Appalachian Methane Initiative 2023

Multi-scale Methane Measurements in the Appalachian Basin: A Pilot Study

Prepared for:
The Appalachian Methane Initiative

Prepared by:

Matthew Harrison, Tecle Rufael
SLR International Corporation

Contributors:

Arvind P. Ravikumar, Shannon Stokes, Lyra Wang, Eldar Sharafutdinov, Shuting Yang
The University of Texas at Austin

March 19, 2024

DISCLAIMER

The conclusions presented in this report are those of SLR International and not the members of the Appalachian Methane Initiative. AMI member companies were afforded an opportunity to review to confirm no confidential information was disclosed and the reader could not attribute data to any one operator. Furthermore, AMI has expanded membership, and only those members covered in the 2023 report were afforded the opportunity to review this report.

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Executive Summary

This report summarizes results from the pilot study of a multi-scale methane emissions measurement campaign of the **Appalachian Methane Initiative** (AMI) for 2023. The AMI coalition in 2023 consists of four upstream and midstream oil and gas operators with assets in the Appalachian Basin. It was formed with the objective of developing a collective approach to methane emissions detection, quantification, and mitigation across the major gas-producing areas of the Appalachian Basin. Such a collective approach would theoretically provide logistical and cost advantages by enabling joint mobilization of resources and deployment of methane measurement technology across the Basin.

The goals of AMI are three-fold: to accurately measure facility-level emissions of AMI member companies, to accurately compare methane emissions across oil and gas facilities in the areas where AMI members operate, and to accurately assess the contribution of different facility types in the Appalachian Basin (coal mines, landfills, and Concentrated Animal Feeding Operations (CAFOs)) to total methane emissions.

Given the distribution of the AMI coalition members, the pilot measurement campaign was divided into two pilot regions – the southwest pilot region and the northeast pilot region as shown in Figure E1. In total, the pilot regions comprise 593 oil and gas facilities (AMI and non-AMI), 14 coal mine operations, 4 CAFOs, and 3 landfills.

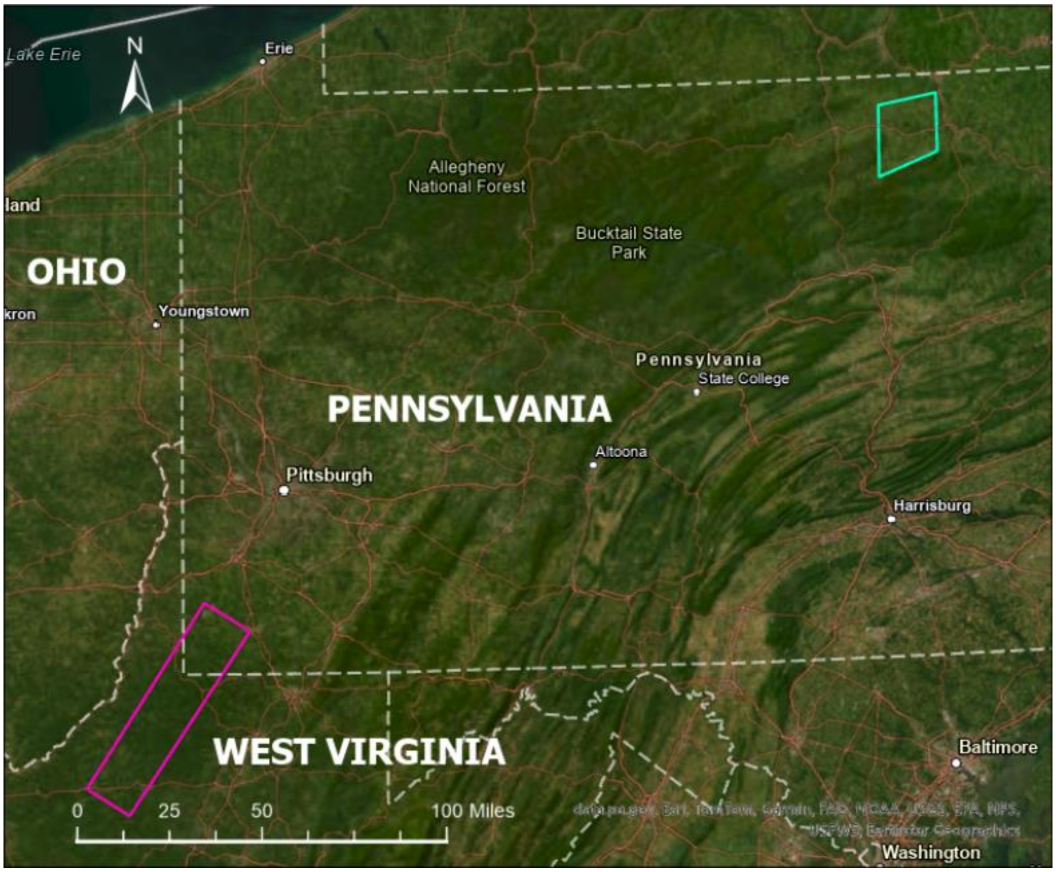

Figure E1: Google earth image of the two pilot regions for the Appalachian Methane Initiative field campaign in 2023.

The pilot measurement campaign had three survey periods one each in Q2, Q3, and Q4 of 2023. These included facility-level measurements using aerial surveys by Bridger Photonics during each of the three quarters, regional mass balance measurements and raster scan for hotspot detection using flyovers by ChampionX in Q3, and continuous monitoring systems deployed on select AMI member facilities. Bridger Photonics provided equipment-level detection and quantification of methane emissions, along with visual plume imagery for follow up by the facilities operated by AMI members. ChampionX provided both regional emissions estimates through mass-balance measurements and select facility-level emissions estimates identified during the raster scan of both pilot regions.

A key aspect of the AMI pilot program is that access to data collected by all technologies were provided directly to the scientific team for analysis – the operators did not play any role in the development of models or analysis of measurement data, except as requested by the scientific team. These requests were based on the scientific needs of the project, including the development of models that incorporated operational data. The Energy Emissions Modeling and Data Lab, or EEMDL, at the University of Texas at Austin, supported by SLR International, led the scientific analysis on the AMI pilot project. EEMDL is a consortium of leading methane emissions measurement and analysis experts from three universities – the University of Texas at Austin, Colorado State University, and Colorado School of Mines.

The key findings of the AMI 2023 pilot program are highlighted in the shaded boxes with the corresponding main results summarized in charts and text below. Reported results in this executive summary correspond to as-measured emissions by Bridger Photonics across both oil and gas and non-oil and gas facilities. Models to incorporate the frequency of emissions to develop measurement-informed inventory estimates are in development. Details on each quarter of measurements are discussed throughout the main text of this report.

Finding 1: Non-oil and gas sources are the largest contributors to total methane emissions within the pilot regions, with contributions varying between 53% and 76%. Of these, the largest contributors are coal mines and coal mine vents.

Figure E2 shows the total emissions from major facility types across both the southwest and northeast regions covered by the AMI pilot program for each of the three quarters of measurement. The contribution of non-oil and gas facilities to total emissions ranged from a low of 53% in Q3 2023 to a high of 76% in Q2 2023. The largest single contributor to total emissions is associated with coal mine operations – either coal mine vents or direct emissions from the mine. Individual emitters from coal mine vents exhibited emissions over 5000 kg/h, orders of magnitude higher than the highest emission from oil and gas sources. Significant temporal variability is also observed in both coal mine and oil and gas emissions. For example, Q2 2023 had the lowest total oil and gas methane emissions around 3200 kg/h which increased to over 4000 kg/h in Q3 and over 6000 kg/h in Q4 2023.

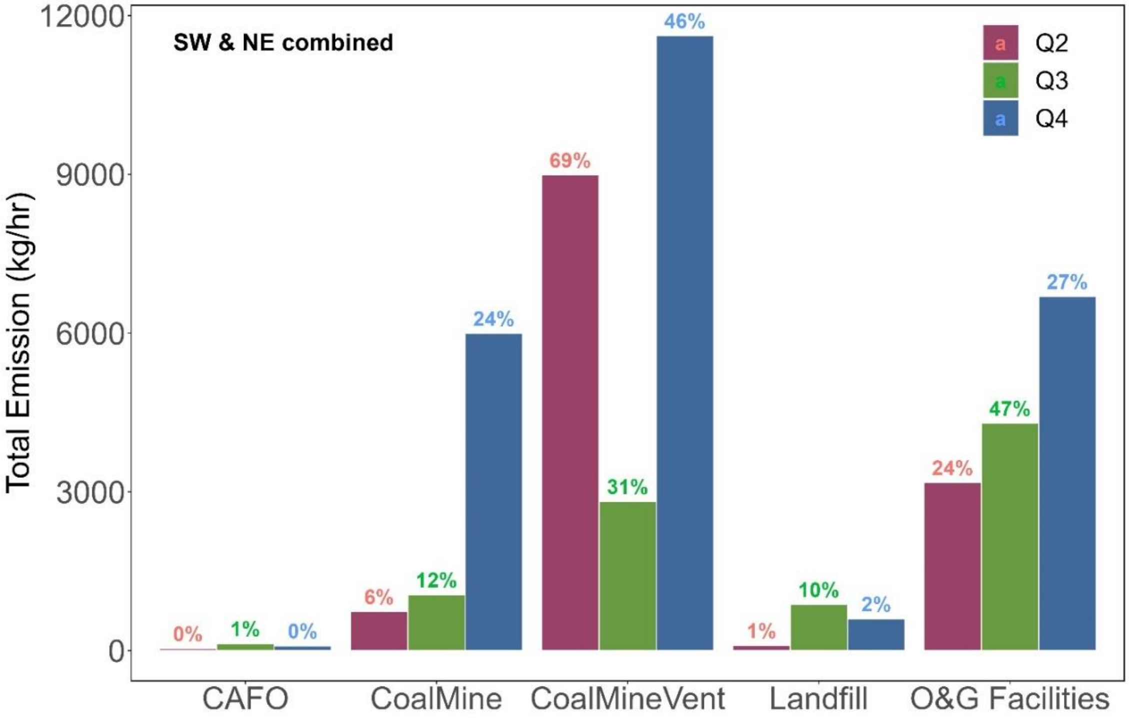

Figure E2: Total methane emissions by Bridger across the southwest and northeast region covered by the AMI pilot program showing relative contributions from different facility types for Q2 (purple), Q3 (green), and Q4 (blue) surveys. The contribution from each facility type to total emissions during that survey is shown as a percentage above the bars.

Finding 2: Across most equipment types, no statistically significant difference in leaker emissions factors were found between AMI and non-AMI facilities. Tanks and compressors tend to exhibit higher emissions factors than other types of equipment.

Figure E3 shows equipment-level leaker emission factors for AMI and non-AMI member companies for each of the three surveys. Leaker emission factors refer to the average emission rate per emitting equipment as measured by Bridger Photonics. Note, the leaker emission factor is a commonly used term by US EPA and can include both true leaks and vents. Similar equipment from the southwest and northeast pilot regions are aggregated to preserve operator anonymization of the AMI members. Although emissions varied during each survey, most equipment did not exhibit statistically significant differences in leaker emissions factor between AMI and non-AMI facilities.

