continuous Emission Monitoring Solutions under a Single-Blind Controlled Testing Protocol.
2. Ilonze et al. [36] – Assessing the Progress of the Performance of Continuous Monitoring Solutions Under Single-Blind Controlled Testing Protocol.
3. Day et al. [30] – Point Sensor Networks Struggle to Detect and Quantify Short Controlled Releases at Oil and Gas Sites.
4. Ilonze et al. [37] – Methane Quantification Performance of the Quantitative Optical Gas Imaging (QOGI) System Using Single-Blind Controlled Release Assessment.

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1 INTRODUCTION

1.1 Project Initiation

In 2019, the United States (US) Department of Energy (DOE) Office of Fossil Energy issued a funding opportunity announcement (FOA) titled “Advanced Natural Gas Infrastructure Technology Development” driven by the DOE’s Natural Gas Infrastructure Program, which "focused on developing next-generation pipeline materials; improving the reliability of gathering, compression, transmission and storage system components; creating sensor platforms capable of identifying and quantifying operational risks and methane emissions, advancing technologies for repairing pipeline damage without disruption of service, and developing cost-effective technologies for the capture and utilization of methane that would otherwise be flared". [53] CSU, with collaboration from Harrisburg University of Science and Technology, University of Texas Arlington, and University of Texas at Austin, was awarded funding under Area of Interest 3 to advance methane detection and measurement technology validation. To accomplish this, CSU created ADED program that would test methane leak detection and quantification solutions to advance their accuracy and effectiveness in methane mitigation efforts.

The ADED program at CSU was a key initiative within the Zimmerle Research Group, dedicated to advancing methodologies for measuring, detecting, quantifying, and mitigating methane emissions in the oil and gas sector. The ADED program focused on research that addresses critical challenges in atmospheric and environmental sciences, particularly the detection and quantification of methane and other greenhouse gases. The ADED team worked collaboratively with industry, government agencies, and research institutions to develop and refine technologies that improve emissions monitoring accuracy, assess mitigation strategies, and enhance the sustainability of energy production.

Central to ADED’s mission is the development of robust methodologies and protocols that can be deployed in real-world settings, providing insights into detecting emissions that support regulatory compliance and environmental stewardship. The program has leveraged advanced analytical techniques, sensor technologies, and mobile measurement systems, including field-based studies to validate these methods. This work not only informs policy and regulatory frameworks but also empowers stakeholders in the oil and gas industry to adopt best practices for emissions control. Through collaborative efforts, ADED has advanced commitment to environmental responsibility, helping to reduce the ecological footprint of energy operations, and contributing valuable knowledge to the global conversation on climate change mitigation.

This study focuses on these primary objectives, that were fulfilled through the ADED program:

- Develop and apply an independent testing protocol that can compare the performance of superior methane emission leak detection and emission quantification technologies to the current Federal environmental regulatory reporting requirements.

- Apply a transparent, scientifically rigorous, and defendable validation procedure/protocol for comparing the performance of the new technologies as they are tested in the field under field conditions using independent and unbiased data gathering, analysis and testing mechanisms.

- Develop and implement an outreach program that effectively engages with industry, government agencies and technology developer stakeholders and encourages the adoption of the advanced technologies being tested and builds consensus towards effective solutions to methane emission detection and quantification challenges.

- Utilize a field laboratory suitable for demonstrating and testing methane emissions detection and quantification technologies under a range of representative field conditions, representative of various natural gas transportation infrastructure unit operations that include but are not limited to: pipelines, valves, pneumatic controllers, compressors, tanks, etc.

1.2 Organization of This Report

This document is organized into three chapters:

- Overview and Background: provides an overview of methane emission detecting and quantification history.
- Methods: describes survey and CM protocols established with strategies used for implementing them into CR and ChR testing.
- Results: study findings from implementing survey and CM protocols during CR and ChR testing.

2 OVERVIEW AND BACKGROUND

Methane emissions are a significant contributor to global greenhouse gas concentrations and have drawn increasing attention due to methane's potent effect on climate change. [34] Methane is over 80 times more effective than carbon dioxide at trapping heat in the atmosphere over a 20-year period, making it a target for mitigation efforts aimed at reducing its concentration in the atmosphere. [38, 4, 15] The O&G industry, including processes related to O&G extraction, transportation, storage, and processing, is one of the leading producers of methane emissions. To address this issue, countries such as the US and Canada have implemented LDAR programs to detect and repair unsolicited equipment component leaks (fugitive emissions) with the goal of mitigating environmental impacts, ensuring regulatory compliance, and enhancing operational efficiency in the energy sector. [14, 28] Research over the last decade has shown a small number of facilities and emitters are often responsible for a disproportionately large amount of total emissions. [26, 56, 57, 19, 50, 29] The US Environmental Protection Agency (EPA) set the first emission regulations for O&G infrastructures in 2016 with the New Source Performance Standards (NSPS)s, creating a demand for accurate solutions to drive these mitigation regulations. The NSPSs include LDAR requirements as an effort to mitigate methane. In order to target these emitters and provide O&G operators with a device to assist with safety and regulations, technology companies have been developing various solution types, ranging from stationary continuous sensors to aerial survey satellites. The ADED project assisted in enhancing research capabilities with these solutions at the METEC and other O&G facilities to understand and verify their performance and accuracy.

2.1 Leak Detection and Repair (LDAR)

Regulations in the US require periodic ground-based LDAR using handheld optical gas imaging (OGI) cameras and portable volatile organic compound analyzers (US Environmental Protection Agency (EPA) Method 21). [13, 3]

Although these approaches can be precise (direct measurement), they are labor-intensive due to their small scope of application (component level) compared to the extensive spatial scale of O&G infrastructure. To be regulatory-compliant in the US and Canada, LDAR must be applied to millions of equipment components spread over large geographical areas with variable OGI assets, which has significant time, human labor, and cost implications for OGI operators. [33] In an attempt to combat this and address mitigation concern, the EPA has developed new standards that allow certified leak detection and quantification (LDAQ) solutions to be used in place of the required LDAR inspection methods. [7, 33]

Historically, OGI did not quantify detected leaks – emissions quantification was performed as an additional measurement step using other tools. For example, in many recent studies that quantified emissions from component leaks, emission quantification was done using a hi-flow sampler (HFS) for sources detected by OGI. [41, 18, 17, 31, 43, 47, 42] The HFS uses attachments to capture and direct emissions into the instrument to measure emission rates. Thus, successful measurement relies on safe access to the emitting sources. Sources that are unsafe, inaccessible, or too large for the attachments to cover cannot be quantified by HFS. The quantitative optical gas imaging (QOGI) is an add-on system to an OGI camera (a tablet) that analyzes plume pixels from videos of hydrocarbon emissions captured by the OGI camera and quantifies emissions using proprietary algorithms. The QOGI system (OGI camera + QOGI tablet) is an approved method by the British Columbia Oil & Gas Commission (BCOGC) for comprehensive LDAR surveys. Unlike the HFS method, the QOGI system does not require personnel to have physical contact with emission sources to complete measurements. Several manufacturers now offer QOGI systems including handheld and mounted solutions. The system tested in this study is the Teledyne FLIR™ QOGI system, which pairs a QL320™ quantification tablet with a handheld GF320™ OGI camera.

2.2 Leak Detection and Quantification (LDAQ)

LDAR programs do not require quantification measurements, as the main function has been to supply operators with the required information to manually detect and then repair leaks at their facilities. In order to save on human labor and cost implications, detection solution (technology) companies have been creating advanced solutions that are marketed with the ability to monitor methane emissions autonomously with improved accuracy. [55, 49, 40] Some of these solutions have the ability to monitor continuously, and some advanced methane detection solutions can estimate an emission flow rate, or quantification, of a facility or equipment group. Methane detection solutions that can quantify leaks can be used for LDAQ with the recent changes under the EPA's final rule - New Source Performance Standards (NSPS) subparts OOOO/OOOOa/OOOOb and Emission Guidelines (EG) subpart OOOOc. [7] The final rule has stipulated work practices for the use of advanced methane detection technologies as an alternative to existing regulatory-approved LDAR approaches at well sites, centralized production facilities, and compressor stations, if the technologies meet certain performance standards and are regulatory-approved. LDAQ solutions are either autonomous, fixed ground-based sensors (continuous monitors) or mobile technologies (handheld, drone-based, automobile-based, and aircraft-based) that require human supervision to operate (survey solutions). Some survey solutions (e.g., aircraft-based technologies) can screen larger spatial areas of O&G facilities to inform prioritized, focused, and faster ground-based inspections of identified emissions compared to traditional LDAR methods (e.g., OGI camera surveys). Quantifying methane emissions from detected sources requires accurately measuring the concentration of methane and translating it into an emission rate. Quantification techniques are often divided into two categories:

Tracer Gas Techniques: This approach involves releasing a known quantity of tracer gas and measuring the methane-to-tracer ratio downwind of the emission source. The ratio, combined with atmospheric modeling, enables estimation of the methane emission rate. This method is highly accurate but requires field deployment of the tracer gas, making it more labor-intensive.

Inverse Modeling and Gaussian Plume Models: In this approach, data from sensors are input into atmospheric models to estimate the emission rate. Inverse modeling, often combined with Gaussian plume models, is used to account for the effects of wind speed, direction, and atmospheric conditions on methane dispersion. This method is widely used but depends on the accuracy of meteorological data and model assumptions.

Mitigating methane emissions is crucial for both environmental and economic reasons. From an environmental standpoint, reducing methane emissions can significantly help slow the rate of global warming. Economically, methane emissions represent a loss of natural gas, which is a valuable energy resource. For industry stakeholders, reducing emissions is essential for meeting regulatory requirements, and for addressing increasing pressures from investors and the public regarding sustainable operations. Methane detection technologies range from ground-based sensors to airborne and satellite-based monitoring systems, each with either survey or continuous monitoring applications.

2.3 Survey Solution Detection

Previous controlled testing evaluations of survey solutions have used study-specific protocols with limited test complexity[52, 48, 25, 51, 39, 45] or a standardized protocol with narrow scope of application.[25] These studies assessed the performance of aircraft-based,[52, 48, 25, 51, 39] drone-based,[48, 45] automobile-based,[48, 25] and handheld solutions.[25] Studies by Ravikumar et al.[48] and Bell et al.[25] during the ARPA-E MONITOR[2] and the Stanford - Environment Defense Fund Mobile Monitoring Challenge programs, respectively, are notable for testing and comparing the performance of multiple, different survey solutions. While Ravikumar et al. used a series of non-standardized protocols with varying complexity and scope during testing, Bell et al. applied a standardized protocol (an early version of the protocol used in this paper) that was not representative of expected field application of survey solutions. The protocol used by Bell et al. [25] limited the emissions scenarios and the number of controlled gas releases conducted during the study, influencing tested solutions' survey methodology and pace. In addition, a recent study by Liu et al. evaluated the quantification performance of 10 solutions composed of mobile (drone, automobile, and aircraft), ground-based (fixed camera system), and handheld (OGI camera) technologies at a non-operational compressor station in Spain. While the study tested a wide range of controlled release rates (0.0150.0 kg CH_4/h) and emission point heights (128 m), the study was partially blind (i.e., only release rate was unknown to participants) and implemented study-specific test protocol (i.e., timing of controlled releases was constrained to $\approx$2 hours, etc.) with a small number of experiments (17).[44] These studies therefore suggest the need for consensus, standardized, and field-representative testing protocols for assessing the performance of survey solutions

2.4 Continuous Monitoring Solution Detection

Methane detection and quantification face several challenges, including variability in emission rates, influence of environmental conditions, and limitations in sensor accuracy. For instance, methane emissions from natural gas operations can be intermittent and highly variable, with factors like equipment malfunctions or changes in operation causing fluctuations. Additionally, wind speed, atmospheric stability, and temperature can affect the accuracy of quantification models.

To address these challenges, innovations in methane monitoring are emerging, including the integration of artificial intelligence to identify emission patterns, advancements in sensor miniaturization for broader deployment, and improved algorithms for more accurate quantification in complex environments. The development of autonomous monitoring networks and advancements in satellite resolution and sensitivity are also contributing to more effective monitoring strategies.

Ground-based detection methods involve placing sensors at specific locations on-site to monitor methane concentrations over time. These sensors, such as tunable diode lasers, infrared sensors, and catalytic bead sensors, can provide real-time data ideal for continuous monitoring at fixed locations, such as compressor stations or well pads. However, ground-based systems have limited spatial coverage, which makes them less effective for large or remote facilities. CMs provide a large advantage if accurate and cost effective to O&G operators

3 METHODS

The survey and continuous monitoring protocols were created after collaboration with over 60 stakeholders (operators, solution developers, regulators, NGOs, etc.) and community partners of interest, allowing a consistent procedure for testing throughout the ADED project. The protocols were established and implemented at METEC as well as several other O&G field locations across the US, including the Upper Green River, Denver-Julesberg, Permian, Marcellus, Utica, and LA Basins.[20, 21] The survey solutions were tested at METEC, while continuous monitors were tested at both METEC and other basins. For the field deployments to other basins, O&G operators provided access to their facilities and solution dashboards for data analysis by the ADED teams.

METEC is an open-air test and research facility (GPS coordinates: 40.59559, -105.13984) located on the CSU foothills campus in Fort Collins, Colorado, that simulates fugitive and vented emissions behavior associated with typical North American production facilities using more than 200 representative emission points (e.g., flanges, connectors, etc.). METEC is composed of decommissioned surface O&G equipment (e.g., wellheads, separators, condensate tanks, flare stacks, and a compressor and dehydrator unit) embedded with strategically hidden emission points, which are arranged into five well pads and a small compression station. Each equipment unit and group is identified with unique tags, respectively. The test center defines an equipment group as a cluster of adjacent, similar equipment units in a well pad. CR are actuated electronically to transport gas from onsite compressed natural gas (CNG) storage tanks through buried, small-diameter steel tubings to the emission points. A matrix of thermal mass flow meters (OMEGA FMA-17xx series) and manual pressure regulators downstream of the CNG storage tanks control gas flow to emission points, and an onsite gas chromatography device is used to determine the composition of gases released at the site at all times. METEC also has a 24-foot stationary 3-D sonic anemometer that records meteorological data (e.g., relative humidity, wind speed, etc.) at a frequency of 1 Hz. See Zimmerle et al. [59], Bell et al. [22], and Ilonze et al. [35] for more details about the test center and the gas transport system.

3.1 Survey Protocol

The survey emission detection and quantification protocol provides a structured approach to assess the performance of survey solutions at facilities with varied environmental conditions and emission rates. This protocol includes many designs and configurations, but generally uses a handheld or otherwise mobile emission detection solution deployed periodically at a facility to detect and locate emission sources to the equipment unit-level or component-level.[21] Survey protocol test methods are broken into three main activities:

- *Documentation of the system under test:* Solutions were required to document descriptions of the system configuration (e.g., model number of each hardware, revision number of software, etc.), components (e.g., sensor, deployment platform, etc.), methodology applied (e.g., number of passes, flight speed and height, etc.), and the personnel needed to perform emissions surveys at O&G facilities.[21].

- *Emission surveys:* The survey protocol divided testing into *experiments* conducted during the day (i.e., typically between 8 a.m. and 5 p.m. US mountain time) for 3 to 5 days. An experiment consisted of multiple, simultaneous controlled releases of CNG, each emitting at a steady emission rate for minutes to hours with longer-duration experiments designed to investigate performance variation due to changing meteorological conditions. Testing was single-blind, as the solutions were unaware of the timing, location, and release rate of controlled releases. A METEC facility operator would initiate releases on a disclosed group of equipment, and the survey solution operator would provide detection and localization estimates. All controlled releases were CNG, with a mean gas composition by volume of 76.0%–88.0% methane, 11.6%–20.1% ethane, 1.4%–3.6% propane, and trace amounts of other gases. The release rates of gases tested were of the order of magnitude of component-level leak sizes measured at natural gas production sites in the US (excluding liquid unloading or major unexpected emission events) [24, 16, 46], which the type of solutions tested would typically encounter during actual field deployments. The emission rates tested overall ranged from 3.0 g CH_4/h to 2590.0 g CH_4/h over a windspeed and temperature range of 0.7 m/s to 13.4 m/s and 2.6°C to 35.3°C respectively.

- *Detection reporting:* The test protocol stipulates a reporting template for solutions to record experiment and data (i.e., timing, emission rate, location(s), etc.) of detected emissions. Solutions were encouraged to submit recorded data to the test center at the end of each test day, including atleast: *ExperimentID*, *FacilityID*, *StartDateTime*, *EndDateTime*, *SurveyTime*, *DetectionReportID*, *EmissionSourceID*, *EquipmentUnit* - The tag of the equipment unit (as provided by the test center) on which an emitter was localized, and type of *Gas*.

For data to be considered valid, solutions were required to submit their survey and detection reports within one week of test completion. This time limit reflects common field practice [27, 54]. The study team collated and quality controlled all data, including release rates and meteorological data collected by the test center, and all data reported by solutions to perform *detection classification*. *detection classification* divides all detections attributed to METEC as either true positive (TP) or false positive (FP), and all CRs occurring as either TP or false negative (FN), and result in the three possible scenarios illustrated in Table 1. If the number of CRs, N_{CR}, is greater than the number of reported detections, N_{RD}, then each reported detection will be classified as TP and the remaining CRs will be classified as FN.

Table 1: Explanation of relation between detection classifications.

Relationship between $N_{\textbf{CR}}\&N_{\textbf{RD}}$	**Number of True Positives,** N_{TP}	**Number of False Positives,** N_{FP}	**Number of False Negatives,** N_{FN}
$N_{\text{CR}} > N_{\text{RD}}$	N_{RD}	0	$N_{\text{CR}} - N_{\text{RD}}$
$N_{\text{CR}} = N_{\text{RD}}$	N_{RD}	0	0
$N_{\text{CR}} < N_{\text{RD}}$	N_{CR}	$N_{\text{RD}} - N_{\text{CR}}$	0

The test center kept an operator log and a maintenance record during the testing period to facilitate the *detection classification* process and the exclusion of data (i.e., controlled releases and detection reports) invalidated by the requirements of the test protocol. [21] The maintenance record documented the list of controlled releases or periods to be excluded from the result analysis, either because the controlled release was non-compliant with the testing protocol or due to an unplanned release (i.e., venting an emission point gas supply line). Key performance metrics for the survey solution analysis are summarized below:

- **Probability of Detection (POD):** This represents the probability of detecting an emission over a set of environmental and measurement conditions (e.g., wind speed, emission rate, release duration, etc.). This is evaluated as the fraction of the count of TP detections to the sum of the counts of TP and FN detections over a set of conditions as shown in equation 1.

$$\text{POD}\big|_{\text{x}} = \frac{N_{\text{TP}}}{N_{\text{TP}} + N_{\text{FN}}}\bigg|_{\text{x}} \tag{1}$$

  Where x is the set of measurement conditions at which the probability-of-detection (POD) is assessed.

- **False Positive Fraction (FPF):** This is the fraction of the count of FP detections to the sum of the counts of TP and FP detections as shown in equation 2.

$$\text{FPF} = \frac{N_{\text{FP}}}{N_{\text{FP}} + N_{\text{TP}}} \tag{2}$$

  To then evaluate solutions' POD curves, an exponential function was used to produce curve-fitting models using the resulting data of the detection classification scheme. The exponential function (equation 3) was selected for two reasons. First, in several cases, the binary logistic regression function predicted non-zero POD at zero controlled release rates, which is unrealistic (see Bell et al.). Second, there were insufficient experimental points to bin data as required for a power curve fit as used in other studies (e.g. Ilonze et al., Zimmerle et al.). For the solutions tested, the range of valid classified data points for each solution (TP and FN) was 70 to 224, with 11 of 15 rounds of controlled testing producing less than 120 data points. The exponential link function selected was:

$$\text{pod} = 1 - \exp(-a \cdot x^b)\big|_{\text{a,b are curve fitting parameters}} \tag{3}$$

- **False Negative Fraction (FNF):** This is the fraction of the count of FN detections to the sum of the counts of TP and FN detections as shown in equation 4.

$$\text{FNF} = \frac{N_{\text{FN}}}{N_{\text{FN}} + N_{\text{TP}}} \tag{4}$$

- **Survey Time:** This is the time taken to complete a survey and is evaluated as the difference between the reported survey start- and end-date times.

- **Localization Precision (Equipment Unit):** This is the fraction of TP detections at the equipment unit, equipment group, and facility levels, respectively.

- **Localization Accuracy (Equipment Unit):** This is the fraction of detection reports at each localization precision level (equipment unit) or better as shown in equations 5, 6, and 7.

$$\text{Correct unit } (\text{LA}_{\text{unit}}) = \frac{N_{\text{TP}_{\text{unit}}}}{N_{\text{TP}} + N_{\text{FP}}} \tag{5}$$

$$\text{Correct group } (\text{LA}_{\text{group}}) = \frac{N_{\text{TP}_{\text{group}}} + N_{\text{TP}_{\text{unit}}}}{N_{\text{TP}} + N_{\text{FP}}} \tag{6}$$

$$\text{Correct facility } (\text{LA}_{\text{facility}}) = \frac{N_{\text{TP}}}{N_{\text{TP}} + N_{\text{FP}}} \tag{7}$$

The secondary metrics primarily focus on accuracy of quantification for the few solutions that provided that function. Following the testing, METEC provided the solutions with a report including an experimental summary, results from the performance metrics, copies of the documentation of test protocol and system under test.

3.1.1 Survey Solution Controlled Release Testing

The survey protocol was tested at METEC during different periods between May 3rd, 2021 and November 5th, 2023 with thirteen survey solutions, divided into the following groups:

- **Mobile:** Survey solutions that are automobile-based and unmanned aerial vehicle (UAV)/drone-based.
- **Handheld OGI:** Traditional handheld OGI camera solutions.
- **Advanced handheld OGI:** Includes other handheld solutions that do not detect emissions using OGI technology alone (if at all). These include sensing techniques like acoustic sensing, infrared absorption spectroscopy, tunable diode laser absorption spectroscopy (TDLAS) technology, etc.

Four solutions per group participated in these rounds of survey protocol testing at METEC, summing to a total of 12 solutions. Three of these solutions participated in survey testing twice over the years. Table 2 summarizes the solutions that participated in the study with their deployment characteristics and selected test conditions. Not all solutions tested at the same time, and some that tested at the same time may or may not have been testing at the same group of equipment at METEC. While all solutions tested detection and source localization capabilities, only solutions I and J provided quantified emissions estimates.

Table 2: Characteristics of participating solutions and testing conditions.

Solution			Test Conditions		Test Year		
ID	**Platform**	**Category**	**Release Rate (g CH_4/h)**	**Wind speed (m/s)**	**2021**	**2022**	**2023**
Solutions that participated in the first round of testing.							
A†	Vehicle	Mobile	214 [26, 895]	5.3 [1.1, 13.4]	✓	X	X
D	Drone	Mobile	73 [3, 297]	3.0 [0.9, 5.7]	✓	X	X
F	Drone	Mobile	471 [30, 2027]	2.5 [1.2, 4.1]	X	X	✓
I	Drone	Mobile	175 [22, 586]	4.5 [1.1, 9.3]	✓	X	X
B	Handheld	Handheld OGI	76 [4, 297]	3.3 [1.3, 5.7]	✓	X	X
E	Handheld	Handheld OGI	198 [4, 808]	3.0 [0.8, 4.6]	✓	X	X
G	Handheld	Handheld OGI	500 [22, 2110]	3.6 [0.9, 9.0]	X	X	✓
L	Handheld	Handheld OGI	553 [23, 2586]	3.6 [0.9, 8.7]	X	X	✓
C	Handheld	Advanced Handheld	198 [4, 808]	3.0 [1.1, 4.6]	✓	X	X
H‡	Handheld	Advanced Handheld	471 [3, 2106]	3.4 [0.9, 8.8]	X	X	✓
J	Handheld	Advanced Handheld	464 [23, 1651]	2.9 [0.7, 8.0]	X	X	✓
K	Handheld	Advanced Handheld	194 [22, 640]	5.2 [1.2, 12.8]	✓	X	X
Solutions that participated in the second round of testing.							
A†	Vehicle	Mobile	164 [11, 982]	4.3 [0.8, 13.3]	X	✓	X
K	Handheld	Advanced Handheld	164 [11, 982]	4.3 [0.8, 13.3]	X	✓	X
H‡	Handheld	Advanced Handheld	355 [4, 1934]	2.6 [0.9, 3.6]	X	X	✓

† The solution tested its quantification capability in 2022.
‡ The solution was tested twice in 2023.

Survey Study Limitations: During these testing rounds, METEC represented near-ideal operational field conditions with little ongoing operational activities that would establish baseline emissions – commonly defined as routine, planned emissions, including combustion slip, gas pneumatics, periodic venting, and similar sources. Additionally, the emissions scenarios simulated for this study did not include large emission rate events, often responsible for a highly skewed share of total emission rates at O&G facilities[26, 56, 57, 19, 50]. The objective of the study was to characterize the POD of the solution, and since all solutions tested here have a high probability of detecting emitters in excess of 3 kg/h, testing at higher rates provides little additional information. Note this testing was conducted prior to the EPA publishing the 0000(b) [32] regulation changes, therefore testing did not target the rates specified under 0000(b).

3.2 Survey QOGI Controlled Release Testing

QOGI testing occurred at METEC from June 20th to June 24th, 2022, performing a systematic quantification assessment of the FLIR QL320 QOGI solution. The QOGI solution consisted of a FLIR GF320 OGI camera and a FLIR QL320 QOGI tablet (henceforth "FLIR tablet"). The Providence Photonics QL320 QOGI tablet (henceforth "legacy tablet"), an older version of the FLIR tablet, was used as a backup whenever the FLIR tablet ran out of battery. Measurement data were collected by a field crew of 2 researchers who operated the equipment and collected the data. The field crew followed the user manual provided by FLIR when deploying the tablets. [9, 10, 58] Similar to the survey testing, this experiment was performed single-blind: the METEC facility operator had a list of components and controlled release rates to test which was unknown to the field crew performing the measurements. The METEC facility operator selected an emission source, initiated a controlled release, waited until the release rate was steady, then informed the field crew of the emissions location. The release rate was not communicated to the field crew. An experiment was defined as a controlled release at a given rate flowing through a specified emission point. The field crew identified an unobstructed view of the leak location and gas plume, considering wind direction and the location of the emitting equipment. Parameter data required for quantification were inputted into the tablet which included wind speed (calm (0-1mph), normal (2-10mph), or high (>10mph)), distance to emitting source, leak type (point or diffuse), and ambient temperature. For each measurement, the field crew documented the background of the plume measured (sky, equipment, or ground). In some instances, 3 successful measurements could not be completed from a selected location due to rapidly changing meteorological conditions. Measurement duration varied substantially as in some cases highly variable meteorological conditions elongated measurement duration.

Quantification error was assessed for each pair with 95% confidence interval (CI) on the mean error evaluated as the 2.5 and 97.5 percentiles of the bootstrapped mean errors. Boxplots were primarily used to investigate the impact of the factors (i.e. windspeed, plume background, etc.) by categorizing elements of each factor into groups (e.g. windspeed – calm, normal, and high windspeeds). Since during the measurements, the study team had limited control of the number of sample data points per group, we set a minimum threshold of 30 data points (based on the central limit theorem) as likely sufficient for statistically significant analysis. Additionally, the Mann-Whitney U and Kolmogorov-Smirnov tests were used to investigate if the error distribution of the groups for each factor investigated were statistically different at a significance level (p) of 0.05.

QOGI Study Limitations: While METEC mimics real O&G upstream and midstream facilities, not all field conditions were replicated for this study. At METEC, no equipment is heated (which can improve or complicate ΔT) or pressurized (which can cool the plume due to Joule-Thompson cooling at the point of release), which is common for separators (liquid separation equipment) on production equipment. Also, the facility is not characterized by elevated background emissions concentration, equipment vibrations, and noise levels typical in real O&G facilities. All METEC controlled releases were at approximately atmospheric pressure at each emission point exit unlike in field conditions where gases are likely to escape at higher pressure hence improving ΔT due to the Joule-Thompson effect. OGI cameras are sensitive to hydrocarbons other than methane that have infrared absorption bands within the spectral range of the camera, particularly ethane and propane. The CNG utilized in this study had a mean gas composition by volume of 84.8%

of methane, 8.5% of ethane, 0.7% of propane, and a trace amount of heavier hydrocarbons and other gases. In field conditions, gas composition varies. Upstream (production) emissions contain higher levels of ethane and propane than tested here, increasing camera response, while midstream and downstream emissions may lower levels of ethane and propane than tested here, lowering camera response. Quantification performance during winter and other associated meteorological conditions were not evaluated. Controlled release rates in this study were designed to explore the range of emission rates seen on O&G facilities that would be candidates for QOGI quantification. However, these rates do not represent the distribution of emission rates at operating O&G facilities. To account for this difference, our analysis includes a Monte Carlo simulation that applies results from this study to observed component level measurements from a field study. Finally, prior work on QOGI surveys indicated a strong correlation between the experience of the QOGI operator and the probability of detecting emissions. Similar dependence may exist in quantification and should be evaluated when broader usage of QOGI would make it possible to statistically sample a range of experience levels in a controlled experiment.

3.3 Continuous Monitoring Protocol

The CM emission detection and quantification protocol provides a structured approach to assess the performance of CM solutions at facilities with varied environmental conditions and emission rates. This protocol includes many CM designs and configurations, but generally consists of (1) one or more gas sensor(s) of any type including auxiliary components such as retroreflectors installed at or near a Facility to monitor emissions, (2) auxiliary sensors (e.g. a meteorological station) installed at or near the facility, (3) analytics which interpret sensor data (e.g. gas concentration readings) to make emission and/or leak detections, localization estimates and/or quantification estimates accounting for variations in background concentration levels or potential interference from nearby, off-facility sources, and (4) a data management system to report detection, localization, and quantification data. Testing under this protocol was conducted for multiple weeks, 24 hours per day, 5-7 days per week. The CM protocol test methods are broken into four main activities:

- *Installation:* With the approval of the METEC facility operators, solutions (performers) were permitted to set up their devices anywhere within the facility's bounds, as long as they were not inhibiting vehicle or foot traffic and were following the facility's safety requirements. Location of devices as well as component details were required to be fully documented following the protocol's test method installation parameters.