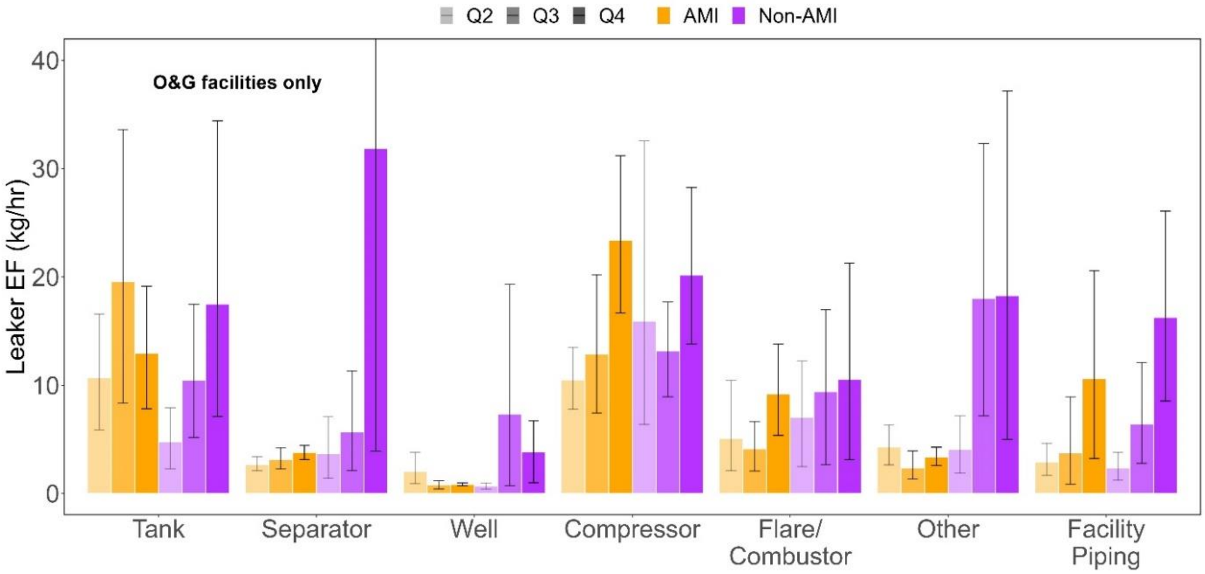

Figure E3: Equipment-level leaker emission factor for AMI and non-AMI facilities across both southwest (shades of yellow) and northeast (shades of purple) pilot region across the three surveys – Q2 (light shade), Q3 (medium shade), and Q4 (dark shade).

Finding 3: Site-level methane emissions estimate in the Appalachian Basin represents the low end of the range of estimates found in other basins in recent peer-reviewed literature. The Appalachian Basin also exhibits significant spatio-temporal variability in emissions.

Table E1 shows a comparison of the emission rates defined by site-level emission rate corresponding to 50% of total emissions measured in the AMI pilot study compared to estimates from other basins in recent peer-reviewed literature. The numbers across different basins are not directly comparable in that they have all been obtained using different methods, technologies, models, and interpretation. However, they provide an effective approach to compare typical emissions estimated across different basins, thus providing a qualitative understanding of basin-level emissions characteristics.

We find that the as-found site-level methane emissions corresponding to 50% of total emissions in the Appalachian Basin represents the low end of the range of estimates found in other basins. The range of estimates – from 90 – 160 kg/h – represents surveys across different seasons and sub-basins of the Appalachian Basin, indicating significant spatio-temporal variability in emissions. Differences in emissions rate across sub-basins of the Applachian Basin can be partly attributed to differences in resource characteristics. The northeast pilot region is a dry gas play while the southwest pilot region has significant natural gas liquids production. Such spatio-temporal variability has been observed previously in other large-scale, periodic measurements of oil and gas basins in the US and Canada. In comparison, a recent comprehensive survey involving nearly one million site-level measurements reveal significantly higher site-level emission corresponding to 50% of total emissions across several basin in the United States.

Specifically, site-level methane emissions that correspond to 50% of total emissions in the Permian Basin have ranged from 100 to 300 kg/h, with a long super-emitter tail.

Table E1: Comparison of the site-level emission rate corresponding to 50% of total emissions in the AMI 2023 pilot study with other peer-reviewed literature. A range is provided for those studies that conducted multiple surveys over the same region.

Table E1: Comparison of the site-level emission rate corresponding to 50% of total emissions in the AMI 2023 pilot study with other peer-reviewed literature.

STUDY	BASIN	MEDIAN EMISSION RATE* (KG/H)
AMI 2023 pilot	Appalachian Basin	90 – 160 kg/h
Sherwin et al. (2024)[1]	Permian Basin	~ 100 – 300 kg/h
	Denver-Julesburg Basin**	~ 10 kg/h
	San Joaquin Basin	~ 20 – 300 kg/h
	Fort Worth (Barnett) Basin	~ 200 kg/h
Chen et al. (2022)[2]	Permian Basin	~ 310 kg/h

** Site-level emission rate corresponding to 50% of total emissions for this study is shown as a range representing the minimum and maximum emissions factors observed in any of the surveys in 2023 across all assets (including upstream and midstream).*

***>80% of emissions were modeled because of high detection threshold of the measuring instrument.*

Finding 4: Operational information is critical to developing accurate measurement-informed emissions inventories and reconciling measurements with inventory estimates.

Operational data, including root cause analysis, provided by AMI members have been critical to appropriately interpreting measurement information. Some examples of the use of operational

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[1] Sherwin et al. (2024). US oil and gas system emissions from nearly one million aerial site measurements. *Nature*. 627, 328. https://doi.org/10.1038/s41586-024-07117-5

[2] Chen et al. (2023). Quantifying Regional Methane Emissions in the New Mexico Permian Basin with a Comprehensive Aerial Survey. *Environ. Sci. Tech.* 56, 4317. https://pubs.acs.org/doi/full/10.1021/acs.est.1c06458

data include the following: (1) correcting errors made by measurement systems on attribution to individual equipment or site, (2) developing boundary conditions for duration of large methane emissions sources to appropriately account for in a measurement-informed inventory framework; (3) identifying whether aerial observations constitute ‘normal’ operating conditions for the facility and therefore indicate potentially large fugitive sources; and (4) attributing aerial observations to one-off maintenance activities, other one-time emission events, or known intermittent emissions. Timely availability of operational data is crucial to the development of accurate measurement-informed emissions inventories. Without the use of operational information, the risks of inaccurate emissions estimation (either underestimation or overestimation) are high.

An example of the use of operational data is described in this report. The measurement informed inventory model integrates Bridger observations with operational data such as a log of maintenance activities or leak detection and repair surveys to develop facility-level, annualized estimates of methane emissions. Thus, when Bridger identifies a large emission from a tank, the model scales that instantaneous emission rate by the frequency and duration of the emission source. Such distributions of the frequency and duration of emissions are developed for each major equipment category to create a measurement-informed inventory estimate.

Finding 5: Coal mines and coal mine vents comprise the majority of large release events Furthermore, coal mines exhibited significant variation in emissions across three surveys.

Figure E4 shows all the large release events detected during the three quarters of surveys across all facility types. Large release events are defined as an instantaneous emission rate of over 100 kg/h as measured by Bridger Photonics. The 100 kg/h threshold corresponds to the definition of large releases in the super-emitter program finalized as part of the US Environmental Protection Agency’s methane rule. Coal mines and coal mine vents are the two most common sources of large emissions across the pilot phase, with individual emission rates exceeding 6000 kg/h. Furthermore, these emission rates vary significantly over time – for example, coal mine vent #6 exhibited emissions lower than 1000 kg/h in Q2 but was over 6000 kg/h in Q3. In each survey, only a few large release events were identified at oil and gas facilities. However, most of these events at oil and gas facilities were below about 200 kg/h and were often found on tanks and compressors.

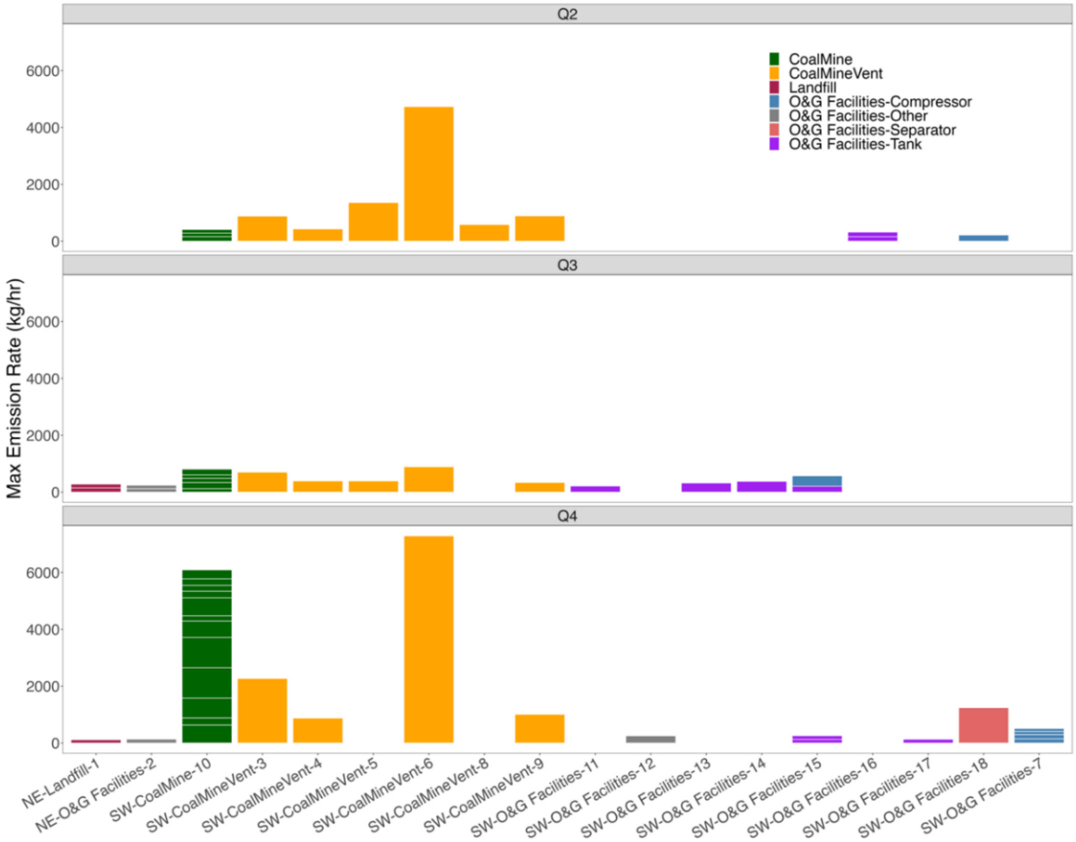

Figure E4: Emissions rates and site types associated with large release events (events with instantaneous emission rate > 100 kg/h) across the three surveys in 2023. All facilities that had a large emission event during one of the three surveys are included in the figure and vertically aligned and provide visual information on temporal variation in emissions.

Finding 6: Intermittency and variability are defining characteristics for oil and gas and non-oil and gas emissions, respectively.