- *Maintenance:* Performers were expected to complete any maintenance required to keep the installed solution operational for the duration of the test period.

- *Operation:* Performer staff were not present at the facility during the operation period except to complete required maintenance. The test center defines the facility to be monitored using a bounding box of coordinates or physical infrastructure, such as a fenceline, or an implied boundary such as a property line, right of way, or easement. The METEC facility operator tried to the best of their ability to supply enough releases with combinations of CR emission rates and environmental conditions of interest to evaluate a PODy curve.

- *Reporting:* The test protocol stipulates a reporting template for solutions to record experiment and data (i.e., timing, emission rate, location(s), etc.) of detected emissions. Performers submitted data to the METEC test center to complete the classification of detection and evaluate all primary metrics and optional secondary metrics. Performers provided the METEC team with detection and offline reports. Offline reports allow performers to indicate when a CM is not operating during the testing period. These reports will be used (1) to compute the fraction of time the system was operational relative to the total testing time, and (2) to limit the metrics to include only results from experiments performed while the system is online. Solutions submitted data to the METEC study team, including atleast: *DetectionReportID*, *DetectionReportDateTime*, *EmissionStartDateTime*, *EmissionSourceID*, and *EquipmentUnit* - The tag of the equipment unit (as provided by the test center) on which an emitter was localized. Similar to the survey protocol, quantification data is optional.

The CM protocol follows the same *detection classification* as the survey protocol, defining N_{CR}, N_{RD}, N_{TP}, N_{FP}, N_{FN}. The same primary and secondary metrics from the CM protocol were used for analysis and after testing METEC provided the solutions with a report including an experimental summary, results from the performance metrics, copies of the documentation of test protocol and system under test.

3.3.1 Continuous Monitoring Solution Controlled Release Testing

After the protocols were established the ADED team implemented the CM protocol with CM solutions at METEC. 20 total CM solutions tested under the protocol, including point sensor networks and scanning/imaging solutions, shown in Table 3. Some solutions tested multiple CM solutions types and some tested in multiple ADED rounds.

Table 3: CM solutions that participated during the ADED project protocol testing.

Baker-Hughes	Honeywell	Pergam Technologies	Sensirion
Blue-Rock	Kuva Systems	Project Canary	Sensit
ChampionX	Luxmuz Technologies	QLM Technologies	Shepherd-Safety
CleanConnect.ai	Molex	Qube Technologies	SLB
Earthview.io	Oiler-Equation	Sensia Solutions	Xplorobot

Three rounds of CM testing, one each year, were performed from 2022 through 2024. The ADED study team designed and scheduled experiments daily during each study period. Controlled release rates and experiment durations were selected considering facility constraints and the expected detection limits communicated by vendors. The study team reviewed performance of the solutions as testing progressed to inform selection of release rates and durations for subsequent experiments to ‘fill in’ regions where data had a low sample count. For example, if the study team identified that solutions had not yet reached 90% detection rates then experiments with higher emission rates were integrated into the test schedule. All rounds of testing followed the protocol, with solution performers installing their solutions and supplying detection reports while autonomously operations their solutions. The METEC study team then classified the detections and followed analysis listed in the protocols.

CM Study Limitations: Several operational constraints exist at the test facility. METEC was initially developed to evaluate leak detection systems in the ARPA-E MONITOR program[1], targeting relatively low emission rates observed from fugitive component leaks in field studies. As noted above, emission rates were varied to sweep, as best possible, across the full range of every solution's POD curve. In general, this required more CNG than the installed capacity at METEC. Therefore, METEC made modifications to increase the amount of CNG capacity to run larger releases in the later testing rounds.

Additionally, since many CM solutions rely on variability in the emission transport to localize and quantify emissions, each experiment should be of sufficient duration to allow the solutions ample monitoring time. A large number of experiments were also required to evaluate the repeatability of detection and quantification. These considerations together necessitated a test program lasting several months. In this study the duration of each experiment was constrained to a maximum of approximately 8 hours, which may impact the performance of some solutions which rely on data collected over long time frames (e.g. days) to detect, localize and quantify emission sources. However, the practicality of this approach at operational facilities is questionable since many emission sources are intermittent or unsteady.

One advantage of the long duration test program was the inherent variability in environmental conditions during the program. Testing was conducted in all weather conditions encountered, and where possible, the influence of wind speed and other meteorological parameters was investigated in the analysis. However, in some cases during the winter season, experiments were either canceled due to limited access to the test facility, or test results were discarded during quality control due to operation at temperatures below the flow meter specifications.

3.3.2 Continuous Monitoring Solution Challenge Release Testing

Meeting the objective to utilize a field laboratory, the ADED team constructed a mobile ChR rig that would use natural gas from a tie-in point on the infrastructure of actual O&G facilities. A ChR refers to a CR that is performed on top of a facilities normal operational emissions, or baseline (BL). The ChRs during the field campaign served to simulate an unintentional emission with a known release rate added to the BL operational emissions from the site. The release rate was controlled by adjusting the flow path on the ChR mobile rig to different sized precision orifice flow restrictors, and could be fine tuned by adjusting an upstream regulator. ChRs were metered by a Fox FT2 mass flow meter calibrated for the range of controlled release experiments. ChRs took place at seven O&G production sites and 4 gathering stations in the Upper Green River (Wyoming), Marcellus (Pennsylvania), Utica (Ohio), and Permian Basins (Texas) in 2022 and 2023. Operator personnel were on-site with the field teams continually for all of the ChRs. The following solutions, all point sensor networks (PSNs), deployed at least once during the field campaign, in alphabetical order: Baker-Hughes, Project Canary, Earthview, Qube, Sensirion, and ChampionX's SOOFIE. Each operator selected PSN solutions to deploy at their sites using their discretion for the testing period. Therefore, not all PSN solutions were deployed at each site.

ChR rates were originally chosen based on typical fugitive component emission rates (0-2 kg/h) and discussions with the operator; However, after no detections were clearly identifiable in data from installed PSN systems during initial releases, the planned release rates were modified to include higher emission rates in an attempt to improve the learnings from the study. (Figure 1).

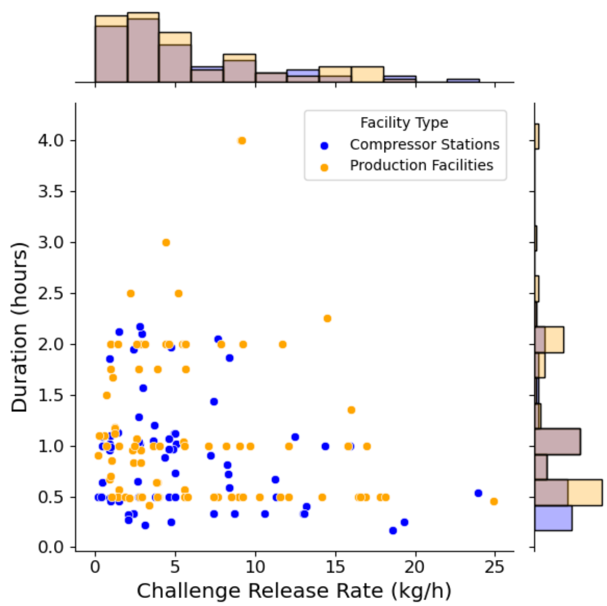

Figure 1: Duration versus release rate of 90 ChRs conducted at production sites and 75 ChRs conducted at compressor stations. The field campaign consisted of ChR rates ranging from 0.2 to 24.1 kg/h that lasted for 10 to 240 minutes from representative fugitive leak or vented locations using the transportable controlled release rig

.

During the field campaign, the solutions *did not* provide detection reports using the same email based reporting method as required during METEC testing. [20] Instead, the study team was granted access to the solution's "dashboard", a graphical user interface provided to operators to receive alerts, interact with data, investigate or acknowledge detections, and export raw or processed emission data from the solutions. Exportable data varied between solutions, but most provided time series of methane or total hydrocarbon gas mixing ratio from each point sensor. Some also provided site-level emission rate estimates.

Independent measurement of all operational emission sources at a given site was not conducted due to challenges coordinating a time-coincident independent measurement, limitations of direct measurement techniques, and other complicating factors. Instead, the field team used data from the continuous monitors when the field team was not running ChRs (weeks preceding and after); these data are identified as non-release (NR) data. NR data was utilized to compare site-level emission rate estimates with/without active ChRs. The mean of NR site-level emission rate estimates from each solution was used to represent what the solution would report in the absence of a ChR at a given site, hereafter referred to as 'BL'. The amount of available NR data varied for site-solution pairs, and ranged from one to six weeks. To avoid subjective bias, this was completed by defining thresholds for what change in emissions constituted a detection. The analysis used *detection classification* thresholds that could be applied to exportable data from the solutions' dashboards, specifically:

1. Mixing ratio data taken from the solutions' sensors
2. Site-level methane emission rate estimates, hereafter 'emission estimates'.

For the mixing ratio analysis, we first identify downwind sensors as any sensor which is within ± 45°of directly downwind from the ChR location. All other sensors are classified as 'not downwind.' A TP_X and FN_X classification based on sensor response, $X_{i,j}$, is defined as any reported mixing ratio by a downwind sensor where:

$$TP_X \leftarrow X_{i,j} \geq \bar{X}_{\text{NR},i,j} + 2\sigma_{X_{\text{NR},i,j}} \tag{8}$$

$$FN_X \leftarrow X_{i,j} < \bar{X}_{\text{NR},i,j} + 2\sigma_{X_{\text{NR},i,j}} \tag{9}$$

Higher percentages of TP_X responses at the downwind sensors compared with the upwind sensors could indicate that the sensors are picking up a response when directly downwind of a ChR.

Detection classification using the site-level methane emission rate estimates from the solutions defines a TP as 'any non-zero emission estimate' overlapping in time with a challenge release as a TP_{POD} detection. This TP_{POD} definition is conservative and accepts any non-zero estimate during the ChR as a TP_{POD}, regardless of attribution indicating the detection was of our release, not some other activity or operational emission at the site. If a ChR was not classified as a TP_{POD} detection following the logic above, then it was classified as a FN_{POD} detection. POD curves were then derived from TP_{POD} and FN_{POD} data, following the CM POD logic. False positives and true negatives could not be attributed during these studies, because the field team was unable to rule out the presence of all fugitive or vented emissions from operational activities at the site.

ChR Study Limitations: CRs at METEC were similar to the ChRs in the field campaign, with two key differences. First, at METEC there were no un-metered emissions from on-site operations during experiments. Therefore, solutions could identify *any* release as an emission without having to establish a non-zero baseline of emissions from the site. Second, during METEC testing, the study team monitored solution reports and manipulated the emission rate so that each solution achieved near-100% detection probability at some release rate (typically large), and near-0% detection probability at another release rate (typically small). Moving release rates in this way effectively 'mapped out' the POD curve for most solutions. This approach requires 300-400 experiments for each solution. In contrast, far fewer releases were possible for each solution in the field campaign and the overall poor performance, even at release rates approaching the upper limit of the release system and far greater than typical fugitive component leaks, made it impractical to map the curve. With no real ground truth representing the baseline at the facilities, the comparison had to be based on the NR data, creating a bias.

4 RESULTS AND DISCUSSION

Table 4 summarizes the solutions that participated during anytime of the ADED program, highlighting the testing session they were involved in. The longest experiment periods included CM, survey, and adhoc testing, which have all been taking place since near the beginning of the ADED program in 2021. Field testing with CM solutions occurred during 2022 and 2023, while the 'METEC Protocol' testing occurred during Fall 2024. This round of testing was conducted to make upgrades to the current protocols to follow in line with regulations and recent infrastructure changes at O&G facilities. As the technologies have advanced across the O&G fields with upgrades on tanks, compressors, and implementation of more electrically powered units, METEC is continuing to advance in parallel for testing emissions monitoring solutions. Of the 25 companies that participated 20 of them engaged in METEC CM, 8 in survey, 6 in field, 7 in adhoc, and 6 in protocol revision testing. Several of these companies are currently involved with the protocol revisions that the METEC group is working on to implement in 2025, starting with a round of spring testing, more details in Section 5.

Table 4: Solution companies that participated during the ADED program.

Solution	METEC CM	METEC Survey	Field CM	METEC Adhoc	METEC Protocol
ABB	-	✓	-	-	-
Baker-Hughes	✓	✓	✓	-	-
Blue-Rock	✓	-	-	✓	-
ChampionX	✓	✓	✓	✓	-
Cimarex	-	✓	-	-	-
CleanConnect.ai	✓	-	-	-	-
Earthview.io	✓	-	✓	-	-
Heath	-	✓	-	-	-
Honeywell	✓	-	-	-	-
Konica-Minolta	-	✓	-	-	-
Kuva Systems	✓	-	-	-	-
Luxmuz Technologies	✓	-	-	-	-
Molex	✓	-	-	-	-
Montrose	-	✓	-	-	-
Oiler-Equation	✓	-	-	-	-
Pergam Technical Solutions	✓	✓	-	-	-
Project Canary	✓	-	✓	✓	✓
QLM Technology	✓	-	-	-	✓
Qube Technologies	✓	-	✓	-	✓
Sensia Solutions	✓	-	-	✓	✓
Sensirion	✓	-	✓	✓	✓
Sensit	✓	-	-	-	✓
Shepherd-Safety	✓	-	-	✓	-
SLB	✓	-	-	✓	-
Xplorobot	✓	✓	-	-	-

4.1 Survey Solution Controlled Releases

Following the survey protocol and similar to Bell et al. and Ilonze et al., the survey study evaluated the detection sensitivity of solutions by defining each solution's detection limit (DL90) as the minimum emission rate the solution can detect 90% of the time across multiple observations over a wide range of weather conditions (i.e., the emission rate the solution has 90% POD). Implementing the survey protocol showed that overall, handheld OGI camera solutions had comparable or better performance than other solution categories across most metrics assessed. A multivariable logistic regression analysis evaluating the impact of release rate, wind speed, wind direction, and ambient temperature on the emissions detectability (TP and FN classification $\rightarrow$ POD) of solutions indicated that emission rate was statistically significant ($p < 0.05$) for 5 (C, D, E, H, and J) of 12 solutions that tested in the first round. Other variables (temperature, wind speed, and wind direction) were separately statistically significant to just 1 solution each.

Of the 5 solutions whose emissions detectability (i.e., POD) was statistically influenced by release rate, only solution D did not have a statistically significant correlation (Rank-Biseral correlation, $p < 0.05$) between release rate and emissions detectability. This suggests that the solution's POD curve will likely benefit from accounting for windspeed (which was statistically significant to the solution's emissions detectability). Table 7 shows that the POD curves of solutions could only predict the DL90 of 7 of 12 solutions with values ranging from 0.08 [0.00, 0.10] kg CH_4/h to 0.81 [0.16, NA] kg CH_4/h with 6 solutions within their tested emission rate range.

Table 5: Results of the detection classification scheme and the 90% POD predicted by each solution sorted in order of increasing 90% POD.