Temporal variation in methane emissions from oil and gas equipment and facilities have been well established in the scientific literature. The AMI pilot study found that only a small number of equipment are found emitting during any survey. For example, only 5% of tanks on AMI member companies' facilities were found emitting in each of the three Bridger surveys. Similarly, only 1% of wells had any detectable emissions during Bridger surveys in each of the three quarters. These observations underscore the importance of accounting for the frequency and duration of intermittent emission events in developing an accurate measurement-informed emissions inventory that could then be reconciled with reported inventory estimates. Unlike oil and gas emissions, nearly all the coal mine related sources were found to be emitting methane in the three Bridger surveys. However, the emission rate from coal mine vents varied significantly across surveys – 3,000 kg/h in Q3 to nearly 12,000 kg/h in Q4 2023. Given the large magnitude of coal mine emissions compared to other sources, such variability poses significant challenges in attributing regional top-down emissions estimates such as those provided by satellites to different source categories. Furthermore, any reconciliation exercise between non-satellite technologies (e.g., aerial surveys, drone surveys, etc.) and satellite data would require quantitative information on the variability in coal mine methane emissions. Improved characterization of the magnitude and variability in coal mine related emissions is needed for effective attribution of satellite observations to emission sources.

1.0 Introduction

Addressing methane emissions from oil and gas supply chains is a key component of global action on climate. Supplying natural gas with the lowest embedded greenhouse gas emissions will have significant regulatory and market advantages, both for domestic customers and international buyers of US liquefied natural gas (LNG). Over the past year, several regulatory and voluntary initiatives have accelerated the need for accurate, site-specific, and measurement-based emissions information. The US Environmental Protection Agency (EPA) finalized methane regulations that allow the use of new technology in conventional leak detection and repair (LDAR) surveys [3]. The EPA has also proposed updates to the methane emissions reporting program – subpart-W of the Greenhouse Gas Reporting Program (GHGRP) [4]. These updated emissions inventories will be used to evaluate the Waste Emissions Charge (WEC) or methane fee liabilities of oil and gas operators as specified in the Inflation Reduction Act. In parallel, oil and gas companies have announced participation in voluntary initiatives such as the oil and gas methane partnership (OGMP 2.0) and MiQ certification that require accurate, asset-level, measurement-informed emissions estimates [5,6]. Furthermore, many of the voluntary initiatives also require that bottom-up emissions estimates are reconciled with top-down measurements [7,8]. An emerging ecosystem of oil and gas operators, financial organizations, government agencies, utilities, and other stakeholders have coalesced around the idea of differentiated natural gas where gas supply chains with verifiable low methane emissions could achieve expanded market access or higher price as a result of its lower emissions[9].

The past several years has seen significant advances in our understanding of methane emissions. Recent multi-scale measurements revealed the critical role of temporal variability in methane emissions in enabling effective reconciliation across technologies and with inventory estimates [10,11]. Multi-scale measurements at midstream compressor stations identified conditions under which commonly used aerial measurements statistically disagree in their quantification of whole site emissions estimates [12,13]. The accuracy of extrapolating aerial measurements to basin-wide emissions intensity estimates strongly depends on accurate

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[3] US Environmental Protection Agency (2023). Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review. 40 CFR Part 60.

[4] US Environmental Protection Agency (2023). Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems. 88 Fed. Reg. 50282.

[5] Oil and Gas Methane Partnership 2.0. https://ogmpartnership.com/

[6] The MiQ Standard. https://miq.org/the-technical-standard/

[7] Rutherford et al. (2021). Closing the methane gap in US oil and natural gas production emissions inventories. *Nat. Commun.* 12, 4715.

[8] Gas Technology Institute (2022). GTI Veritas protocols. https://veritas.gti.energy/

[9] Ravikumar et al. (2023). Measurement-based differentiation of low-emission global natural gas supply chains. *Nat. Energy* 8, 1174. https://www.nature.com/articles/s41560-023-01381-x

[10] Wang et al. (2022). Multiscale Methane Measurements at Oil and Gas Facilities Reveal Necessary Frameworks for Improved Emissions Accounting. *Environ. Sci. Tech.* 56, 14743.

[11] Daniels et al. (2023). Toward Multiscale Measurement-Informed Methane Inventories: Reconciling Bottom-Up Site-Level Inventories with Top-Down Measurements Using Continuous Monitoring Systems. *Environ. Sci. Tech.* 57, 11823.

[12] Brown et al. (2023). Informing Methane Emissions Inventories Using Facility Aerial Measurements at Midstream Natural Gas Facilities. *Environ. Sci. Tech.* 57, 14539.

[13] Brown et al. (2023). Evaluating development of empirical estimates using two top-down methods at midstream natural gas facilities. Pre-print, ChemrXiv. https://chemrxiv.org/engage/chemrxiv/article-details/652712ca45aaa5fdbbcc6934

accounting of maintenance activities [14]. These studies collectively underscore the importance of several factors in developing accurate measurement-informed emissions inventory estimates. These include (i) appropriate accounting for the frequency and duration of intermittent emission events, (ii) reconciling aerial observations with operational information including records of maintenance activities, (iii) developing estimates for unmeasured emission sources, and (iv) careful attribution of aerial observations to operational states at time of measurement including processes, equipment, and events.

The **Appalachian Methane Initiative,** or AMI, consists of several upstream and midstream oil and gas operators with assets in the Appalachian Basin [15]. The AMI coalition was formed to publicly demonstrate, through measurements and transparent reporting, the commitment of the natural gas industry in the Appalachian Basin in tackling methane emissions associated with oil and gas operations. Furthermore, such a coalition would also present logistical and cost advantages by enabling joint mobilization of resources and deployment of technology vendors to conduct multi-scale measurement campaigns.

The goals of AMI are three-fold:

1. Develop accurate facility-level, measurement-informed emissions information for oil and gas facilities using multi-scale measurements.
2. Develop accurate and consistent comparisons of methane emissions from AMI and non-AMI member companies.
3. Develop accurate estimates of the contribution of different sources of methane emissions in the region, including coal mines, landfills, and CAFO operations.

These AMI goals were translated into the following four project objectives:

1. Develop facility-level, measurement-informed emissions inventory estimates that account for intermittency, below detection threshold emissions, and one-time emissions events such as those arising from maintenance activities.
2. Reconcile emissions estimates from multiple technologies through statistical modeling, operator root-cause analysis, and measurement data.
3. Reconcile measurement-informed emissions inventory with operator reported emissions inventory estimates (e.g., EPA greenhouse gas reporting program).
4. Identify minimum operational data required to reasonably estimate measurement-informed emissions inventories.

This report summarizes the results of the measurement campaign from the 2023 pilot program. It discusses insights from the multi-scale measurements, identifies differences across surveys, and provides aggregate analyses of methane emissions from different facility types in the two pilot areas in the Appalachian Basin. While models to estimate facility-level emissions estimates are complete, these are not presented in this report to preserve anonymization. However, operator-specific measurement-informed emissions inventories have been discussed with each individual operator through other modes of engagement. An example of the use of such models is presented in the results section.

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[14] Zimmerle et al. (2023). Unaddressed Uncertainties When Scaling Regional Aircraft Emissions Surveys to Basin Emission Estimates. Pre-print, ChemrXiv. https://chemrxiv.org/engage/chemrxiv/article-details/653d69a948dad231209b07f6

[15] See https://www.businesswire.com/news/home/20230111005195/en/Leading-U.S.-Natural-Gas-Companies-Establish-Appalachian-Methane-Initiative

This report is divided into four sections. Section 1 is this introduction that provides an overview of the project. Section 2 provides details on the measurements, technologies, and analysis protocols used in the pilot program. Specifically, it includes a description of the anonymization and aggregation protocols used to present results across the selected pilot regions in this report. Section 3 provides anonymized results of the measurement campaign from the three surveys conducted in 2023. Section 4 summarizes lessons from the 2023 campaign and provides recommendations for future measurements.

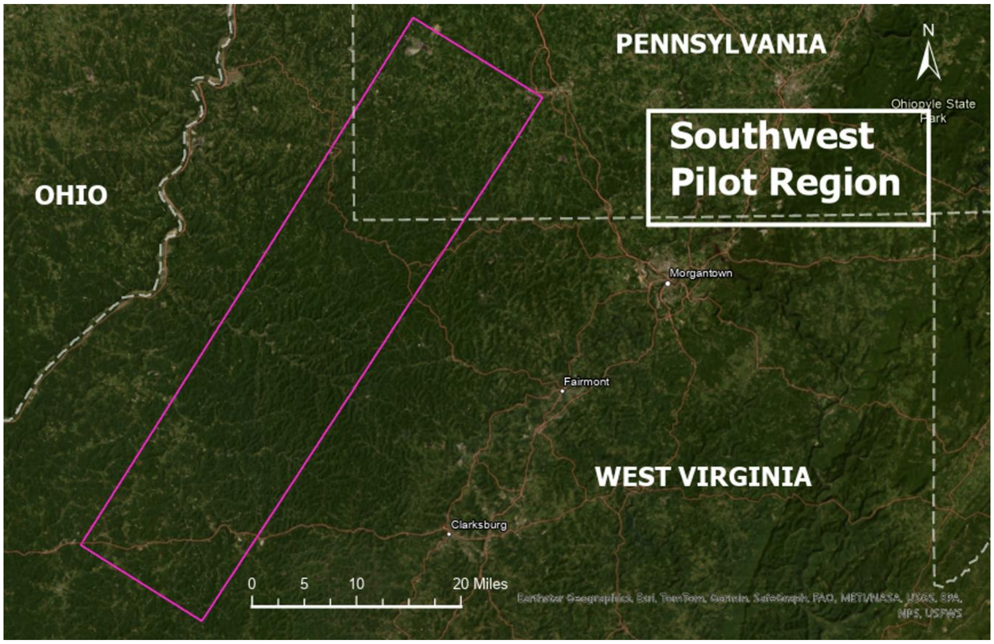
2.0 Measurements and Methods

2.1 Site Selection

Following a comprehensive scoping plan involving EEMDL researchers, SLR, and AMI members, two pilot regions – one in the southwest and one in the northeast of the primary gas-producing regions of the Appalachian Basin – were selected for conducting pilot measurements. Several conditions were imposed on the pilot regions as follows:

1. It should include a representative number of facilities of each of the AMI members.
2. It should include a representative number of facilities of non-AMI members.
3. It should include common non-oil and gas facilities in the region including CAFOs, coal mines, coal mine vents, and landfills.
4. It should encompass a compact geographic region to enable regional mass balance measurements.

Figure 2-1 shows the two pilot regions for the AMI 2023 campaign where different O&G and non-O&G facility types were surveyed. Overall, the southwest pilot region consisted of 425 oil and gas facilities (AMI and non-AMI), 14 coal mine operations, and 1 landfill. The northeast pilot region consisted of 168 oil and gas facilities (AMI and non-AMI), 4 CAFOs, and 2 landfills.



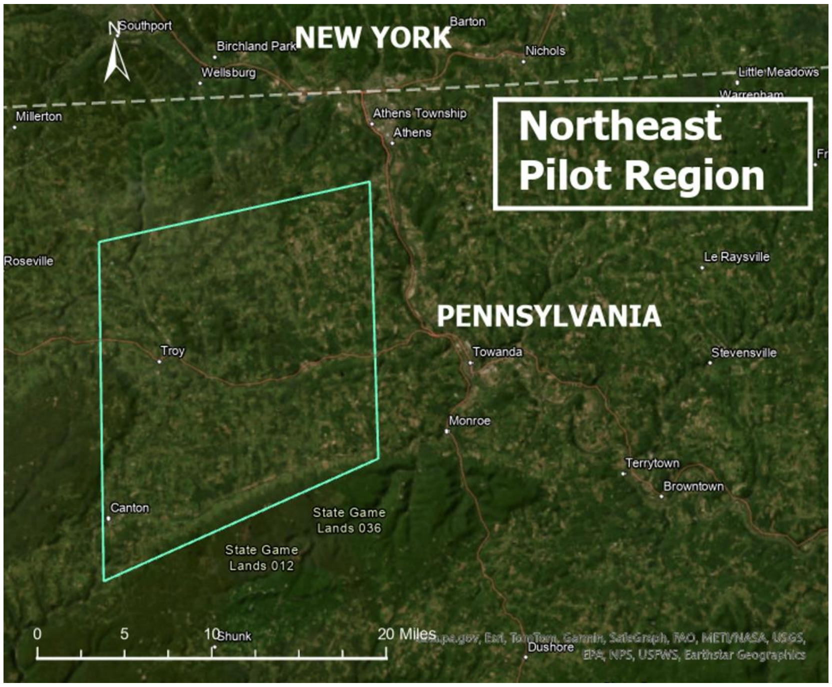


Figure 2-1: Google earth image of the southwest (top) and the northeast (bottom) pilot region for the Appalachian Methane Initiative field campaign in 2023.

2.2 Measurement Technologies

AMI is designed to be technology-agnostic – the AMI companies worked with the EEMDL science team and SLR to evaluate all commercially available technologies and choose those that best fit the goals of the pilot project. For the 2023 pilot campaign, three measurement technologies were deployed as part of the AMI 2023 pilot campaign. These included three surveys of facility-level measurements using Bridger Photonics, one survey of regional mass balance measurements using ChampionX, and continuous monitoring systems that were pre-deployed on select facilities.

2.2.1 Bridger Photonics

Bridger Photonics gas mapping LIDAR uses a downward looking laser system that sweeps perpendicularly across the direction of flight of an aircraft and calculates a path-integrated methane concentration (ppm-m) from the aircraft to the ground. Bridger's technology is based on frequency modulated continuous-wave LIDAR. This system detects concentrated (point source) emissions that produce sufficient imaging contrast to separate the emissions plume from background methane concentrations. This method utilizes wind data to compute emissions rate from the plume image (i.e., concentration) data. Bridger obtains meteorological data from nearby weather station(s); they do not install an anemometer on the facility. The accuracy of the measurement relies on assumptions about the height of the source as very tall sources where the distance between the source and the ground is a non-negligible fraction of the distance between the aircraft and the ground may pose additional challenges to quantification.

Bridger also collects high-definition aerial photos and superimposes colorized pixels to represent plume data on the photos to provide context for the detections. Mounted on appropriate aircraft, Bridger typically scans dozens of sites daily. The number of passes over each site depends on the physical footprint of the site. Larger sites may require more than a single pass – thus, some equipment on these sites may be scanned multiple times during each visit where the scan swath overlaps. Therefore, detected emitters may have multiple 'plumes' and multiple emissions rate estimates, depending on the number of passes.

Bridger technology has been extensively tested through controlled release tests that have been published in peer-reviewed literature [16,17,18]. For the aircraft-based system used in the AMI pilot program, the detection threshold varies between 1 and 3 kg/h. However, the exact value of the detection threshold depends on local atmospheric conditions. Recent studies have developed methods to estimate deployment invariant probability of detection that helps minimize uncertainty around below detection threshold emissions [19].

Initial results that provide indication of detected emissions including preliminary safety reports with visual results and concentration enhancements (ppm-m) are typically provided within 24 hours. Quality-controlled quantification estimates are typically available in 1-2 weeks after the measurement. In the pilot phase, Bridger was asked to revisit sites where an emission source was detected to have a concentration enhancement greater than 650 ppm-m. During each revisit, Bridger was required to measure all equipment on that site, irrespective of whether all equipment on the site had exhibited methane enhancements above 650 ppm-m. This was done to ensure that repeat measurements are conducted over the entire site instead of specific equipment.

2.2.2 Champion X

ChampionX uses a cavity ringdown spectrometer on an aerial platform to conduct mass balance measurements. A Picarro G2301 gas analyzer (Picarro Inc., Santa Clara, CA) measures ambient methane (CH4) concentrations with a precision less than 0.5 parts per billion (ppb) for 5 second average measurements. The latitude and longitude coordinates and aircraft headings were measured by a dual global positioning system (GPS) compass and then integrated with CH4 concentrations after correcting the residence time of air samples traveling inside the sampling tubes.

Two types of measurements were conducted using ChampionX in the AMI pilot program. The first type included traditional regional mass balance measurements where ChampionX would conduct large perimeter methane concentration measurements to estimate regional emissions.

These regional mass balance measurements consist of perimeter box flights around the region of interest through the methane plume column. The measurement begins at as low an altitude as allowed by FAA regulations (e.g., 200 ft – 400 ft above ground level) and climbing until on-board measurements detect no plumes. This is indicated by the absence of any strong methane concentration enhancement upwind or downwind of the region. Figure 2-2 shows an example of a mass balance flight in the northeast pilot region.

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[16] Bell et al. (2022) Single-blind determination of methane detection limits and quantification accuracy using aircraft-based LiDAR. *Elem. Sci. Anthro.* 10 (1), 00080.

[17] Conrad et al. (2023). Robust probabilities of detection and quantification uncertainty for aerial methane detection: Examples for three airborne technologies. *Remote Sens. Environ.* 288, 113499.

[18] Johnson et al. (2022). Blinded evaluation of airborne methane source detection using Bridger Photonics LiDAR. *Remote Sens. Environ.* 259, 112418.

[19] Thorpe et al. (2024). Deployment-invariant probability of detection characterization for aerial LiDAR methane detection. Pre-print, EartharXiV. https://eartharxiv.org/repository/view/6612/

ChampionX mass balance flights have been extensively used in peer-reviewed studies to measure methane emissions from oil and gas operations [20,21]. Recent work has also tested this technology under controlled and field conditions for point source emissions[22,23].

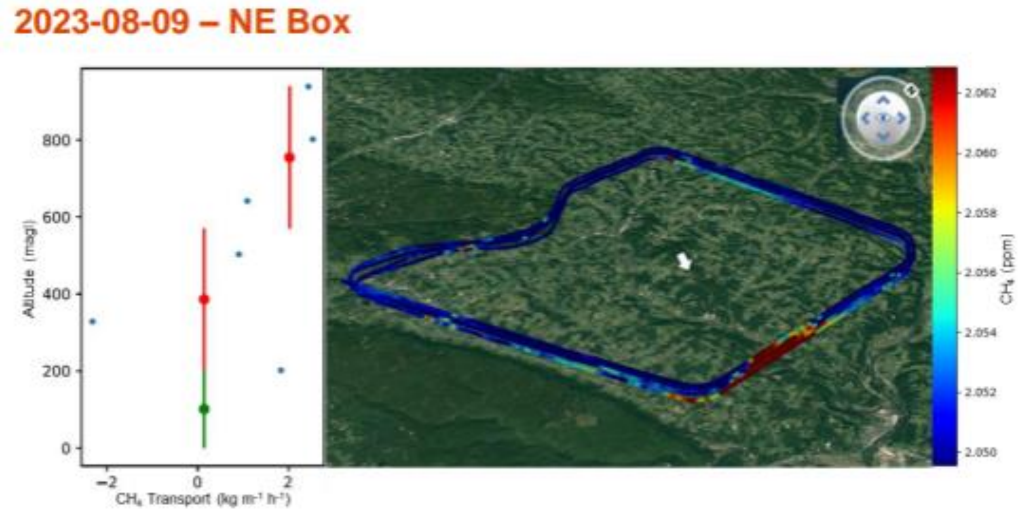

Figure 2-2: Regional mass-balance measurements conducted by ChampionX in the northeast pilot region.

The second type of measurement, raster scans over the pilot regions, consisted of a constant altitude flight along a pre-determined raster scan about 1 km apart to identify methane hotspots. The raster scan was followed by detailed spiral mass balance measurements on select high-emitting sources as identified in the raster scan. The goal of the raster scan was to identify unknown sources of emissions in the region – for example, several coal mines are not specified in public databases and yet are found to be emitting methane. Figure 2-3 shows a raster scan flight in the northeast pilot region, along with the hotspots detected. Some of these hotspots were attributed to known sources such as CAFOs or landfills while other hotspots could not be successfully attributed.

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[20] Ravikumar et al. (2024). Developing Measurement-Informed Methane Emissions Inventory Estimates at Midstream Compressor Stations. Pre-print, ChemRxiv. https://chemrxiv.org/engage/chemrxiv/article-details/65c674d266c13817294db299

[21] Petron et al. (2020). Investigating large methane enhancements in the U.S. San Juan Basin. *Elem. Sci. Anthro.* 8 (1), 038.

[22] El Abbadi et al. (2023). Comprehensive evaluation of aircraft-based methane sensing for greenhouse gas mitigation. Pre-print, EartharXiV. https://eartharxiv.org/repository/view/5569/

[23] Stokes et al. (2022). An aerial field trial of methane detection technologies at oil and gas production sites. Pre-print, ChemRxiv. https://chemrxiv.org/engage/chemrxiv/article-details/625f27d2742e9f9470644f24

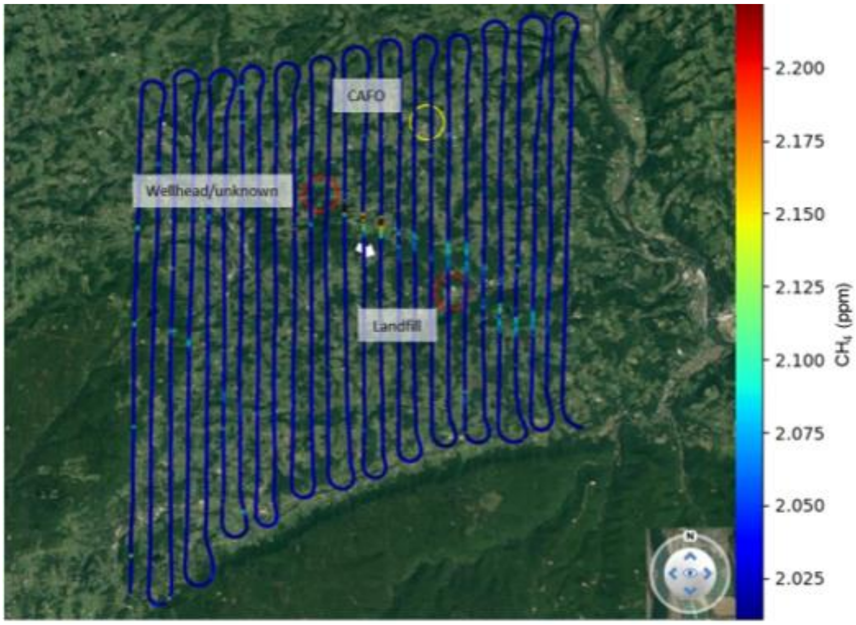

Figure 2-3: Raster scan flights by ChampionX in the northeast area of the pilot region along with hotspot detection.

2.2.3 Continuous Monitoring Systems

Multiple AMI operators have installed continuous monitoring systems on their facilities to complement periodic leak detection and repair surveys. Because the insights from the analysis of continuous monitoring systems are specific to individual operators, they are not discussed in this anonymized report. However, every AMI operator that has continuous monitoring systems on site and has provided data to us have been receiving periodic updates on our analysis through individual operator engagement.