Solution		Survey Time	Localization (Unit)†		Detection Classification		
ID	Category	per Unit (minutes)	Accuracy (%)	Precision (%)	FPF (%)	FNF (%)	DL90‡ (kg CH_4/h)
Solutions' results from the first round of testing.							
G	Handheld OGI	5.86 [1.11, 15.0]	98.5	98.5	0.0	5.7	0.08 [0.00, 0.10]
H	Advanced Handheld	5.09 [0.78, 14.0]	91.0	100.0	9.0	16.5	0.14 [0.11, 0.67]
L	Handheld OGI	2.3 [0.72, 4.86]	95.7	100.0	4.3	8.2	0.15 [0.00, 1.70]
E	Handheld OGI	1.91 [1.0, 6.17]	97.1	98.8	1.7	24.1	0.26 [0.17, 0.39]
C	Advanced Handheld	1.89 [0.94, 4.39]	79.5	97.2	18.2	19.6	0.36 [0.18, 1.05]
J	Advanced Handheld	1.03 [0.39, 2.86]	95.2	100.0	4.8	31.0	0.65 [0.36, 1.60]
B	Handheld OGI	1.66 [0.67, 5.0]	92.8	96.2	3.6	25.2	0.81 [0.16, NA]
K*	Advanced Handheld	2.53 [1.14, 5.0]	62.9	97.7	35.6	6.6	0.00 [0.00, NA]
D	Mobile	2.02 [0.94, 8.0]	62.9	87.4	28.0	31.7	NA [0.60, NA]
I	Mobile	1.63 [0.56, 3.57]	61.2	78.8	22.4	22.4	NA [0.78, NA]
A	Mobile	0.94 [0.44, 2.57]	55.0	68.0	19.2	20.3	NA [2.32, NA]
F	Mobile	2.68 [1.56, 8.5]	32.0	64.0	50.0	48.5	NA [4.44, NA]
Results from the second round of testing for solutions that participated in the first round.							
K*	Advanced Handheld	0.51 [0.06, 1.5]	92.2	92.2	0.0	7.3	0.05 [0.00, 0.27]
H	Advanced Handheld	2.34 [0.72, 6.67]	97.9	100.0	2.1	8.7	0.11 [0.00, 0.24]
A	Mobile	1.73 [0.5, 3.67]	55.1	71.7	23.1	45.5	NA [6.98, NA]

† This is time taken to survey an equipment unit in a facility.
‡ When the POD curve cannot evaluate the DL90 or the DL90 is ×20 of the maximum release rate tested, its value is "NA". Similarly, when the lower and upper empirical 95% confidence intervals on a solution's DL90 could not be evaluated, they were given as 0 and NA, respectively.
* The DL90 is 0 because the POD curve is approximately constant at POD $> 90\%$.

The five solutions that could not predict their respective DL90s or had large DL90 values ($> 70\times$) relative to the maximum release rates tested consisted of all 4 mobile solutions (drone- and automobile-based) tested in the study. Table 7 also shows that mobile solutions had some of the largest false positive fraction (FPF) (19.2% to 50.0%) and false negative fraction (FNF) (20.3% to 48.5%) values evaluated in this study. This result is likely due to potential difficulties at either distinguishing methane (or other gas species of interest) signals from background noise by these solutions (increases FPF), high detection limits (increases FNF), or redundant TP detections due to the limitations of the test protocol (inflates FPF).

The DL90s of 3 of 4 handheld OGI camera solutions tested (B, E, G, and L) were among the top 4 lowest DL90s obtained in the study. Unlike advanced handheld solutions, emission rate and other test conditions were not statistically significant to the emissions detectability of 3 solutions which aligns with data from Zimmerle et al. that indicated the experience level of an OGI camera surveyor had a more statistically significant impact on emissions detection rate than other variables tested. Additionally, handheld OGI camera solutions had the lowest FPF values in the study (0.0% to 4.3%) which were statistically significantly lower (T and Kolmogorov-Smirnov tests; $P < 0.05$) than that of mobile solutions but comparable to advanced handheld solutions (4.8% to 35.6%). Although the FNF values of 2 of 4 handheld OGI camera solutions were less than 10%, the FNF values of handheld OGI camera solutions were not statistically different from that of mobile and advanced handheld solutions, respectively.

While these results highlight why handheld OGI camera solutions are typically used, and are anecdotally effective, for follow-up investigations and regulatory-compliant LDAR inspections at O&G facilities, results also showed that the DL90s of all advanced handheld solutions were within the minimum detection threshold stipulated in the EPA's final rule (NSPS OOOO(b) rules) for quarterly monitoring (≤ 1 kg CH_4/h) of well sites and centralized production facilities with alternative technologies[7].

Figure 2 and Table 7 shows the equipment unit-level localization accuracy and precision of all tested solutions from both the first round and second round of testing. For the first round of testing (circular markers), we find that the equipment unit-level localization accuracies of handheld solutions (i.e., OGI cameras and advanced handheld solutions) were statistically significantly (T and Kolmogorov-Smirnov tests; $p < 0.05$) higher than those of mobile solutions, with the two categories of handheld solutions having comparable localization performance. These findings highlight the effectiveness of handheld solutions at pinpointing leak sources for repairs or reporting, even though cost and labor requirements are major concerns when scaled over thousands of O&G facilities. Also, solutions showed a similar trend in localization precision performance as observed for localization accuracy.

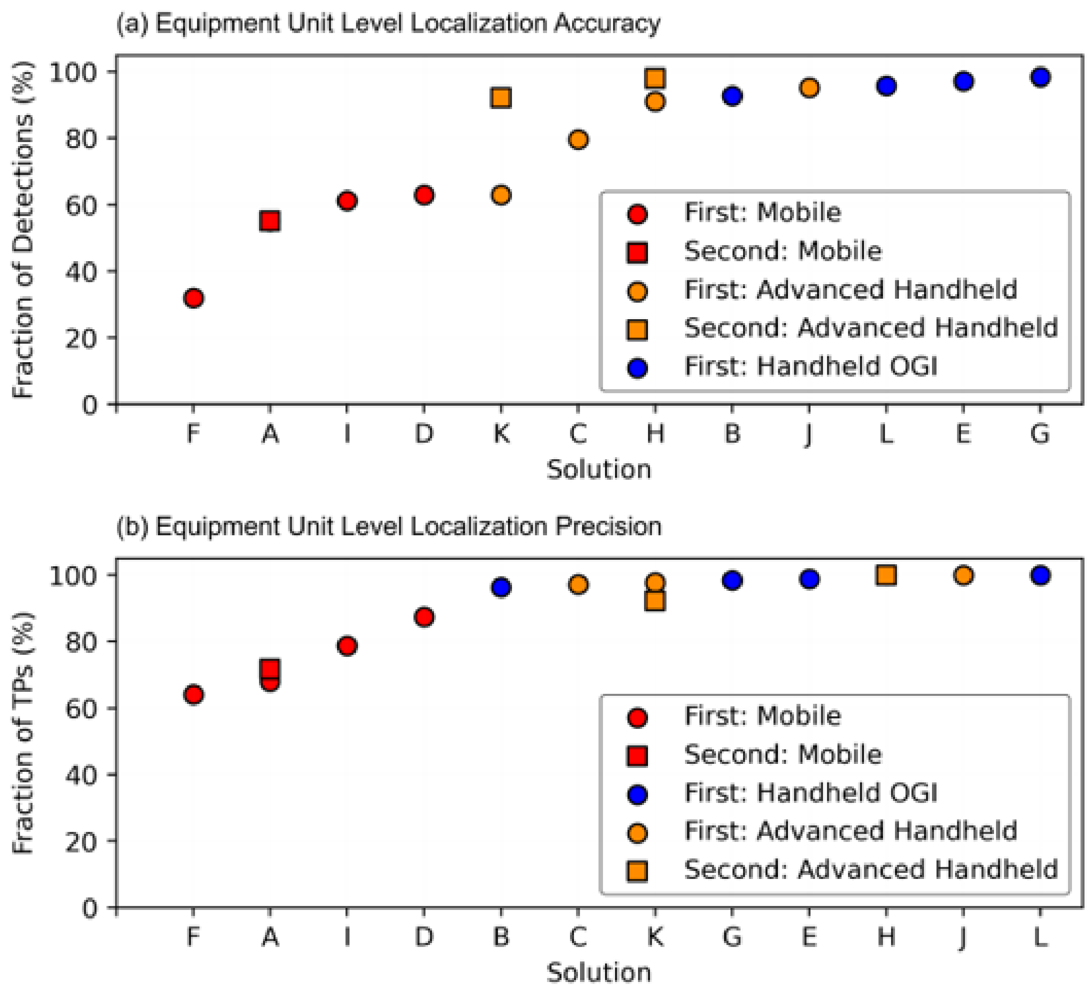

Figure 2: A scatterplot of equipment unit-level localization accuracy for all solutions arranged in increasing order. The y-axis shows the fraction of detection reports that identified a leak source at the correct equipment unit The marker colors in both figures identify handheld OGI, advanced handheld, and mobile solutions. The circular-shaped marker represents each solution's first-round test results. In contrast, the square-shaped markers identify results from their second round of testing (for solutions tested multiple times).

Although some mobile solutions in this study presented promising equipment unit-level localization performance (accuracy and precision $>$ 50% and 60%, respectively), with additional development, mobile solutions may currently be best deployed to rapidly screen for general emissions locations, followed by investigations with handheld solutions (e.g., OGI camera surveys) to identify emitters for repairs and reporting. For regulatory compliance, the EPA's final rule on advanced methane detection technologies has stipulated secondary inspection work practices at O&G facilities based on the spatial resolution of emission sources by LDAQ solutions[7].

This study's results should be applied with caution for two reasons. First, since the test facility used for the study mimics near-ideal real facility operational conditions, solutions' results likely represent best-case scenario performance (unless detection performance depends on high thermal contrast between the equipment surface and the gas plume). Second, as shown by Day et al.

for continuous monitors, field testing performance can vary substantially from that of controlled testing; therefore, robust field testing of the solutions is needed to validate and build confidence in assessed controlled testing performances.

4.2 QOGI Controlled Releases

In total, 357 measurements were conducted with the QOGI system across 73 camera positions and 26 experiments. Each experiment had a controlled release rate ranging from 2.2 to 88 standard liters per minute (slpm). Each experiment included 1 to 6 camera positions (mean of 2.8) and 4 – 27 (mean of 13.7) total successful individual estimates per experiment. Eight types of components were used as emitting sources in this study: connector, control box, flange, pressure transducer, pressure release valve (PRV), temperature regulator, thief hatch, and valve packing.

Figure 3 examines quantification accuracy of individual estimates. Figure 3(a) compares individual rate estimates against controlled release rates. A linear regression analysis with intercept set to zero indicates a regression coefficient of 1.27 (95% CI [1.13, 1.40]) – an overestimation bias of 27%. Since the mix of emitter sizes on real facilities differs from that in the study, these results should be used with caution. Across all estimates, individual relative errors ranged from -90% to +831% compared to -90% to +330% from the AMFC study even though the latter tested much larger rates.39 Results show that 46% (N = 165) of individual estimates were within a quantification factor of 2 (-50% to +100%) of the controlled release rates while 75% (N = 266) individual estimates were within a factor of 3 (-67% to +200%).

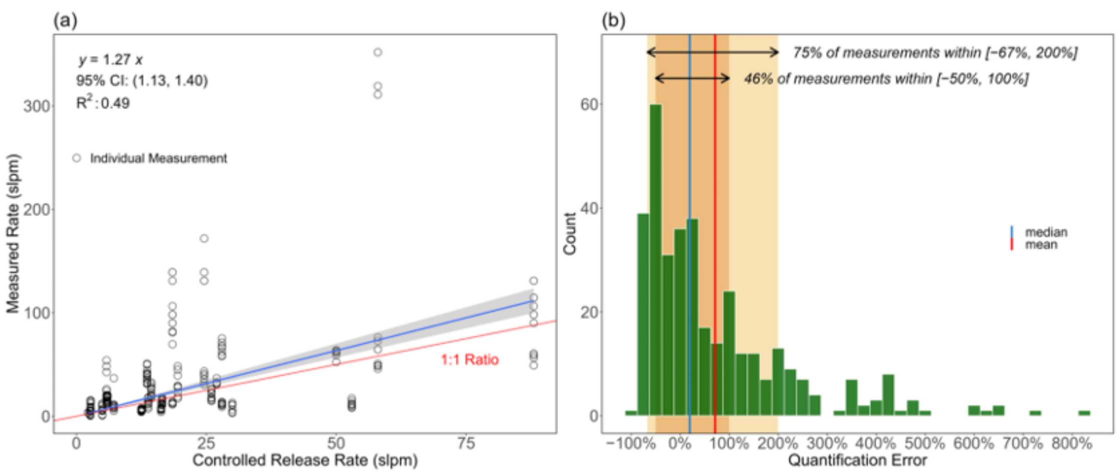

Figure 3: Quantification accuracy of individual estimates: (a) measured rates versus controlled release rate and (b) distribution of quantification error of individual estimates. In (a) the blue line represents linear regression through the origin with the gray shading showing the 95% confidence interval of the regression when bootstrapped. The red line represents the 1:1 ratio, where the measured rate matches the controlled release rate. In (b) the orange shading represents measured rate within factor of two of the controlled release rate (-50% to 100% quantification error), and the yellow shading represents measured rate within factor of three of the controlled release rate (-67% to 200% quantification error).

Quantification precision was evaluated by comparing the quantification error of individual measurements under the same camera position and the same experiment. As highlighted earlier, the field crew took 1 to 11 (average 4.9) successful measurements at each camera position and 4 – 27 (average 13.7) total successful measurements per experiment. Ideally, because the controlled release rates of each experiment remained approximately the same, the quantification errors of individual estimates under the same camera position were expected to be the same, assuming the prevailing measurement conditions (e.g. wind speeds and background) remained consistent. Likewise, the quantification errors at various camera positions under the same experiment should be similar. As controlled release rate increased, both the accuracy of measurements (mean error at a camera position) and precision of measurements (range of error observed at a camera position) improved.

Distribution of samples is not uniform across all emission rates. For example, 11% of measurements were conducted at controlled release rates 50 slpm. At the camera position level, the differences between the maximum and minimum error (henceforth precision range) spanned from 2% to 439% with 75% of camera positions having precision range <50%. All the 9 camera positions with precision range >100% had controlled release rates below 25 slpm; an emission rate range which also had high mean quantification error (Figure 2(a1)).

Results indicate wider quantification error range (-90% to +831%) than the prior study (-90% to +330%) that tested similar QOGI tool, although the maximum rate in the current study was about an order of magnitude less than that of the prior study. Our result also shows a reduction in quantification error as release rate increased even though the tested rates were relatively low compared to prior studies. Further investigation will be needed to understand quantification performance for rates outside the tested range, especially larger rates (i.e. super emitters) which is an important emission source category.

Study results indicate combinations of conditions which are more favorable to quantification than other conditions, specifically calm windspeed (< 1 mph) and viewing emissions against a clear sky background. Since computational algorithms are proprietary, the cause of improved performance cannot be stated. However, less turbulent plume dispersion in calm winds provides imaging favorable for plume identification, as does viewing the emission plume against a clear sky where the sky's apparent temperature is usually low, improving thermal contrast needed for clear plume identification. Conversely, cloudy sky, vegetation on the ground, and/or backgrounds with poor deltaT were unfavorable for quantification. Although our results indicated that the distance range of 2m to 10m was more favorable for quantification, caution must be taken when applying this result, as with the available data we could not reliably assess quantification performance for measurement distances > 10m.

4.3 Continuous Monitoring Solution Controlled Releases

4.3.1 Performance of Continuous Emission Monitoring Solutions Under a Single-blind Controlled Testing Protocol (March 2023)

This study covers the introduction of single-blind testing at METEC implementing the CM protocol [20] for methane leak detection and quantification solutions in 2021 and 2022. In the two campaigns included in this study, 11 solutions tested, including point sensor networks and scanning/imaging solutions. There was a large variation seen in the POD results, ranging from 3 to 30 kg/hr. There was high uncertainty across the board, and 6 out of the 11 solutions had PODs < 6 kg/hr. The large variability in performance between CM solutions, coupled with highly uncertain detection, detection limit, and quantification results, indicates that the performance of individual CM solutions needed further clarification before relying on results for internal emissions mitigation programs or regulatory reporting. The results presented here indicate that users should utilize CM solutions with caution. Detection limits, POD, localization, and quantification may or may not be fit-for-purpose for any given application. If performance is clearly understood, and uncertainties are robustly considered, the solutions tested here, as a group, provide useful information. For example, most will detect large emitters at high probability and sooner than survey methods, and will quantify those emitters well enough to inform the urgency of a field response. In contrast, relying on quantification estimates from these solutions for emissions reporting is likely premature at this point in testing.

Classification of Detections: Detection reports and controlled releases were classified as TP or FP, and as TP or FN, respectively, as described above. Table 6 summarizes the classified detection reports (FP rates) and controlled releases (TP and FN rates) for all participating solutions, sorted in order of decreasing TP rates. Although many of the solutions participated in testing simultaneously, the number and characteristics of controlled releases included in their performance analysis varies due to solutions installing after the program start, uninstalling prior to the program end, or submitting offline reports during the program.

Table 6: Summary of the localization precision, and classification of controlled releases and detection reports participating solutions. Solutions are sorted in order of declining true positive (TP) detection rate.

	Count		**Number of TP Localization**					
ID	**Controlled Releases**	**Detection Reports**	**Equipment Unit**	**Equipment Group**	**Facility**	**TP(%)**	**FN(%)**	**FP(%)**
E	567	2382	232	207	58	87.7	12.3	79.1
F	571	469	98	200	100	69.7	30.3	15.1
A	571	834	111	156	129	69.4	30.6	52.5
D	571	346	0	0	335	58.7	41.3	3.2
B	442	213	122	26	23	38.7	61.3	19.7
C	557	214	2	1	191	34.8	65.2	9.3
J	284	68	67	0	1	23.9	76.1	0.0
H	368	37	3	17	14	9.2	90.8	8.1
I	354	31	17	4	7	7.9	92.1	9.7
G	206	12	0	2	6	3.9	96.1	33.3
K	746	2	0	1	1	0.3	99.7	0.0

TP(%) shown in this table is the percentage of controlled releases detected by a solution across all localization levels.

Table 6 clearly illustrates the wide range of performance for CM solutions – ranging from near-zero TP to TP rates in excess of $2/3^{rd}$ of all controlled releases, accompanied by FP rates from near zero to over half of all detection alerts. This level of variability clearly indicates the need to set performance standards before qualifying solutions for LDAR deployments or regulatory reporting. The table also illustrates the trade-off between detection sensitivity and false positive rates. Of the 4 solutions with TP rates over 50%, two had FP rates exceeding 50%. In field conditions, a high

FP rate may force unacceptably high follow-up costs.

Probability of Detection: The POD describes the probability that an emission source will be detected by a solution as a function of many independent parameters including characteristics of the emission source itself (e.g. the emission rate, source type, position, etc.) and environmental conditions (e.g. wind speed and direction, precipitation, etc.). The POD curve as a function of emission rate is used here for illustrative purposes. The POD curves for two point sensor network solutions (A and F - upper panels) and two scanning/imaging solutions (I and J - lower panels) are shown in Figure 4. We define a solution's detection limit (DL) as the emission rate where the solution achieves 90% POD. Most solutions have a smaller lower detection limit (LDL), however, field implementation or regulatory performance metrics typically require a more rigorous metric. Here we suggest that metric be defined as the emission rate where the solution will detect nine of ten emission sources across a wide range of meteorological conditions. The DLs of 3 solutions could not be estimated with logistic regression due to limited distribution of TPs compared to FNs across the range of the independent variable (i.e. controlled emission rate).

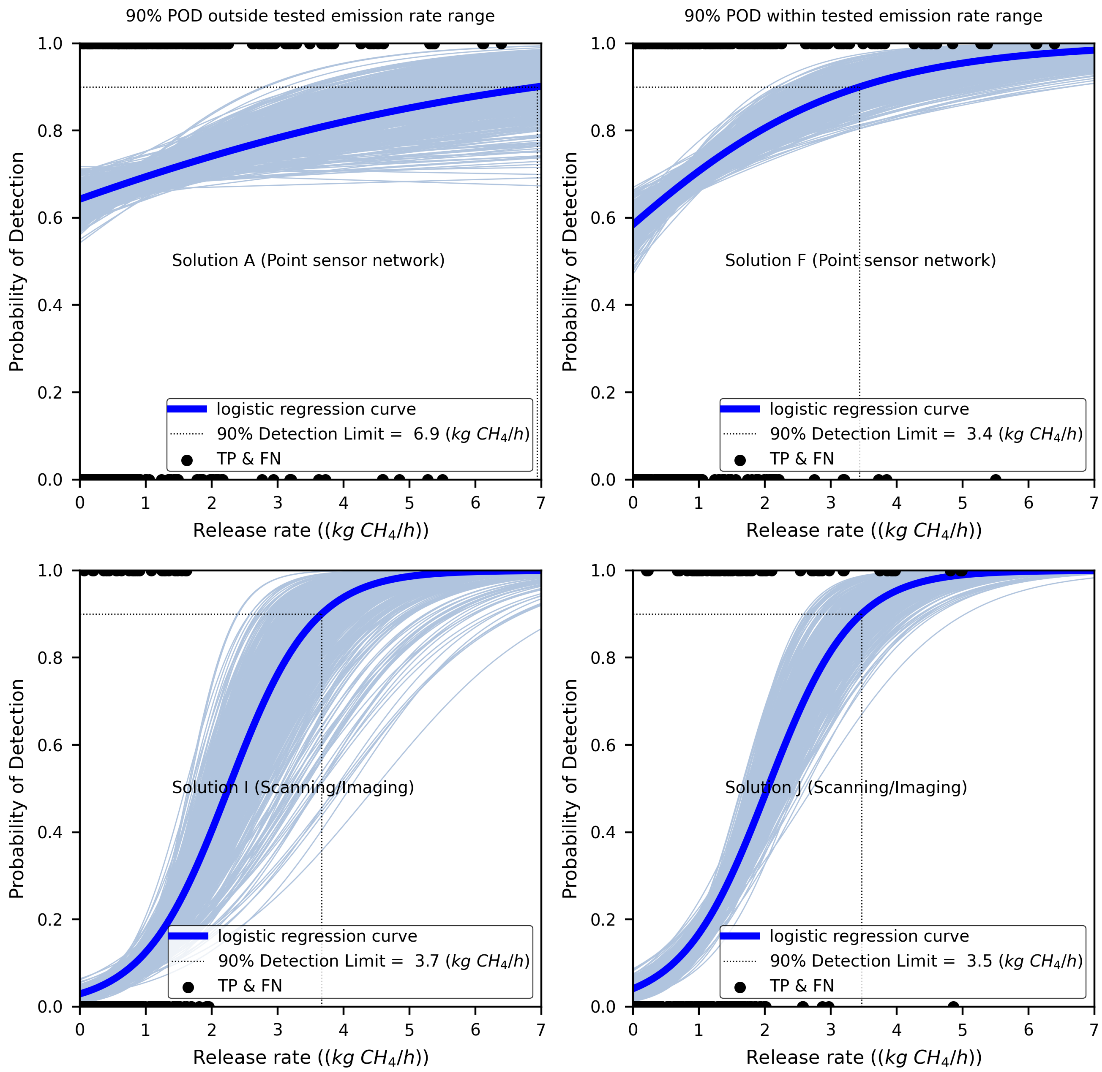

Figure 4: The probability of detection versus emission rate (kg CH_4/h) fit using logistic regression. Solution A and F (upper two panels) are point sensor networks, while I and J (lower two panels) are scanning/imaging solutions. True positive and false negative controlled releases are shown with markers at y = 1 and y = 0 respectively. The regression is bootstrapped to produce a cloud of curves illustrating uncertainty in the result. The emission rate at which the POD reaches 90% is indicated as the detection limit for each solution. For solutions A and I, left side, test releases did not exceed the computed 90% detection limit, while for solutions F and J, right side, release did exceed that rate. As a result, POD uncertainty is substantially larger for solutions A and I.

Localization: Table 6 also illustrates the equipment-level localization estimates of solutions. Localization is often dictated by the algorithm implemented by a solution. Some solutions may function only at the 'full facility' level, and have no ability to localize within the facility. Others may prioritize localization, and can provide specific locations for emission sources. Four of 11 solutions attributed the majority (46.7% to 98.5%) of TP detections at the equipment unit level, 3 localized a plurality (39.4% to 50.3%) at the equipment group level, while 3 solutions localized most (75% to 100%) TP detections at the facility level.

Quantification: Recent works focusing on the certification of natural gas production have raised interest in the use of CM solutions to provide near-continuous quantification of emissions at facilities [11, 12, 5, 8]. In this study, not all solutions reported emission rate estimates, if they were reported by a solution, source-level quantification accuracy metrics were evaluated. Six solutions reported quantification estimates, 5 reporting methane, and solution E reporting whole gas emissions rate. The dependence of quantification accuracy on controlled release emission rate is a key variable to understand field performance, and is typically the parameter of interest in modeling and regulatory program analysis. This study found that longer release duration did not improve quantification estimates while the mean and median relative errors with respect to emission rate, were substantially skewed. For instance, the mean error of controlled releases of (0.01-0.1] kg/h of whole gas was $\approx 4\times$ the median error. However, as release rate increased, quantification errors became less skewed (more symmetric) as mean approached the median for release rates of > 1 kg/h of whole gas. Essentially, the mean relative error decreased with increasing emission rates but never got to zero.

4.3.2 Assessing the Progress of the Performance of Continuous Monitoring Solutions Under Single-Blind Controlled Testing Protocol (June 2024)

This study is the second implementation (first by Bell et al.) of a consensus protocol [21] to assess progress of solutions. Results from the study highlights a few key points. Firstly, solutions that tested before generally exhibited better performance on many performance metrics relative to (1) their previous performance in Bell et al., (2) other solutions testing for the first time under the protocol. Majority of solutions that retested in this study had the lowest FP rates and DL90s, and the highest localization accuracy at equipment group or better performance in the study. They were also among solutions with the lowest FN rates and highest quantification performance (estimates within a factor of 3) across different emission rate ranges (0.1 - 1 kg CH_4/h and >1 kg CH_4/h). Similarly, across all metrics assessed, most of the solutions that retested improved in performance when compared to their previous results highlighting the benefits of regular quality testing. Users however should be cautious given that these results are likely more representative of non-intermittent emissions from fugitive events which make up relatively smaller fraction of reported upstream emissions. Secondly, single source emission estimates by solutions still have wide uncertainty which is unsuitable for accurate measurement-based inventory development and reporting programs. On the other hand, solutions had better quantification accuracy with narrower uncertainty at the facility-level. This result, if replicable in the field and applied to sites similar to METEC, shows promises of reliable facility-level quantification performance by these solutions, especially when adopted for regulatory programs in the near-future, provided that the observed rapid development of CM solutions is sustained. Overall, solutions need not have excellent performance across all metrics assessed in this study to be useful i.e., rapid detection of large emissions sources for repairs might not require accurate quantification. As well, higher DL90 at low FP rate could mitigate larger emissions with minimal cost of followup investigations.

Probability of Detection (POD): Results indicate that emission rates significantly ($p < 0.05$) affected the POD of all solutions, with other variables affecting only a subset of solutions. Figure 5 compares curves for the 4 solutions that participated in both the current study and that by Bell et al.. Bell et al. defined the Method Detection Limit (DL90) of each solution as the emission rate at which the solution, as deployed (method), detected emitters 90% of the time, over a wide range of meteorological conditions. The study team deviated from the acronym MDL used by Bell et al. to avoid it being misinterpreted as "minimum detection limit" which might mean something different. The DL90 metric is an important consideration during the formulation of methane emissions reduction policies/programs [6] by regulations and their implementation by O&G operators.