2.3 Measurement Schedule

Three Bridger surveys, one for each quarter starting in the second quarter, were conducted in 2023. The exact timing of these measurements depended on several factors including availability of the technology vendor, weather conditions, and contractual obligations. For example, Q3 measurements in July of 2023 were affected by significant smoke from wildfires in Eastern Canada which resulted in two postponements of the scheduled measurements for the northeast area of the pilot project. Table 2-1 summarizes the measurements that were part of the AMI 2023 pilot campaign.

Table 2-1: Survey periods and technologies deployed for the AMI 2023 pilot program field campaign.

Survey Period	Technology
Q2 2023	Bridger Photonics
Q3 2023	Bridger Photonics
	ChampionX
Q4 2023	Bridger Photonics

2.4 Anonymization Protocol

All measurements described in this report have been anonymized and aggregated according to standard protocols as described below.

Anonymization: All results in this report are presented after anonymization of operator information. The anonymization procedure is based on the following principle: there should be at least three different entities of the parameter in question for effective anonymization. This is based on the principle of mutual single-blind protocol where an operator knows the identity of their data in analysis but cannot uncover the identity of other entities. For this to work, at least three entities are required. For example, let us assume we report site-level average emissions for operators A, B, and C. Operator A would know which data is theirs but will be unable to identify operator B or C’s dataset. However, if there were only two operators (A and B), each operator would know their own data, and by trivial extrapolation, will be able to identify the dataset of the other operator.

Aggregation: The aggregation process is based on the type of analysis being conducted. Because of the geographic distribution of AMI member facilities in the pilot program, it would not be possible to preserve anonymization discussing differences in emissions between AMI and non-AMI companies while also disaggregating across the southwest and northeast areas of the pilot regions. Similarly, it would not be possible to discuss differences in emissions between the southwest and northeast areas of the pilot region while also disaggregating across AMI and non-AMI companies. Thus, the following approach for aggregation was adopted. When discussing AMI vs. non-AMI facility emissions, data from both the southwest and northeast areas of the pilot region were combined. When discussing differences in emissions between the southwest and the northeast areas of the pilot region, data from both AMI and non-AMI companies were combined. This approach protects the confidentiality of individual member companies while also identifying key differences in emissions across geographic regions and facility ownership. In all results discussed in this report, midstream and upstream assets are not discussed separately to preserve anonymization.

2.5 Analysis Methodology

As-measured emissions estimates: As-measured emission rates refer to instantaneous emission rates estimated by Bridger Photonics during the survey and have not been adjusted for intermittency of emissions. The calculation of leaker and population emissions factors as described below rests on the Central Limit Theorem – the expectation that measurements sample a representative set of equipment and therefore the mean of the sampling distribution converges to the population mean.

Leaker emission factors: Leaker emission factors refers to the average, equipment-level, as-measured emission rate of all leaking equipment. These leaker emission factors correspond to all emissions associated with a particular equipment and does not reflect the nature of the emission. Thus, not all emitters included in the calculation of leaker emission factors are leaks, they could be permitted vents (e.g., uncontrolled tanks) or anomalous vent events (e.g., open thief hatch). Leaker emissions factor is calculated using the formula shown below:

$$Leaker\ emission\ factor_t = \frac{\sum_{i,leak} Emissions_{i,t}}{\sum Emitters_t}$$

where t refers to a specific equipment, $\sum_{i,leak} Emissions_{i,t}$ refers to the total emissions from equipment t, and $\sum Emitters_t$ refers to the total number of emitters from equipment t.

Population emission factors: Population emission factors refer to the average, equipment-level, as-measured emission rate of all equipment, both leaking and non-leaking. It is calculated using the formula shown below:

$$Population\ emission\ factor_t = \frac{\sum_{i,leak} Emissions_{i,t}}{\sum Count_t}$$

where t refers to a specific equipment, $\sum_{i,leak} Emissions_{i,t}$ refers to the total emissions from equipment t, and $\sum Count_t$ refers to the total count of equipment of type t.

Large release events: Large release events are defined according to the proposed updates to the subpart-W of the EPA greenhouse gas reporting program where any instantaneous measurement of an emission rate over 100 kg/h is considered a large release event. Even if only one of multiple passes over an equipment detects an emission over 100 kg/h, it will be considered a large release event. The effect of this classification allows for rapid root-cause analysis (for oil and gas facilities) and a separate methodology to determine duration of such large release events.

2.6 Uncertainty Analysis

Errors bars in the results presented throughout this report are calculated using bootstrapped monte-carlo analysis based on the principles of the Central Limit Theorem. Bootstrapped analysis refers to repeated re-sampling of sample data (in this case, 10,000 times) to obtain a distribution of the relevant sample statistic (e.g., mean emission rate by equipment). The parameters of this sampling distribution – mean, 2.5th percentile, and 97.5th percentile – represent the mean and confidence intervals of the parameter in the population. The error bars presented throughout this work only accounts for sampling errors and do not include measurement errors. Future work in developing an integrated uncertainty analysis approach that includes effects of measurement errors, sampling errors, and spatio-temporal extrapolation errors is ongoing.

3.0 Results and Analysis

This section presents the results of the measurements by Bridger Photonics and Champion-X across all assets within the pilot study. Results are anonymized and aggregated following procedures described in Section 2.4. Measurements from each quarter are described separately in this section. As needed, comparison across surveys is analyzed to identify potential seasonal or temporal trends. Combined summary statistics for all three surveys in 2023 and corresponding data charts are presented in the Executive Summary.

For all the analysis presented here, data from select re-visit surveys conducted by Bridger has been excluded. These re-visit surveys were based on a concentration path-length threshold (650 ppm-m) observed during the initial flyover and prior to quantification of initial flyover data. Because the re-visit surveys were not randomly selected, it does not represent a statistically representative sample. Thus, any summary statistic calculated with re-visit data (e.g., fraction of site emitting or population emission factor) will likely overestimate emissions as sites with higher emissions are more likely to be re-visited than sites with lower emissions. The one exception is when calculating leaker-specific metrics like leaker emission factors where the initial vs. revisit measurement does not make a difference – in these cases, revisit data are included in the calculations. Future work will evaluate methods to incorporate re-visit data into modeling tools.

3.1 Q2 2023 Measurements

Bridger Photonics was deployed in Q2 2023 and conducted aerial surveys in April 2023. Table 3-1 shows the summary of all facilities visited by Bridger in the southwest and northeast pilot region, along with the number of sites found to be emitting. Overall, 44% and 26% of oil and gas sites visited by Bridger were found to be emitting methane in the southwest and northeast pilot region, respectively. The higher fraction of emitting oil and gas facilities in the southwest compared to the northeast region can be attributed to two factors – one, resource characteristics of the southwest region resulting in significant liquids production compared to the northeast, and two, a large fraction of atmospheric tanks in the southwest region that results in detection of a higher number of tank flashing events. Most non-oil and gas facilities are found to be emitting in the southwest and northeast pilot regions. For example, 10 out of 14 coal mining related facilities were emitting in the southwest region and so were all four CAFO operations in the northeast pilot region.

Table 3-1: Count of total facilities and emitting facilities in the southwest and northeast pilot region (both AMI and non-AMI) disaggregated by major facility types in Q2 2023.

Facility Type	Total	Southwest			Northeast		
		Total	Emitting	%	Total	Emitting	%
Total	589	415	-		174	-	
Total (O&G)	568	400	177	44%	168	43	26%
Total (non-O&G)	21	15	10	67%	6	5	83%
CAFO	4		-	-	4	4	100%
Coal Mine	2	2	1	50%	0	-	-
Coal Mine Vent	12	12	9	75%	0	-	-
Landfill	3	1	0	0%	2	1	50%

Figure 3-1 shows the total as-measured emissions from major facility types, aggregated across both the southwest and northeast areas of the pilot region. Coal mines and coal mine vents are the single largest source of methane emissions in the pilot regions of Appalachian Basin, contributing to nearly 75% of total measured emissions. CAFOs and landfills, many of which were found to be emitting (see Table 3-1), only have negligible contribution to total emissions. Oil and gas facilities, both AMI and non-AMI, together contribute 24% of total emissions in Q2. The presence of large volume non-oil and gas sources of methane that are practically co-located with oil and gas facilities have significant implications for the interpretation of satellite measurements of methane over the region. This is further discussed in Section 4.

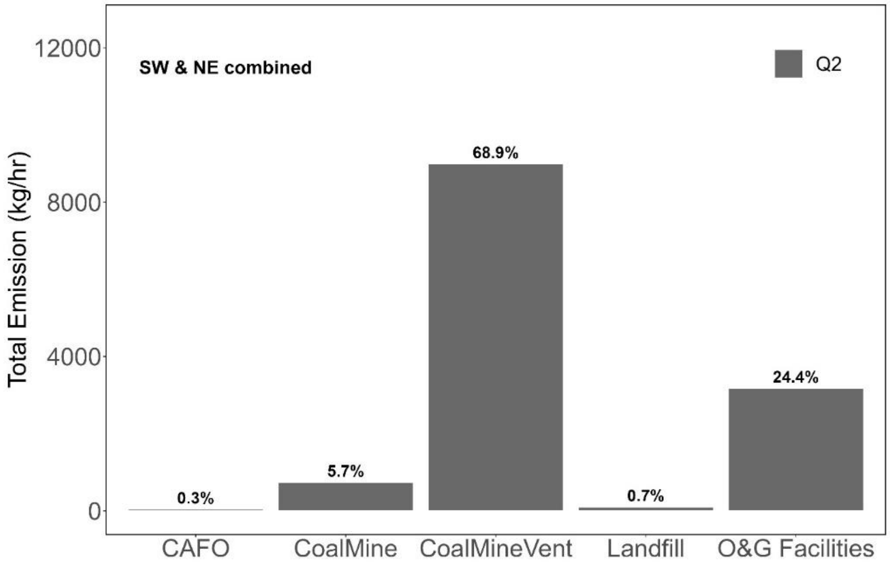

Figure 3-1: Total as-measured emissions by Bridger across the southwest and northeast areas of the pilot region showing relative contributions from different facility types in Q2 2023.

Figure 3-2 shows the total as-measured methane emissions from major facility types in the southwest pilot region. The oil and gas facilities include both AMI and non-AMI facilities. Coal mines are concentrated in the southwest pilot region and contribute to 76% of total methane emissions. Oil and gas facilities account for the remaining 24%.

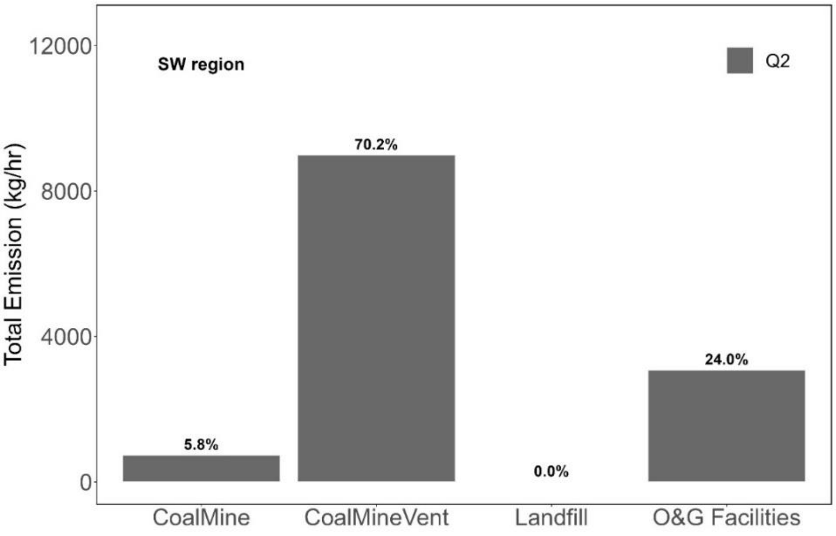

Figure 3-2: Total as-measured emissions by Bridger across the southwest pilot region showing relative contributions from different facility types in Q2 2023.