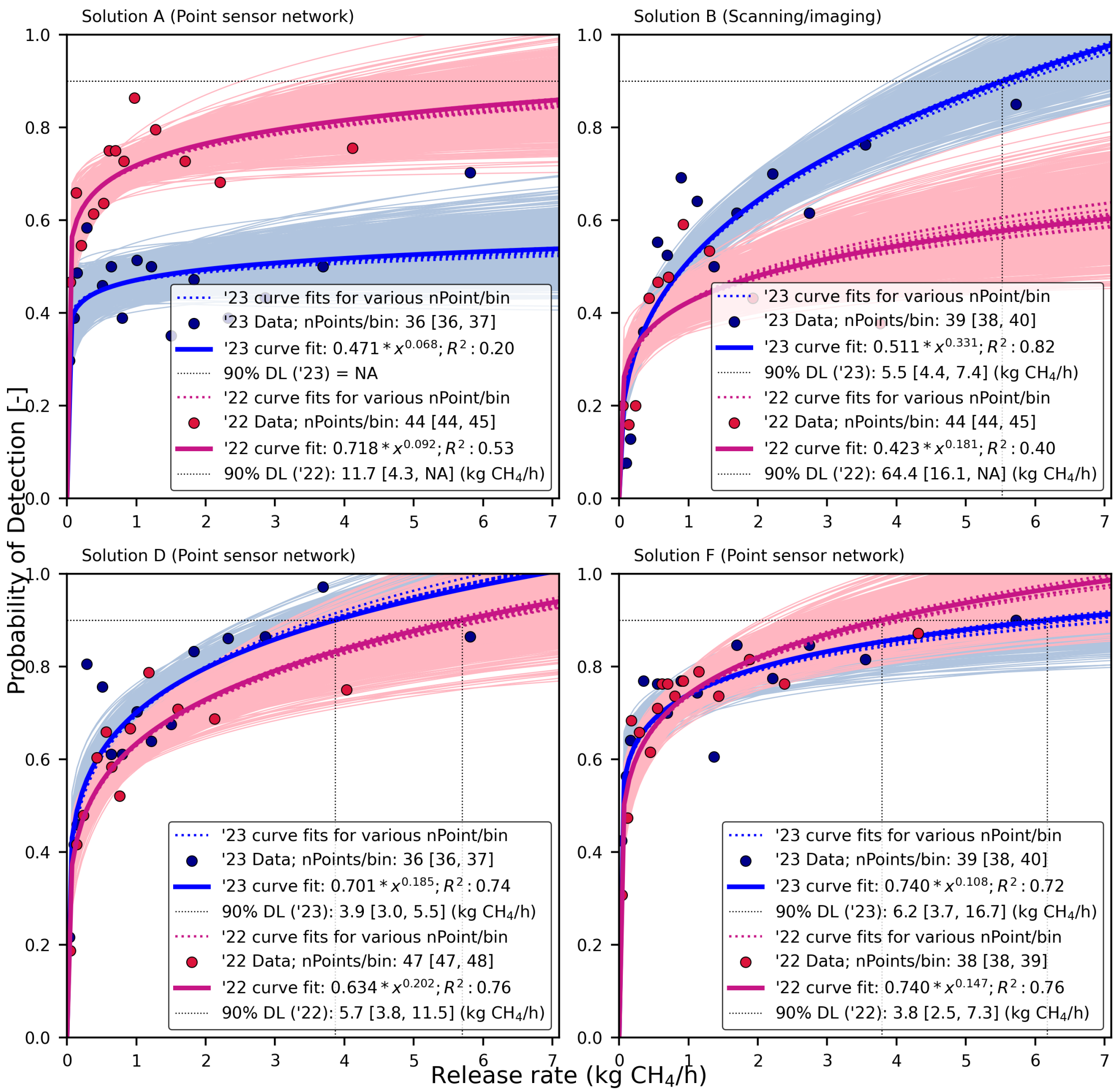

Figure 5: The probability of detection (POD) versus emission rate (kg CH_4/h) for point sensor network solutions solutions (A, D, and F) and a scanning/imagine solution (B) fitted using power functions. The x-axis is divided into equal-sized bins with each marker (pod) as the fraction of controlled releases in a bin classified as true positives. Data points from the study by Bell et al. (2022) is overlayed on the current results for comparison. The emission rate at which the POD reaches 90% is indicated as the method detection limit (DL90) for each solution. Each pod data point is bootstrapped to produce a cloud of curves illustrating associated uncertainty. When the bootstrapping could not evaluate the lower and upper empirical Confidence Limit (CL) on a solution's DL90 best estimate, they are given as 0 and NA respectively. Curve fits (dotted colored lines) obtained using other quantile-based discretizations are shown for comparison. The DL90s of 3 of the 4 solutions (B, D, and F) in the current study were within tested emission rate range. The mean count of points per bin along with the min. and max. counts across all bins is also shown in the figure.

Results from the study by Bell et al. showed that more solutions struggled at balancing low

MDL, FP rate, and FN rate when compared to current test results. Two of 11 solutions showed efforts at balancing all 3 metrics relative to other solutions, while others showed mixed performance. The DL90s of 4 of the 8 solutions fell within the range of emission rates tested in the study. Table 7 shows that the 4 solutions with the lowest FP rates (6.9% to 13.2%) also had the lowest DL90s (3.9 [3.0, 5.5] kg CH_4/h to 6.2 [3.7, 16.7] kg CH_4/h), while 3 of the 4 solutions had the lowest FN rates (27.4% to 32.9%) in the study.

Table 7: Summary of the number of controlled releases and detection reports considered in the analysis of each CM solution. The break down of the false positive rates for all solutions using the ADED protocol is also shown together with the false negative rate, and DL90s predicted by each solution. Solutions are sorted in order of increasing All false positive rate.

	Count		FP (%)†				
ID	**Controlled Release**	**Detection Reports**	**All**	**No Controlled Release**	**Excess Detections**	**FN (%)**	**DL90‡ (kg CH_4/h)**
			Result from the current study for all participating CM solutions				
D	547	403	6.9	28.6	71.4	31.4	3.9 [3.0, 5.5]
B	547	300	7.7	39.1	60.9	49.4	5.5 [4.4, 7.4]
F	547	444	10.6	8.5	91.5	27.4	6.2 [3.7, 16.7]
P	547	423	13.2	23.2	76.8	32.9	6.0 [4.1, 11.6]
N	417	223	18.4	29.3	70.7	56.4	14.1 [7.3, 55.3]
L	256	254	35.0	95.5	4.5	35.5	10.2 [5.3, 61.8]
O	357	324	34.6	33.0	67.0	40.6	18.2 [7.9, 90.5]
Q	547	260	38.1	21.2	78.8	70.6	11.7 [7.7, 22.6]
A[1]	547	487	47.8	61.8	38.2	53.6	NA
			Results from Bell et al. for the 4 CM solutions that participated in both studies.				
D	574	376	10.4	79.5	20.5	41.3	5.7 [3.8, 11.5]
F	574	516	22.5	39.7	60.3	30.3	3.8 [2.5, 7.3]
B	445	250	31.2	61.5	38.5	61.3	64.4 [16.1, NA]
A	574	986	59.8	26.9	73.1	31.0	11.7 [4.3, NA]

† **All** is the percentage of all detections classified as false positive based on the ADED protocol.

† **No controlled release** is the fraction of all false positives that is due to detection reports sent when there was no controlled release at the test center.

† **Excess TP Detections** is the fraction of all false positives that is due to excess detections identifying controlled releases that have been matched already as a new and/or different emitter.

‡ When the POD curve could not evaluate the DL90, they are given as "NA". Similarly, when the lower and upper empirical 95% Confidence interval (CI) on a solution's DL90 could not ve evaluated, they are given as 0 and NA respectively.

[1] One of the sensors installed failed during the study.

This indicates efforts at balancing method sensitivity (i.e. low DL90) with low FP and FN rates. In contrast, the remaining 6 solutions had relatively higher DL90s (no solution within tested emission rate range), FP rates (all solutions $>$ 20%), and FN rates (5 solutions $\geq$ 50%) which might indicate struggles at emissions detection. At a minimum detection threshold of 0.40 kg CH_4/h (as stipulated in the final rule by the US EPA), results indicate that 5 of the 9 solutions will have $\geq$

50% POD [32]. For the *scanning/imaging* solutions, FP rate spanned between 7.7% to 34.6% with the DL90 of 1 of the 3 solutions within tested range. While the FP rates of *point sensor network* solutions were between 6.9% to 38.1% with the DL90 of 3 of the 5 solutions that estimated DL90s within tested range.

Wind speed significantly influenced the POD of 5 out of 9 solutions tested ($p < 0.05$), with many solutions, especially point sensors, relying on favorable wind transport for effective detection (i.e., sensors must be situated downwind of an emission plume). In field applications, these solutions are deployed to operate continuously and report emissions data at all times, regardless of prevailing weather conditions, as was the case in this study. Given that the test center utilized in this study offers conditions close to ideal operational field conditions (e.g., the absence of highly variable baseline emissions from non-fugitive sources) and that weather conditions may vary greatly across different field locations (e.g., Denver-Julesburg Basin, Permian Basin, Appalachian Basin), the DL90s assessed in this study, as well as those by Bell et al., likely represent best-case scenario estimates.

A Spearman's rank correlation analysis showed that the count of sensors deployed by solutions did not necessarily affect method sensitivity of solutions (p value > 0.5) as solutions that deployed more sensors did not always have lower DL90 compared to solutions that installed fewer sensors. Aside from the difference in the sensor type, quality, and proprietary algorithms which can vary the performance of solutions, one potential explanation for this observation might be over-deployment of sensors by some solutions. However, given the reporting constraints of the test protocol, solutions did not attribute detections to any sensor(s) hence making the assessment of over-deployment (if any) challenging in this study. In general, TP rate tended to increase with release rate for all solutions as shown by the figures above and SI Table.

These results have noted the tendency for solutions to trade-off detection sensitivity with false positive and negative rates: Changing solution settings to reduce DL90 tends to increase FP rate. Additionally, at a minimum detection threshold of 0.40 kg CH_4/h, 4 of the 11 solutions had $\geq$ 50% POD [32]. In general, setting algorithms to reduce DL90 also makes it more difficult to distinguish smaller fugitive emissions from background concentrations (i.e. sensor or algorithmic noise), leading to background fluctuations being classified as false positive emissions detections. Conversely, higher DL90s can imply solutions missing relatively smaller rate emissions which typically makes up majority of field measurement studies (by count) resulting in high FN rates. However, generally, solutions from the current study showed more efforts at balancing low DL90 with low false negative and positive rates compared to the results by Bell et al..

These data indicate a general improvement in efforts to balance method sensitivity with FP and FN rates. Given that these solutions installed same number of sensors as in Bell et al. except for solution F which increased from 8 to 10, improved performance could be attributed to improved analytics/algorithms and/or more favorable test conditions (higher emission rates, longer release durations, and lower windspeeds). At higher emission rates, solutions either exceeded or approached their respective DL90s while testing at calmer wind speeds likely reduced turbulent gas plume dispersion in support of more stable/steady measurements. Longer release durations likely gave *scanning/imaging* solutions multiple opportunities to visualize and identify emissions or longer averaging time of ambient concentration measurement to infer detections by *point sensor network* solutions.

Localization: At the equipment unit level, all 3 *scanning/imaging* solutions had the highest localization precisions ($> 70\%$) and accuracies ($> 40\%$) with the smallest sensor densities (0.000118 sensors/m^2). For the 6 *point sensor network* solutions, only 1 solution (also with the largest sensor density) had localization precision and accuracy $> 40\%$. At the equipment group level or better (equipment group + unit level), all *scanning/imaging* solutions had $> 95\%$ localization precision, and accuracy range of 58.3% to 91.3% while for the *point sensor network* solutions, 3 solutions had precisions $> 90\%$ and accuracies $> 70\%$, with sensor density range of 0.000947 sensors/m^2 to 0.00213 sensors/m^2.

Table 8: Summary of emission source localization (equipment unit) precision and accuracy for all participating solutions arranged in decreasing localization precision equipment unit level.

			Source Localization (Equipment Unit)					
			Precision (%)			**Accuracy (%)**		
ID	**Sensor Density (sensors/m^2)**	**Count of TPs**	**Unit Level**	**Group Level**	**Facility Level**	**Unit**	**Group Level or Better**	**Facility Level or Better**
Result from the current study for all participating CM solutions								
B	0.000118	277	89.5	9.4	1.1	82.7	91.3	92.3
L	0.000118	165	86.7	10.9	2.4	56.3	63.4	65.0
O	0.000118	212	76.4	12.7	10.9	50.0	58.3	65.4
N	0.00213	182	51.6	41.8	6.6	42.2	76.2	81.6
F	0.00118	397	40.8	53.9	5.3	36.5	84.7	89.4
Q	0.00154	161	28.0	54.0	18.0	17.3	50.8	61.9
D	0.000947	375	27.2	68.8	4.0	25.3	89.3	93.1
P	0.00071	367	27.0	56.9	16.1	23.4	72.8	86.8
A[1]	0.000947	254	26.0	49.6	24.4	13.6	39.4	52.2
Results from Bell et al. for the 4 CM solutions that participated in both studies.								
B	0.000118	172	70.9	15.7	13.4	48.8	59.6	68.8
A	0.000947	396	28.0	39.4	32.6	11.3	27.1	40.2
F	0.000947	400	24.8	50.2	25.0	19.2	58.1	77.5
D	0.000947	337	0.0	52.8	47.2	0.0	47.3	89.6

[1] One of the sensors installed failed during the study.

These results illustrate the higher tendency of *scanning/imaging* solutions in this study to correctly narrow down emitters for follow-up OGI surveys than *point sensor network* solutions despite installing the lowest number of sensors. In general, 6 of the 9 solutions had localization precisions more than 90% at the equipment group level or more, while 5 of 9 solutions had localization accuracy $> 70\%$ also at that level. The localization precisions and accuracies of solutions B, D, and F (with larger sensor density in the current study) improved at both equipment unit level, and equipment group level or better, relative to the study by Bell et al.. Solution A had mixed result with only localization precision at equipment group level or better improving.

Quantification: Seven of 9 solutions tested emissions quantification capability. Panels (a) and (b) of Figure 6 are box and whisker plots showing quantification relative error distribution for each solution for controlled release rate ranges of 0.1 - 1 kg CH_4/h and >1 kg CH_4/h respectively. Emission rates in the range 0.1 - 1 kg CH_4/h roughly represents equipment component leak rates typically identified through OGI surveys[24, 60, 61] while rates in the range >1 kg CH_4/h represents relatively larger leak rates due to process failures at production facilities [24, 16]. Panel (c) of the figure is an error bar plot showing facility level quantification relative errors (actual and simulated mean) for solutions over the duration tested, along with associated uncertainties obtained through bootstrapping. Across all panels, the grey shaded area shows emission rate estimation range within a quantification factor of 3 $(-67\%|\frac{1}{3}\times,\ +200\%|3\times)$ of actual release rates. Results of the 4 solutions that also tested in the study by Bell et al. are shown in the plots for comparison.

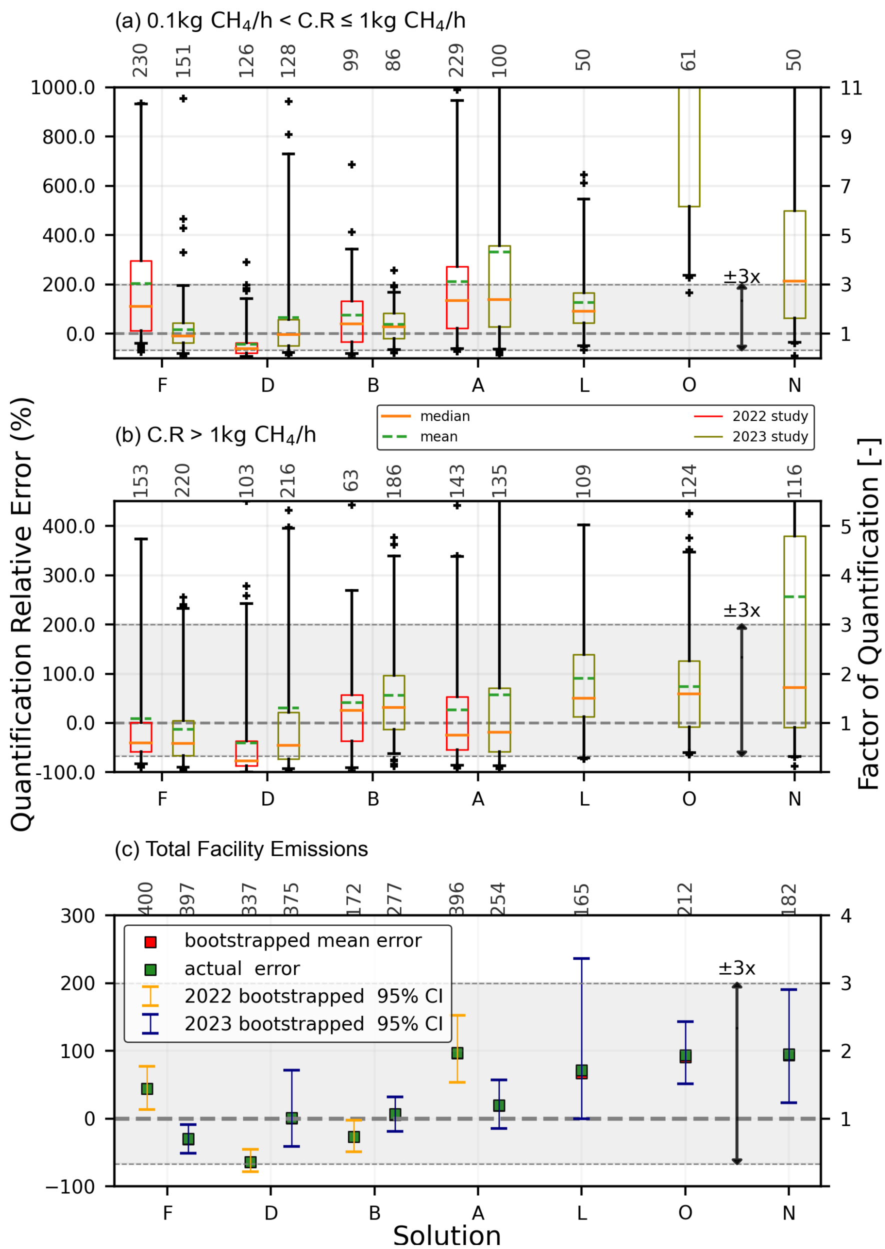

Figure 6: Quantification relative error for solutions categorized by (a) controlled release rate [0.1 - 1) $\mathrm{kg\,CH_4/h}$, (b) controlled release rate $\geq 1\mathrm{kg\,CH_4/h}$, and (c) total facility emissions. The bottom panel (c) summarizes the site-level relative error for each solution arranged in increasing order from left (sol. F) to right (sol. M) based on current study data. The site-level relative error is bootstrapped to estimate the uncertainty on the actual error. Markers represent bootstrapped site-level mean relative error (red), and the actual site-level relative error (green) respectively. Whiskers represents the 95% CI on the bootstrapped mean relative error. The middle (b) and top panels (a) are boxplots summarizing relative error distribution for each solution over selected range of controlled release rates. Each box represent the inter-quartile range of data with whiskers including 95% of data. The upper y-axis of (a) and (b) are arbitrarily trimmed at 400% and 1000% respectively with the full 95% CI. Across all panels, results from the study by Bell et al. (2022) is also shown to facilitate comparison. The x-axis of all panels are arranged based on (c) while the shaded zone indicates region within a quantification factor of 3.