Figure 3-3 shows the total as-measured methane emissions from major facility types in the northeast pilot region. The northeast pilot region does not contain any coal mines. Total emissions, across all facility types, are significantly lower in the northeast pilot region compared to the southwest pilot region. Although this is largely because of coal mines being a significant contributor to emissions in the southwest region, the dry gas nature of the northeast Appalachian Basin also contributes to lower oil and gas emissions. Overall, landfills and CAFOs contributed 41% and 17% of total emissions, respectively. Oil and gas facilities (both AMI and non-AMI) contributed 42%.

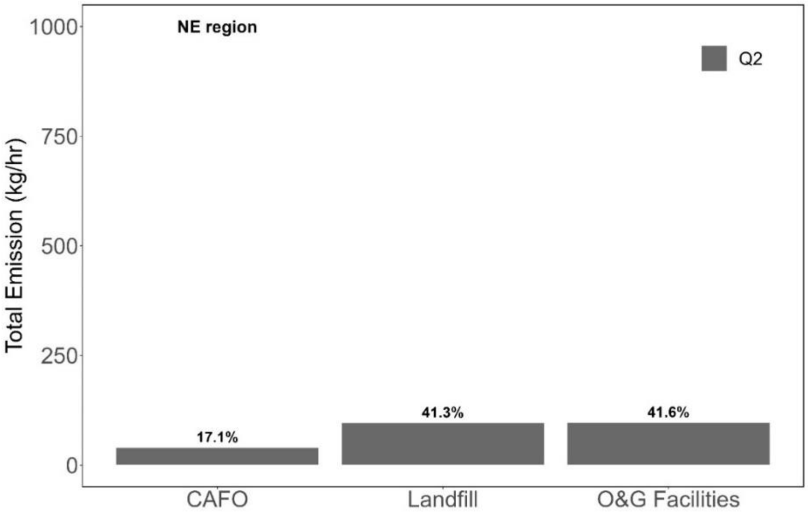

Figure 3-3: Total as-measured emissions by Bridger across the northeast pilot region showing relative contributions from different facility types. Note, there are no coal operations in the NE region of the pilot.

Figure 3-4 shows the rank-ordered cumulative distribution of equipment-level emissions across all oil and gas facilities (AMI and non-AMI) and aggregating both the southwest and northeast areas of the pilot region. Equipment-level emissions are highly skewed where a small fraction of emitters contribute to the majority of emissions – this has been repeatedly shown across oil and gas facilities in the US. During Q2 measurements, over 50% of emissions can be attributed to equipment emitting at least 21 kg/h. This corresponds to only 5% of all emitting equipment. Although there is no statistical pattern in the type of equipment most prone to be large emitters, tanks and compressors are likely to be emitting over the 21 kg/h limit. Only 3 emitters are classified as large release events emitting over 100 kg/h in Q2 – two of these were from tanks and one from a compressor.

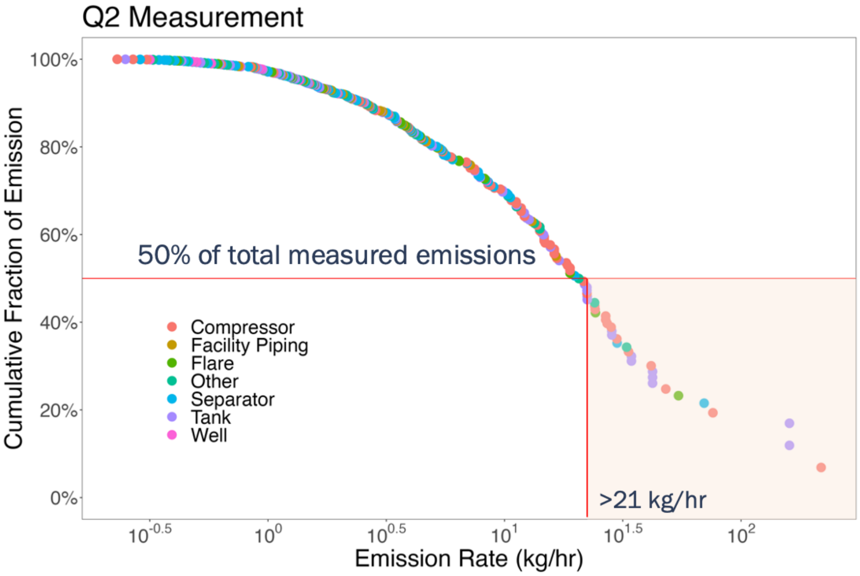

Figure 3-4: Rank ordered cumulative distribution of equipment-level, as-measured methane emissions estimates across both the northeast and southwest pilot regions. 50% of emissions can be attributed to equipment emitting at least 21 kg/h.

Combining both the southwest and the northeast pilot region, Figure 3-5 shows the difference in equipment-level leaker emission factor between AMI and non-AMI oil and gas sites. We did not find any statistically significant difference in the leaker emission factor. The average leaker emission factor for compressors was higher for non-AMI companies while the average tank leaker emission factor was higher for AMI companies. While this is only one survey, it points to the need for further observations of potential differences between AMI and non-AMI companies. There has long been suspicion in the methane community that there is a coalition of the willing problem – that is, the companies that are most likely to have low emissions will also be most likely to join such measurement campaigns. Preliminary evidence from the Q2 measurements indicates that the coalition of the willing problem might not be applicable in the Appalachian Basin.

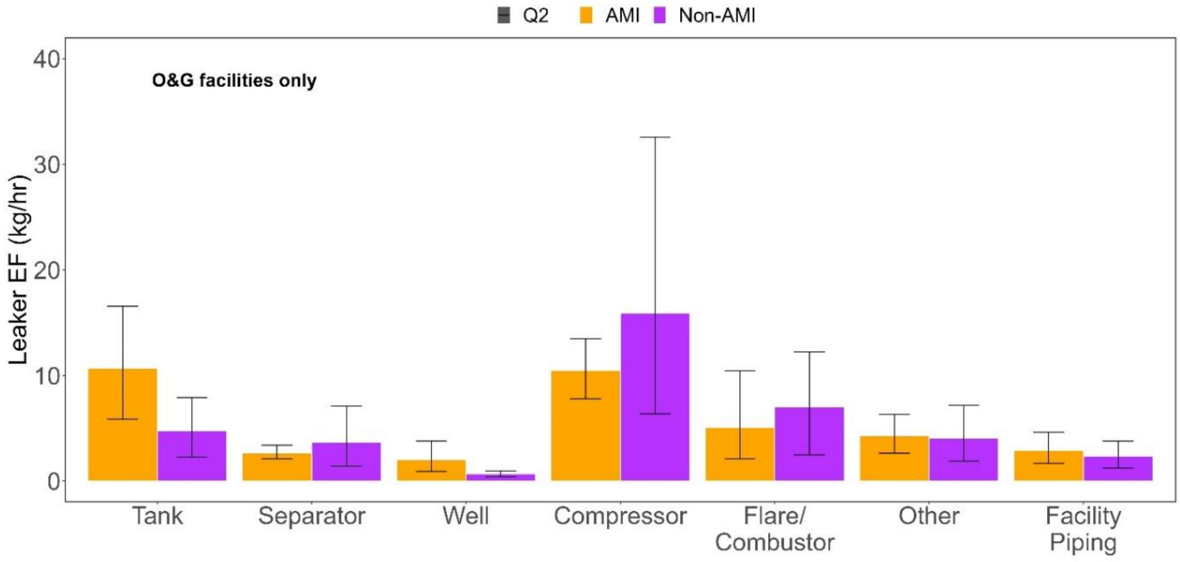

Figure 3-5: Equipment-level leaker emission factor for AMI and non-AMI facilities across both southwest and northeast pilot region in Q2 2023.

Table 3-2 shows the difference in equipment-level emitter statistics between AMI and non-AMI companies by aggregating data from both the southwest and northeast pilot regions. There is no statistically significant difference in the fraction of emitting equipment between AMI and non-AMI companies.

Table 3-2: Equipment-level emitter statistics for AMI and non-AMI facilities across both southwest and northeast pilot region in Q2 2023.

Equipment Type	Equipment Count		% Equip. Emitting	
	AMI	Non-AMI	AMI	Non-AMI
Tank	1519	525	5%	4%
Separator	2595	912	4%	5%
Well	1576	683	1%	1%
Compressor	164	68	43%	43%
Other	161	55	14%	16%
Flare/Combustor	42	17	-	-
Facility Piping	16	22	-	-

Figure 3-6 shows a summary of individual large release events detected by Bridger in Q2 2023. Large release events are defined as those detections by Bridger with an instantaneous methane emission rate over 100 kg/h. In Q2 2023, 12 events were classified as large release events, of which 9 were on coal mines or coal mine vents and 3 on oil and gas facilities. Coal mine methane emissions exhibited some of the largest emissions observed during Q2, including a coal mine vent that was emitting over 4000 kg/h. The nine highest large release events were associated with coal mine operations. The three oil and gas large release events were associated with two tanks and one compressor, each with emission rates below 200 kg/h.

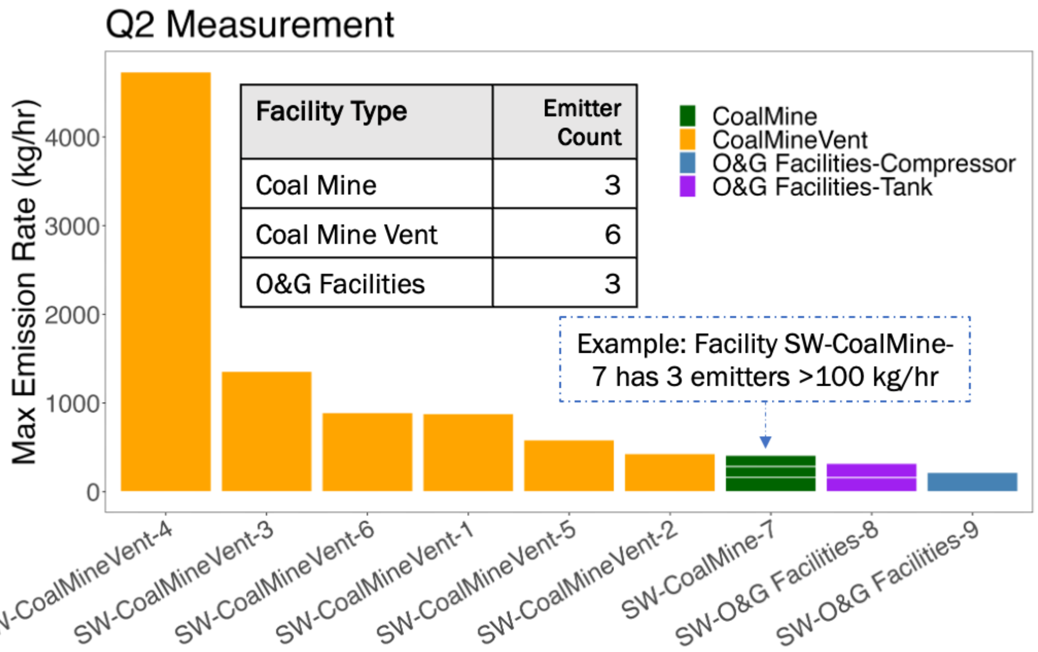

Figure 3-6: Emissions rates and site types associated with large release events (events with instantaneous emission rate > 100 kg/h) in Q2 2023.