Considering all controlled release rates classified as TP, solutions had 54% to 90% of their estimates within a factor of 3. Four of 7 solutions (including 2 of 3 *scanning/imaging* solutions) in this range had 79% to 96% of their estimates within a factor of 3 while the remaining solutions had 1% to 55% of their estimates also within the factor of 3. In general, individual estimates ranged from $\approx \frac{1}{5}\times$ to $\approx 42\times$ the actual rates in this range. Typically, field operations are characterized by higher background methane concentration than what is obtainable at METEC. Hence, the detection and quantification of some emissions with rates in this range can be challenging for solutions as emissions are intermittent and can easily blend with background methane concentration. However, assuming current solutions performances are extrapolated to the field, the majority of rates estimates in this range by most solutions might be within a factor of 3 (mostly by over-estimation as mean relative errors are skewed high) with individual estimates having wide uncertainty. For emission rates within the range >1 kg CH_4/h, the individual estimate relative errors for all solutions were positively skewed. All the solutions had 61% to 89% of their estimates of rates in this range within a factor of 3. Five of 7 solutions (including all *scanning/imaging* solutions) had $\geq$71% of their estimates within a factor of 3, while the remaining solutions having about 62% of their estimates also within the factor. At 95% empirical confidence interval, 5 of 7 solutions (including all *scanning/imaging* solutions) had both lower and upper individual estimate relative error limits within a factor of 10. In general, single estimates ranged from $\approx \frac{1}{13}\times$ to $\approx 18\times$ the actual rates in this range. In field deployments, the wide uncertainty limit on individual estimates for rates in this range can produce grossly misleading results for LDAR programs. For example, overestimating a relatively large emission (e.g. leak rate of 7.1 kg CH_4/h - maximum rate tested in this study) by $18\times$ can lead to a bogus alert of emissions at a scale of a super emitter ($\geq$100 kg CH_4/h). Generally, in this emission rate range, solutions with a majority of their estimated emissions within a factor of 3 increased, indicating that solutions were likely better at quantifying larger emissions compared to smaller ones.

4.3.3 Assessing the Performance of Emerging and Existing Continuous Monitoring Solutions under a Single-blind Controlled Testing Protocol (Winter 2025)

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 CH4 hr-1) than smaller emissions (< 1 kg CH4 hr-1). 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. Some solutions have 90% DL that qualify for current voluntary and regulatory leak detection programs. 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 of 15 kg/h.

Probability of Detection: This study shows 10 out of 13 solutions had 90% DLs ranging from

0.5 to 76.5 kg CH4 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, 5 of the six solutions had the lowest FP rates (8 to 19%), and 4 had the lowest FN rates (8-33%). 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). 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. Finally, the 4 PSNs with 90% DLs within the tested emission rate range had 90% DLs of 0.5 to 5.5 kg CH4 hr-1, somewhat better than the scanning/imaging solutions' 90% DL of 5.5 to 7.7 kg CH4 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.

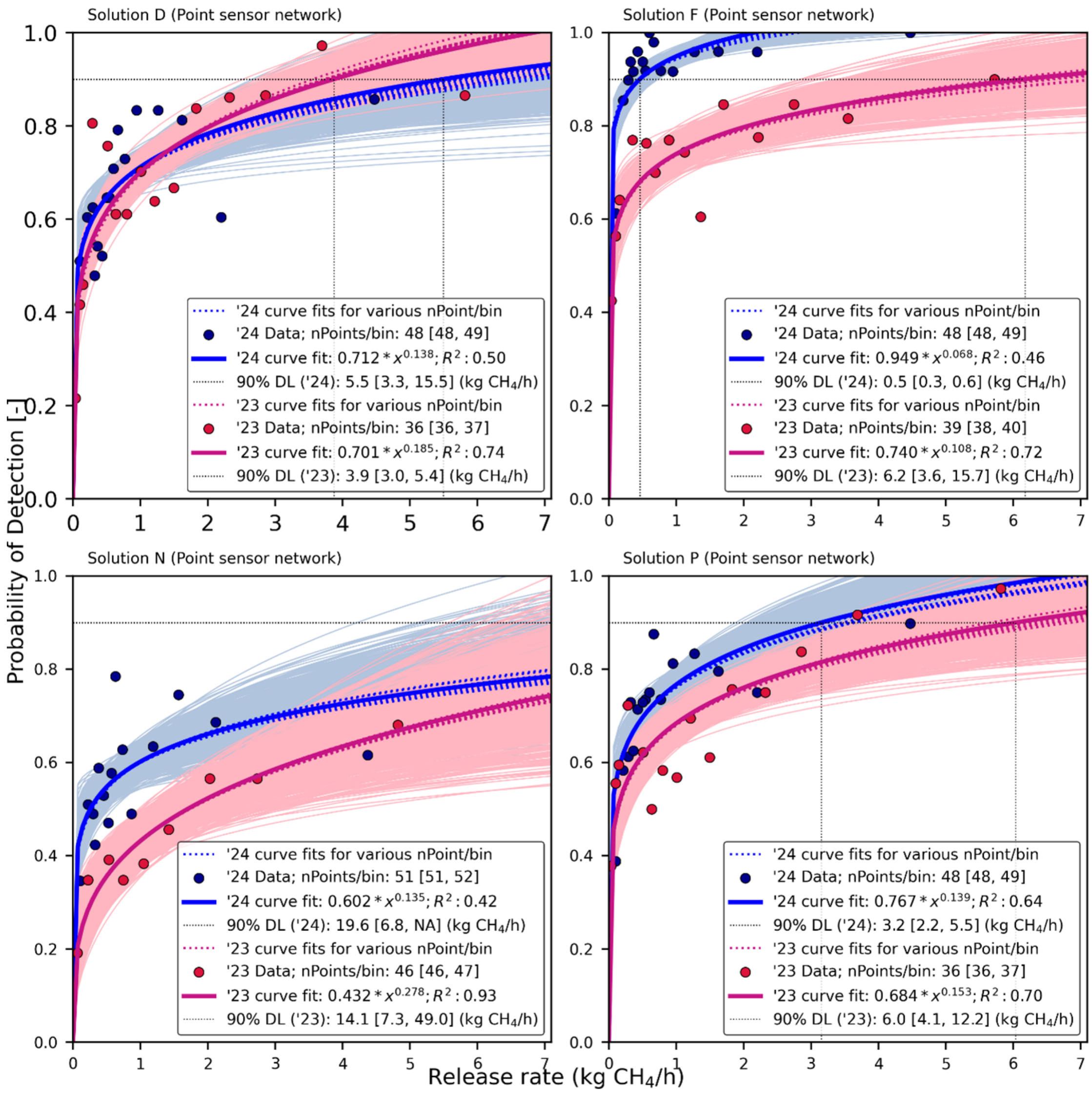

Figure 7: The probability of detection against the controlled release rate for PSNs tested in the current study and in the study by Ilonze et al. The plots also show the 90% DLs for these solutions. The figure shows that three of four solutions (Solutions D, F, and P) are within the range of tested release rates. Although solution N's 90% DL is out of the range, the lower bound of the 90% DL is within the range.

In the two previous studies using this protocol at METEC, the 90% DL ranged from 2.7 to 30.1 kg CH4 h-1 in Bell et al. and 3.9 to 18.2 kg CH4 h-1 in Ilonze et al.. Six of 11 and four of 9 solutions had a 90% DL within the range of controlled release rates in Bell et al. and Ilonze et al., respectively. The 90% DLs for the four solutions tested in Ilonze et al. and subsequently the current study showed substantial improvements, though with increased variability, in Ilonze et al., 90% DLs for these solutions ranged from 3.9 to 14.1 kg CH4 hr-1. By the current study, these limits improved, ranging from 0.5 to 19.6 kg CH4 hr-1, with notable gains for solutions F and P. Solution F's 90% DL improved from 6.2 [3.6, 17.4] kg CH4 hr-1 in Ilonze et al. to 0.5 [0.3, 0.6] kg CH4 hr-1 in the current study, while solution P improved from 6.0 [4.1, 11.8] kg CH4 hr-1 to 3.2

[2.2, 5.7] kg CH4 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[7]) for continuous monitoring systems by 0.1 kg CH4 h-1. The EPA regulation requires detecting a fugitive emission of 0.4 kg CH4 hr-1 in the presence of baseline emissions: routine emissions common to most O&G sites. However, the current testing has no baseline emissions.

Localization: Generally, all scanning/imaging solutions indicate higher precision (> 50%) and accuracy (> 40%) at the unit level relative to the PSNs. 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 9, 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 9: Summary of emission source localization (equipment unit) precision and accuracy for all participating solutions arranged in decreasing localization precision equipment unit level.

			Source Localization (Equipment Unit)					
			Precision (%)			**Accuracy (%)**		
Solution ID	**Type**	**Sensor Density (sensor/m^2)**	**Unit Level**	**Group Level**	**Facility Level**	**Unit**	**Group Level or Better**	**Facility Level or Better**
Result from the current study for all participating CM solutions								
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 4 CM solutions that participated in both studies.								
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 4 CM solutions that participated in both studies.								
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

Comparing this study's equipment unit localization to Bell et al. and Ilonze et al., precision and accuracy for solutions tested in the previous studies changed slightly relative to the current stud (<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. The increase in precision and accuracy for 2 of 4 and 2 of 3 solutions relative to Ilonze et al. and Bell et al., respectively, shows that, as a group, the current study's localization precision and accuracy partially improved compared to the two previous studies.

Quantification: In the current study, 11 solutions reported the source emission rate; 8 solutions had $\geq$ 50% of their single estimates within a factor of 3. Overall, the percentage of single emission estimates within a factor of 3 for the 11 solutions ranged from 31 to 92%. The mean relative error in single emission estimates for CRs) between 0.1 and 1 kg CH4 h-1 for two solutions was $\leq$ 35%. For larger CRs) ($> 1\,\mathrm{kg}\,CH_4\,h^{-1}$), the mean relative error in single emission estimates for eight solutions ranged from 3% to 33%Ṡmall emission rates (between 0.1 and 1 kg CH4 hr-1), often associated with component leaks, have consistently high uncertainties for most solutions (9). The larger emissions (> 1 kg CH4 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 CH4 hr-1). Section 8.4 and S10.3 of the SI further provide more information on the quantification accuracies for various solutions.

Figure 8 shows the reported against the actual emission rates for the four retested solutions relative to Ilonze et al.. 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.. 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. 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.

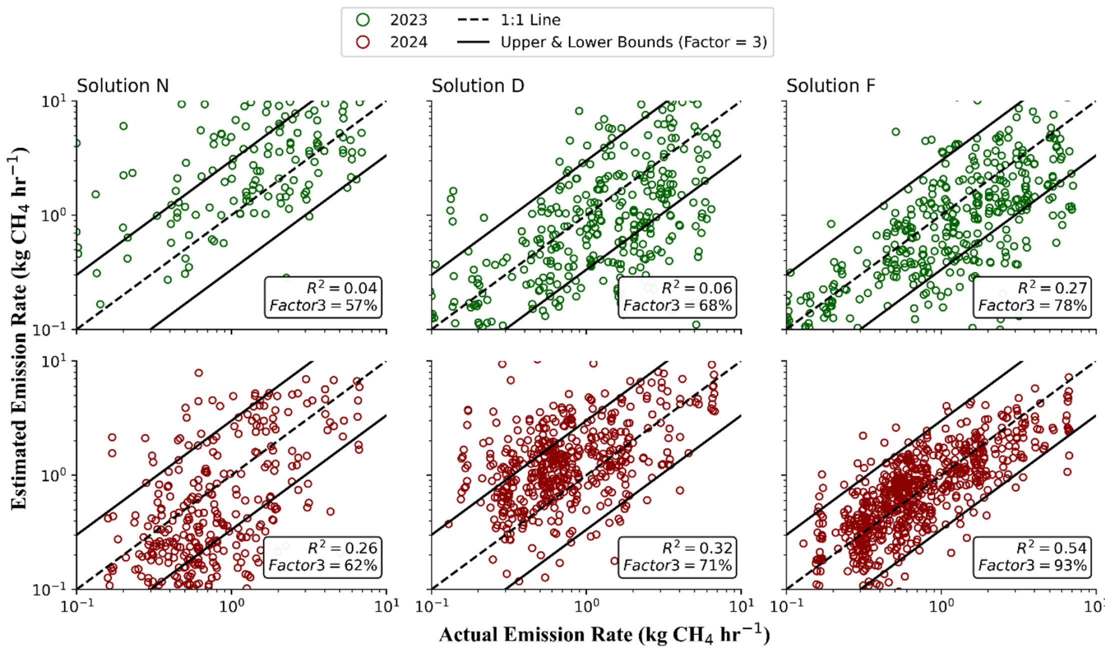

Figure 8: The reported emission rates against the actual (or controlled) emission rate for the three solutions (N, D, and F) that were tested in 2023 by Ilonze et al. and in 2024 (current study). The plots with green points are from 2023 quantification data, while the plots with red points are from quantification 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 R2 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.

Relative to Ilonze et al. and Bell et al., 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. Additionally, the solutions consistently tested in previous studies had the lowest relative quantification errors for small and large leaks. Continued testing of CM solutions throughout the ADED program has consistently shown improved performance at METEC.

4.4 Continuous Monitoring Solution Challenge Releases

4.4.1 Point Sensor Networks Struggle to Detect and Quantify Short Controlled Releases at Oil and Gas Sites (April 2024)

A key selling point of continuous emissions monitoring system (CEM) is rapid detection of large emitters, shortening the time to detect and mitigate, thus reducing total emissions. Therefore, detection performance is a key input to CEM mitigation performance. This study shows that the field campaign POD rate is significantly higher than the POD in controlled test conditions at METEC and indicates that controlled testing may not reflect field conditions accurately. Therefore, new methods are needed to translate controlled testing performance into field conditions. Controlled testing remains essential for characterizing solution performance, but testing in the field provides a more precise depiction of actual use cases of the solutions' performance. Comparatively, the field campaign presented a small number of experiments, relative to METEC testing. This field campaign consisted of roughly 40 days, where the ADED testing periods extended to three months. In this study, results from the ChRs indicate that most solutions, at most sites, do not accurately report the incremental emissions represented by ChRs ranging from 0.2 - 24.1 kg/h. During releases, PSNs reported site-level emission rate estimates of 0 kg/h between 38-86% of the time. When non-zero site-level emission rate estimates were provided, no linear correlation between release rate and reported emission rate estimate was observed. When analysis controls for wind conditions and times when emissions are directly upwind of a sensor, mixing ratio readings when ChRs are active differ from times when ChRs are not active, indicating that a signal exists using current sensor technology. This suggests that point sensors may be sufficient to detect emissions at field sites, but current algorithms seem unable to reliably extract accurate emission rate estimates from the sensor readings. Additional investments in analytics are likely required, although improvements in sensing technologies may also be necessary.

Probability of Detection: None of the solutions achieved a 90% POD across the range of ChRs conducted, as shown in Figure 9. Implementing the METEC POD framework to the field campaign results in substantially reduced performance at operational sites when comparing the same solutions' METEC POD curves. One variance in test method between METEC and the field campaign that may have affected results was the number of sensors per area. Each solution that participated in METEC testing deployed more sensors per acre at METEC than at any location in the field campaign. This leads to increased "blind-spots" in the field deployments where a ChR may disperse between sensors and not transect any sensor location downwind for the duration of the experiment. While this implies a lower POD, and our field results confirm, it is important to recognize the ChR in this study were relatively short in duration (0-4 hours) and a CM solution performance may improve given longer opportunities to detect where the wind may have increased directional variability. However, controlled releases at METEC were generally of similar duration, with the large majority lasting between 0-4 hrs.

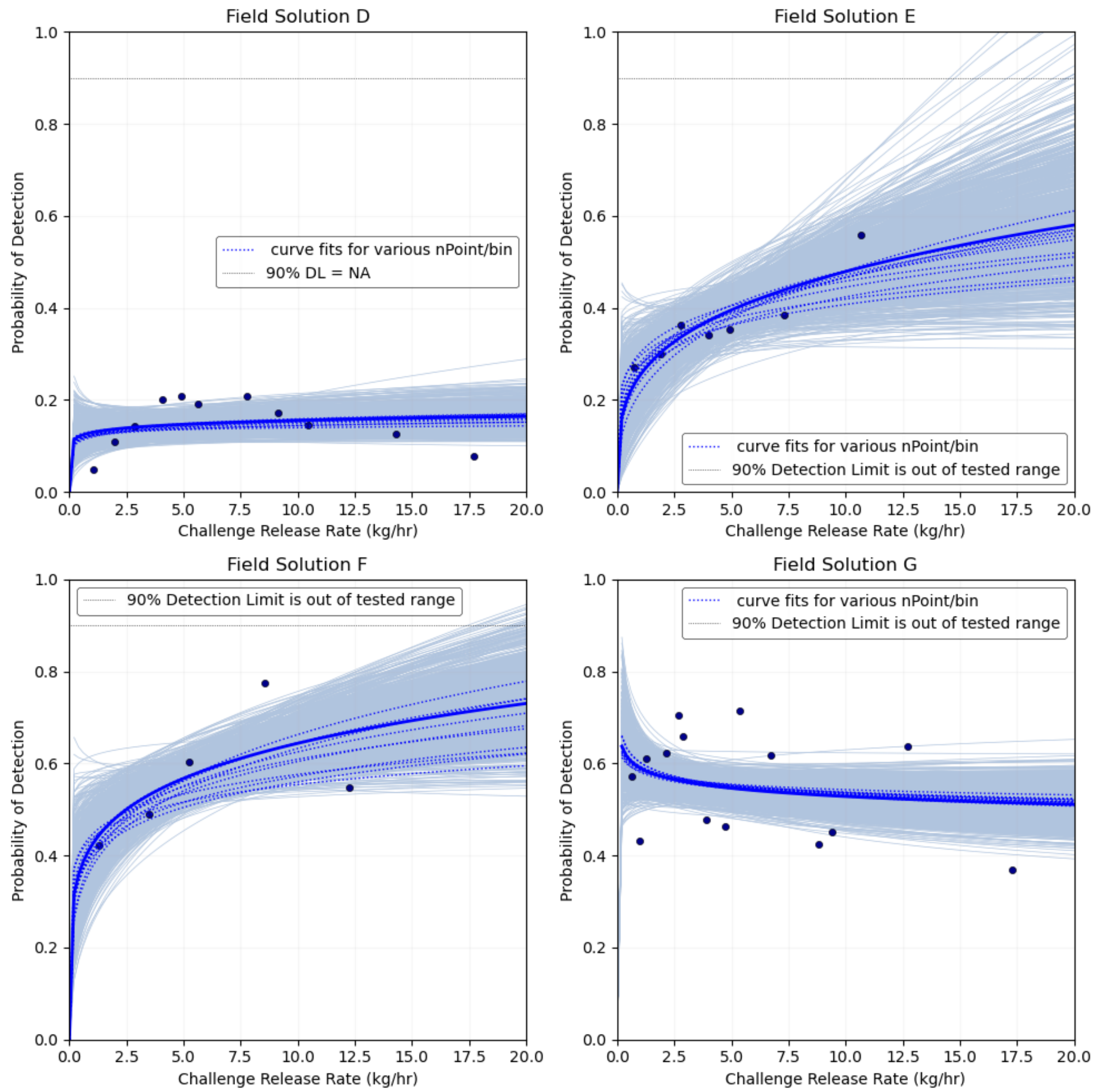

Figure 9: Probability of detection as a power curve function of site rate estimates during ChRs for the four solutions with emission rate estimates during all deployments. The definition of detection, or a TP_{POD} reading, for the field campaign includes any estimate above 0 kg/h for solutions D, E, and G. As solution F does not have any 0 kg/h estimates, the definition of detection is any estimate above 2.23 kg/h, the BL site rate estimate, see *Methods*.

Mixing Ratio Results: The poor relationship between ChRs and detections may be driven by multiple factors which may also vary between solutions. However, a successful detection for any solution would require two sequential events to be true: (a) the solution's sensor must respond to the ChR with increased readings, and (b) the solution's algorithms must identify a detection by successfully analyzing the sensor data. We analyze (a) by reviewing time series of mixing ratio data as per Equations 8 and 9. From site-solution combinations that provided reviewable mixing ratio data, sensors downwind averaged 5% of readings indicating enhancements greater than $2\sigma_{X_{\mathrm{NR},i,j}}$, while sensors upwind averaged 1% of readings indicating enhancements. Since sensors were $\approx$ 100 meters from the ChR emission sources, the low 5% enhancement rate observed during ChRs is unsurprising, given the instability of transport in near-field dispersion. These data indicate the presence of a signal at the sensors, and therefore the presence of information which could potentially identify controlled releases. Figure 10 provides an example of the enhancement analysis, showing sensor activity with respect to the ChR rates, under ideal and non-ideal wind conditions.

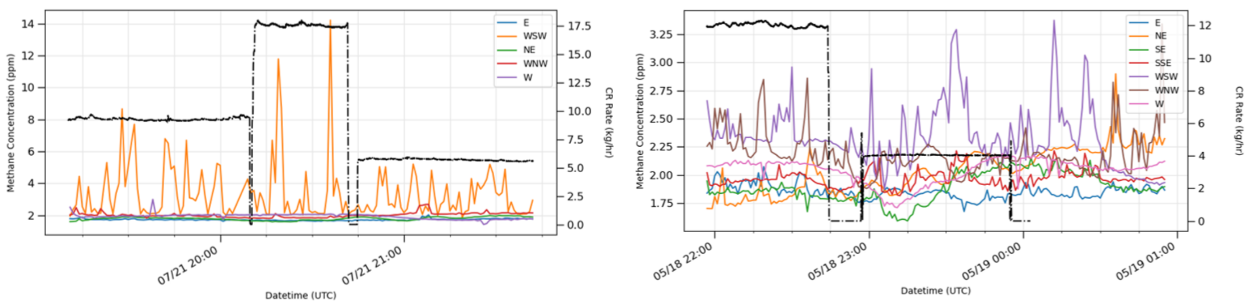

Figure 10: Solution C's mixing ratio estimates in comparison with the ChR rates at Site 1. The black dashed line shows the ChR rate and the colored lines are mixing ratio measurements from the point sensors at the site. The left panel illustrates a period with wind from the NW and the closest downwind WSW sensor measuring peak mixing ratios that increase and decrease with the ChR rate. Other sensors which are not downwind of the ChR show little response. Right plot shows the same solution at Site 1, with the wind direction moving through a section with no sensors. Mixing ratio enhancements are therefore not present in any sensor, and variability in sensor mixing ratio is random or associated with routine operational emission sources at the site.

These qualitative results suggest that algorithms may need to consider multiple wind transport parameters to know when mixing ratio enhancements are likely to occur, over what upwind angle, at what intensity, and may need to modify both detection and quantification algorithms to match meteorological conditions. For conditions outside of operable parameters, observations are unlikely to be indicative of emissions, and may need to be discarded. This would result in fewer emission reports of higher accuracy than data provided by algorithms at the time of testing.

Quantification: While the study design was primarily intended to evaluate detection and alerting of unintentional emission sources using ChRs, many solutions are now attempting to provide site-level, time resolved emission rate estimates. The Final Methane Rule allows CM solutions to be implemented by operators as an alternative means for fugitive emission detection using site-level emission rate based action limits. The rule specifies action levels for sites with major production and processing equipment, centralized facilities, and compressor stations as a deviation of 1.6 kg/h in a 90 day rolling average and a deviation of 21 kg/h in a 7 day rolling average above a site-specific baseline. These averages need to be coming from solutions with equal abilities of accuracy in order to provide accurate results. In Table 10, we present the percentages of non-zero emission estimates falling within a range of $\pm$ 2.5 kg/h of the study onsite estimate (SOE). Note, the band of $\pm$ 2.5 kg/h is greater than the action level defined in the EPA OOOOb NSPS, indicating that solutions may not currently be capable of providing data with high enough precision to make the rule effective. The estimates in the table are not rolling averages, but individual estimates, so their ability could improve with prolonged averaging at facilities.

Table 10: Percent of emission estimates within ± 2.5 kg/h of ChRs and BLs.

Emission Estimates within ± 2.5 kg/h

	Site Type	*(D)*	*(E)*	*(F)*	*(G)*
Site 1	Production	2%	1%	36%	7%
Site 2	Production				41%
Site 3	Production				0.2%
Site 4	Production				39%
Site 5	Production				36%
Site 6	Compressor		1%		27%
Site 7	Gas plant		1%		
Site 8	Compressor		6%		25%
Site 9	Compressor	6%			5%
Site 10	Production	0%			0%
Site 11	Production	0%			8%

The infrequent alignment of solution estimates within the bounding range and frequent reports of no emissions suggests underlying issues with their estimation accuracy. Table 11 shows the mean relative error for nearly all solutions at nearly all facilities is negative, indicating emission estimates during ChRs were consistently biased low, i.e. a smaller incremental increase above BL was observed during a ChR than the release rate of the ChR. These are the same results that have been presented about estimates from the Greenhouse Gas Reporting Program (GHGRP) with current emission factor reporting.

Table 11: Relative error between the individual emission estimates and the SOE. Only periods during ChRs are included in the figure. No NR periods (ChR = 0) are included. The percentage is the average relative error for individual site-level emission estimates for each solution.

Emission Estimate Relative Error

	Site Type	*D*	*E*	*F*	*G*
Site 1	Production	-32%	-43%	-25%	-47%
Site 2	Production				-41%
Site 3	Production				-54%
Site 4	Production				-52%
Site 5	Production				430%
Site 6	Compressor		-100%		-64%
Site 7	Gas plant		-88%		
Site 8	Compressor		-46%		-72%
Site 9	Compressor	-56%			-10%
Site 10	Production	24%			-99%
Site 11	Production	-100%			-84%
Mean Error		**-35%**	**-70%**	**-25%**	**-51%**

The field campaign brought to light larger differences than anticipated between field sites and the METEC site. Difference in data input and solution installation were some of the many variances seen between the two testing environments. Seemingly when a sensor is directly downwind of a release under ideal wind conditions, a detection in the form of concentration can be provided. Furthering that concentration into a quantification value appears to provide more of an issue, especially under non-ideal conditions. Although the results were not able to be analyzed following the intended CM protocol, the results provided a forward pat for changes to be made to the protocol and the METEC facility to align with the changes in the methane emission monitoring space over the last decade. Advancing the knowledge around the unknowns helps layout the pathway for where to improve in future testing. Improvement has been seen across all of the methane monitoring solution types testing at METEC and expanding the testing even further will continue to advance the benefits already seen with these strategies of monitoring.

5 FUTURE WORK

With the finalization of the ADED program, many tasks and action items are being set into place to continue the knowledge and advancement of emission monitoring and measurement technologies. As previously mentioned in this report, the advancement of equipment across O&G fields has created changes to some of their infrastructure, requiring a different environment to representatively conduct testing at METEC. The infrastructure modifications create possible new emission locations potentially creating different effects to the dispersion of emission plumes. To follow along side these advancements, the METEC team is currently in the process of construction on a new METEC 2.0 facility. The METEC 2.0 facility will advance testing capabilities by bringing in newer equipment pieces to update release point options and expand on under pipeline testing. Alongside the physical upgrades to the METEC facility, revisions to the testing protocol will allow testing techniques to be more inline with emission profiles of operating O&G facilities. Over the last year, the METEC team has been leading an advisory board with stakeholders on the revisions to the protocol. This collaboration has assisted in production of the revised protocol draft that went out for review by the board in January 2025. The finalized protocol will be run in the METEC team's first round of testing in Spring 2025.

International facilities have also been a part of this protocol process, and the goal is to have facilities running the same protocols and producing the same level of data globally. The METEC team has been in collaboration with TotalEnergies in France on these revisions and plan to implement this protocol testing there in the near future. Discussions around the protocol have also been occurring with the Alberta Methane Emissions Program, as well as with the Southeast Asia Methane Emissions Technology Evaluation Centre at INSTEP in Malaysia. Furthering this work is funded as apart of DE-FE0032276.

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