3.2 Q3 2023 Measurements

Bridger Photonics was deployed in Q3 2023 and conducted aerial surveys in July-August 2023. Table 3-3 shows the summary of all facilities visited by Bridger in the southwest and northeast pilot regions, along with the number of sites found to be emitting. Overall, 37% and 23% of oil and gas sites visited by Bridger were found to be emitting methane in the southwest and northeast pilot region, respectively. Compared to Q2 2023, the southwest pilot region saw a smaller fraction of sites that were emitting (44% vs 37%) while the number remained unchanged in the northeast region. Similar to Q2 2023, coal mines were the largest source of emissions – 11 out of 14 coal mine related facilities were emitting in the southwest region and so were all four CAFO operations in the northeast pilot region. The difference in the count of sites visited between Q2 and Q3 2023 is because of a mapping error in Q2 2023 – co-located equipment on the same pad that belonged to different operators was considered a single site instead of separate sites. This aggregation mainly affected a small number of sites in the southwest pilot region. This error was corrected prior to the Q3 2023 measurements, which resulted in a higher total number of facilities visited in Q3 2023.

Table 3-3: Count of total facilities and emitting facilities in the southwest and northeast areas of the pilot region disaggregated by major facility types in Q3 2023.

Facility Type	Total	Southwest			Northeast		
		Total	Emitting	%	Total	Emitting	%
Total	614	440	-	-	174	-	-
Total (O&G)	593	425	156	37%	168	39	23%

Facility Type	Total	Southwest			Northeast		
Total (non-O&G)	21	15	11	85%	6	5	83%
CAFO	4	-	-	-	4	4	100%
Coal Mine	2	2	1	50%	-	-	-
Coal Mine Vent	12	12	10	83%	-	-	-
Landfill	3	1	-	0%	2	1	50%

Figure 3-7 shows the total as-measured emissions from major facility types, aggregated across both the southwest and northeast pilot regions. The oil and gas sector was the single largest contributor in Q3, contributing 47% to total methane emissions. This was closely followed by coal mines and coal mine vents, which together contributed to 42% of total emissions. This switch between the highest contributing two sectors between Q2 and Q3 can be attributed to two factors that occurred simultaneously: lower as-measured emissions from coal mine operations and higher as-measured emissions from the southwest oil and gas pilot region, compared to Q2. While the variability in oil and gas methane emissions is well documented in scientific literature, temporal variation in methane emissions from coal mine vents and coal mines has not been studied extensively. Future surveys in the southwest region would benefit from detailed characterization of coal mine related methane emissions as it will have a significant impact on remote methane measurements. This is further discussed in Section 4.

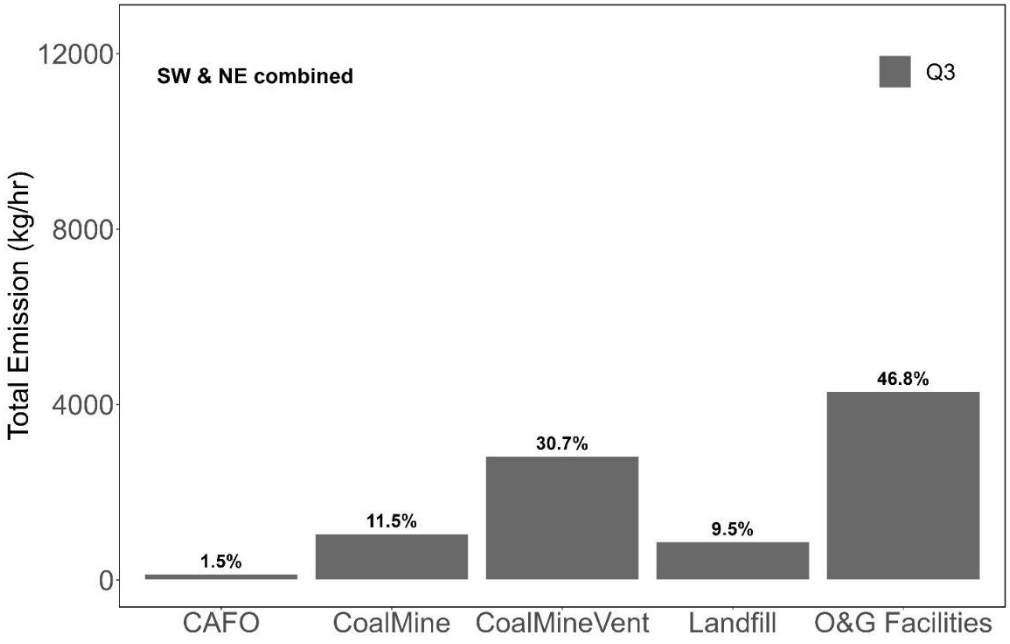

Figure 3-7: Total as-measured emissions by Bridger across the southwest and northeast pilot region showing relative contributions from different facility types in Q3 2023.

Figure 3-8 shows the total as-measured methane emissions from major facility types in the southwest pilot region in Q3 2023. The oil and gas facilities include both AMI and non-AMI facilities. Coal mines are concentrated in the southwest pilot region and contribute to 50% of total methane emissions. Oil and gas facilities account for the remaining 50%. This is higher than the contribution of oil and gas facilities to total emissions in Q2 2023 – despite the increase in absolute oil and gas section (see Figure 3-8 below), a significant reduction in coal mine emissions compared to Q2 2023 was responsible for varying proportional contribution from oil and gas facilities.

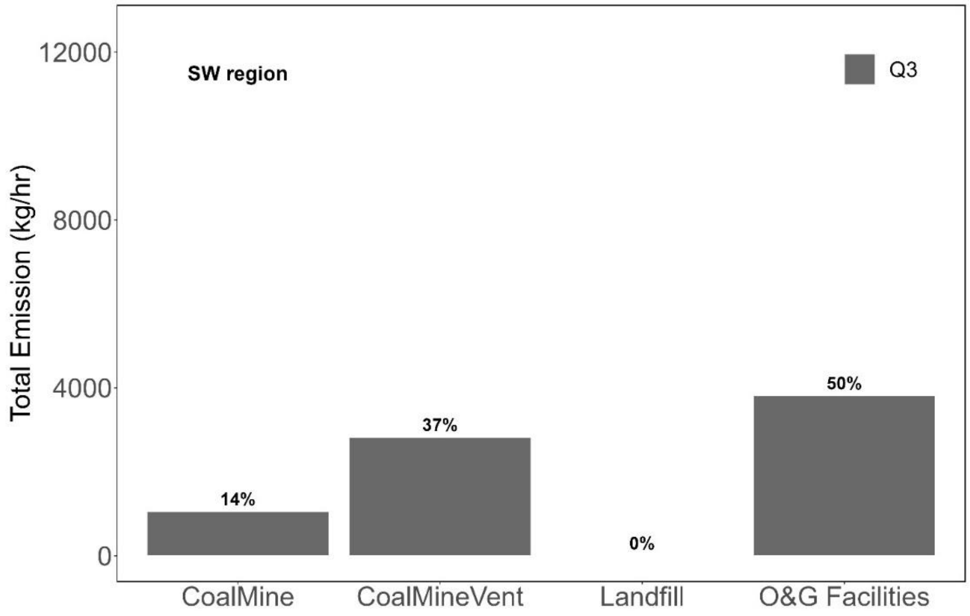

Figure 3-8: Total as-measured emissions by Bridger across the southwest pilot region showing relative contributions from different facility types in Q3 2023.

Figure 3-9 shows the total as-measured methane emissions from major facility types in the northeast pilot region in Q3 2023. Coal mines are not present in the northeast pilot region. Total emissions, across all facility types, are significantly lower in the northeast pilot region compared to the southwest pilot region. In contrast to Q2 2023, landfills are the largest source of methane emission with a cumulative emission rate of over 800 kg/h contributing to 58% of total emissions. Oil and gas facilities contributed to 33% of total emissions in the northeast pilot region, with a cumulative emission rate of about 480 kg/h.

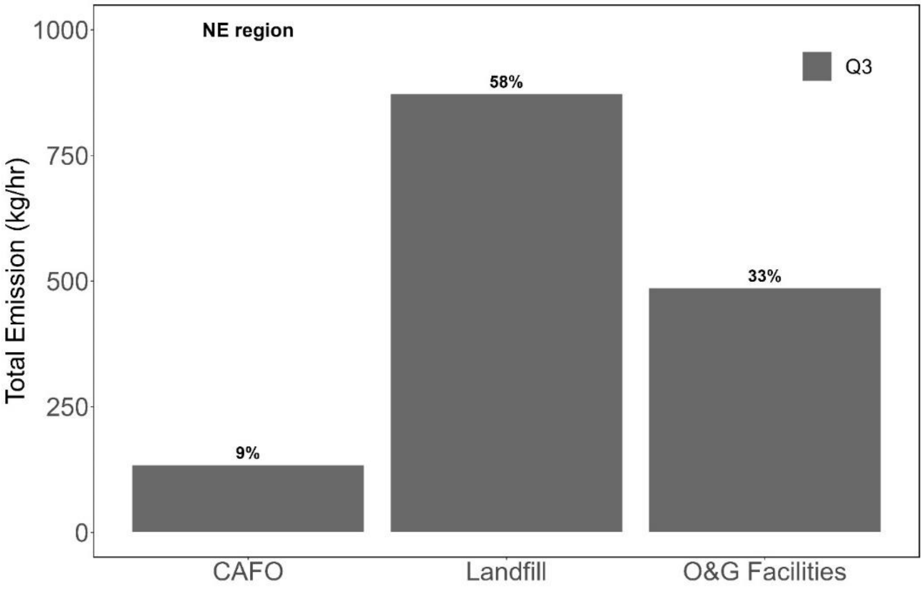

Figure 3-9: Total as-measured emissions by Bridger across the northeast pilot region showing relative contributions from different facility types in Q3 2023.

Combining both the southwest and the northeast region, Figure 3-10 shows the difference in equipment-level leaker emission factor between AMI and non-AMI oil and gas sites in Q3 2023. We did not find any statistically significant difference in the leaker emission factor between AMI and non-AMI facilities, similar to observations in Q2 2023. A key difference is that emission factors associated with the ‘other’ category, where non-AMI facilities have statistically higher leaker emission factor than AMI facilities. Because ‘other’ category corresponds to sources that Bridger was not able to classify from aerial imagery and we did not have any direct interaction with non-AMI operators, the benefit of clarification was not available. Thus, it is possible that known sources that were mistakenly classified by Bridger as ‘other’ were not corrected prior to the development of the emission factors. However, for AMI facilities, clarification with operators on each individual source classified as ‘other’ helped significantly reduce the number of sources in this category.

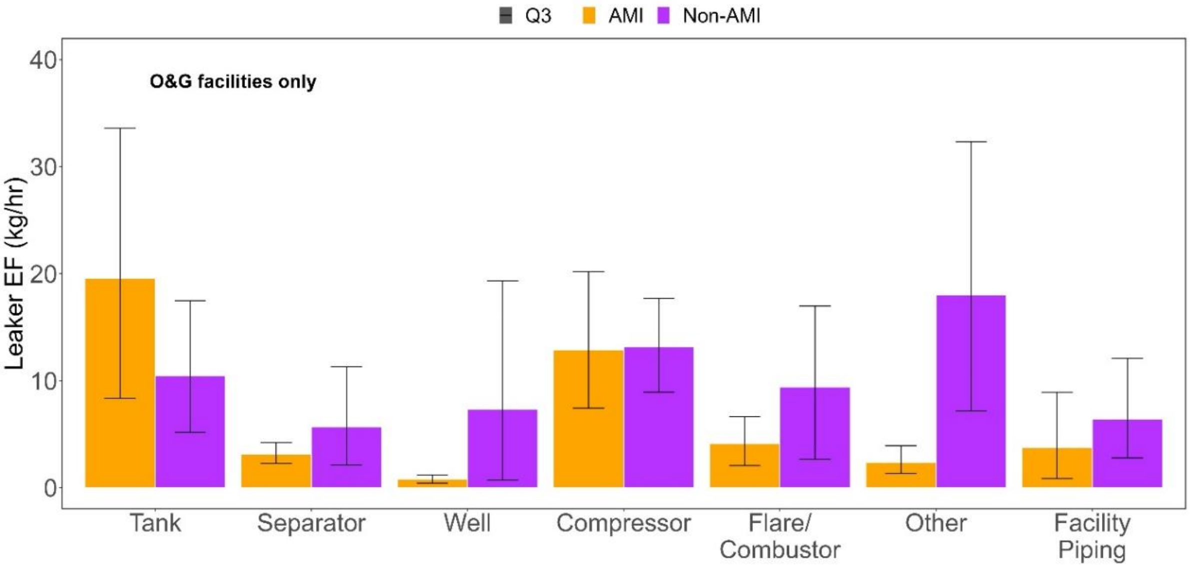

Figure 3-10: Equipment-level leaker emission factor for AMI and non-AMI facilities across both southwest and northeast pilot region in Q3 2023.

Table 3-4 shows the difference in equipment-level emitter statistics between AMI and non-AMI companies by aggregating data from both the southwest and northeast pilot regions. There is no statistically significant difference in the fraction of emitting equipment between AMI and non-AMI companies.

Table 3-4: Equipment-level emitter statistics for AMI and non-AMI facilities across both southwest and northeast pilot region in Q3 2023.

Equipment Type	Equipment Count		% Equip. Emitting	
	AMI	Non-AMI	AMI	Non-AMI
Tank	1525	524	5%	4%
Separator	2603	904	3%	4%
Well	1575	683	1%	<1%
Compressor	167	65	41%	49%
Flare/Combustor	166	54	15%	13%
Other	33	21	-	-
Facility Piping	12	11	-	-

Figure 3-11 shows the rank-ordered cumulative distribution of equipment-level emissions across all oil and gas facilities (AMI and non-AMI) and aggregating both the southwest and northeast pilot regions. Equipment-level emissions are highly skewed where a small fraction of emitters contribute to the majority of emissions – this has been repeatedly shown across oil and gas facilities in the US. During Q3 measurements, over 50% of emissions can be attributed to equipment emitting at least 40 kg/h. This is higher than the 50% cut-off observed in Q2 survey (~21 kg/h) – emissions from oil and gas facilities were generally higher across all facility types in Q3 compared to Q2. However, similar to Q2, tanks and compressors are likely equipment to be emitting over the 40 kg/h limit. 7 emitters are classified as large release events, emitting over 100 kg/h in Q3 – four of these large emitters were from tanks.

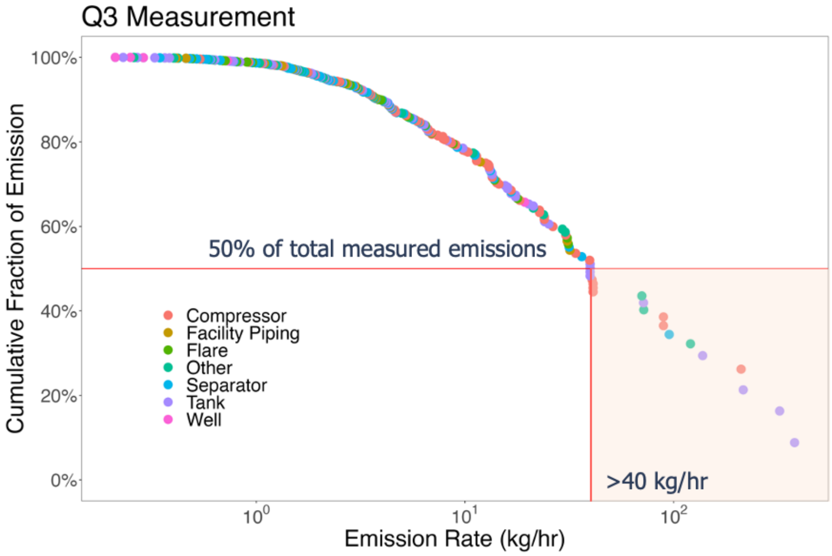

Figure 3-11: Rank ordered cumulative distribution of equipment-level, as-measured methane emissions estimate across both the northeast and southwest pilot regions. 50% of emissions can be attributed to equipment emitting at least 40 kg/h.

Figure 3-12 shows a summary of individual large release events detected by Bridger in Q3 2023. Large release events are defined as those detections by Bridger with an instantaneous methane emission rate over 100 kg/h. In Q3 2023, 19 events were classified as large release events, of which 10 were from coal mines or coal mine vents, 2 were from landfills, and the remaining 7 were from oil and gas facilities. Compared to Q2, emissions from coal mines and coal mine vents were significantly lower in magnitude, with no individual emission above 1000 kg/h. Large release events from oil and gas facilities exhibited higher emissions with individual emitters between 200 – 500 kg/h, compared with below 200 kg/h in Q2 2023.

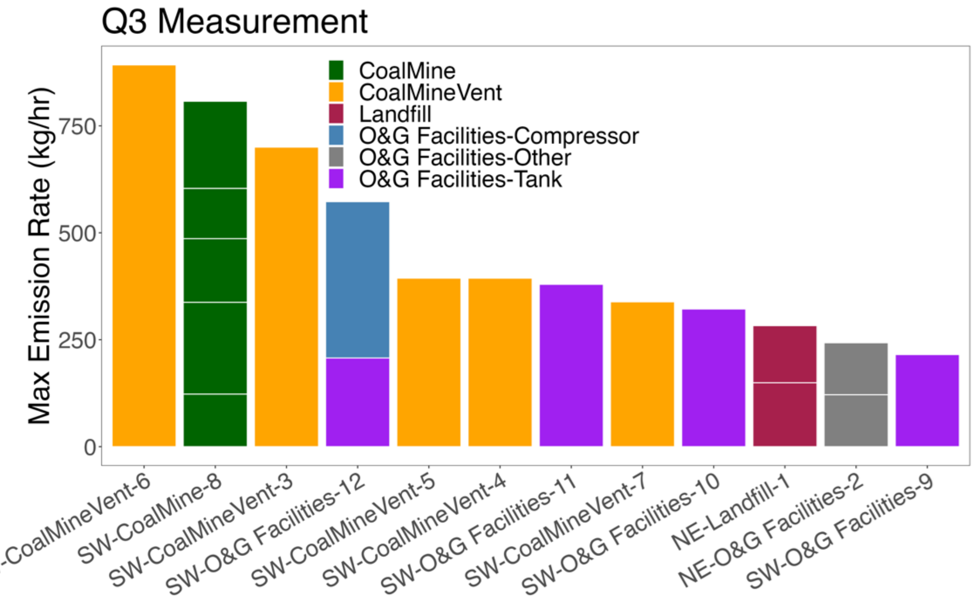

Figure 3-12: Emissions rates and site types associated with large release events (events with instantaneous emission rate > 100 kg/h) in Q3 2023.

3.3 Q4 2023 Measurements

Figure 3-13 shows the total as-measured emissions from major facility types, aggregated across both the southwest and northeast pilot regions in Q4 2023. Coal mine related emissions were the largest contributor to total emissions – over 70% of methane emissions measured in Q4 2023. The oil and gas sector was the next largest contributor in Q4, contributing 27% to total methane emissions. These measurement estimates are similar to those observed in Q2 2023 because of high methane emission rates from coal mine vents. The high temporal variability in coal mine vent emissions from Q2 through Q4 2023 warrants additional investigation (see Section 4).

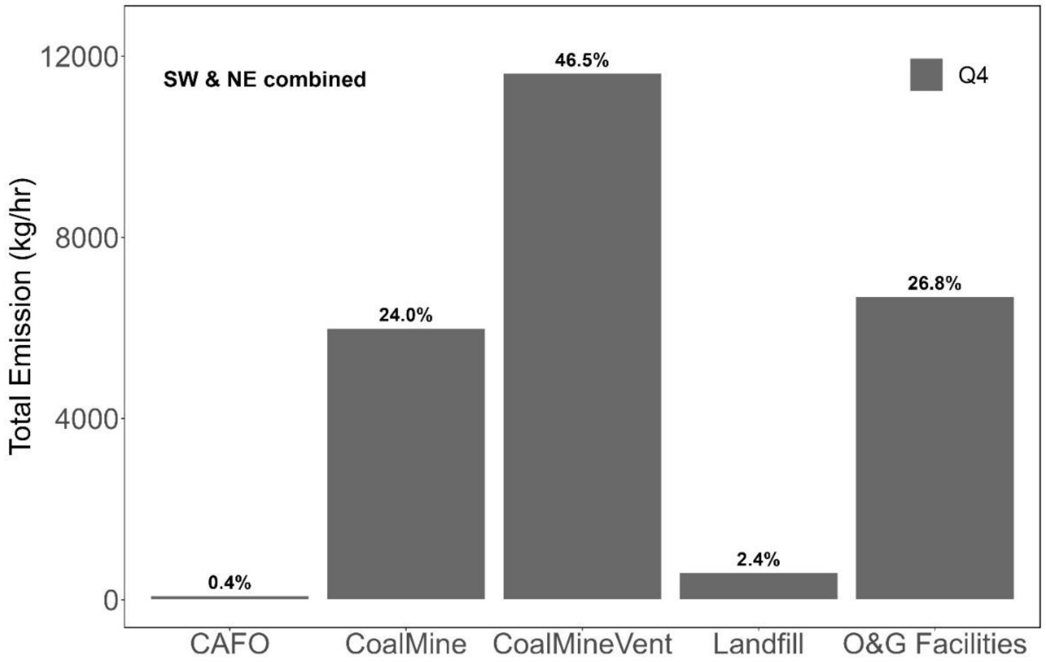

Figure 3-13: Total as-measured emissions by Bridger across the southwest and northeast pilot region showing relative contributions from different facility types in Q4 2023.

Figure 3-14 shows the total as-measured methane emissions from major facility types in the southwest pilot region in Q4 2023. The oil and gas facilities include both AMI and non-AMI facilities. Coal mines are concentrated in the southwest pilot region and contribute to 73% of total methane emissions – this is the highest contribution from coal mine operations ever observed across the three surveys in 2023. Unlike Q2 and Q3, no emissions were observed from landfills during Q4 2023. Oil and gas facilities accounted for 27% of all methane emissions. However, Bridger measured higher overall emissions in Q4 2023 compared to either Q2 or Q3 2023. Thus, even though oil and gas contributed only 27% to total emissions in the southwest region, the absolute total emission (~5500 kg/h) is the highest across the three surveys in 2023.

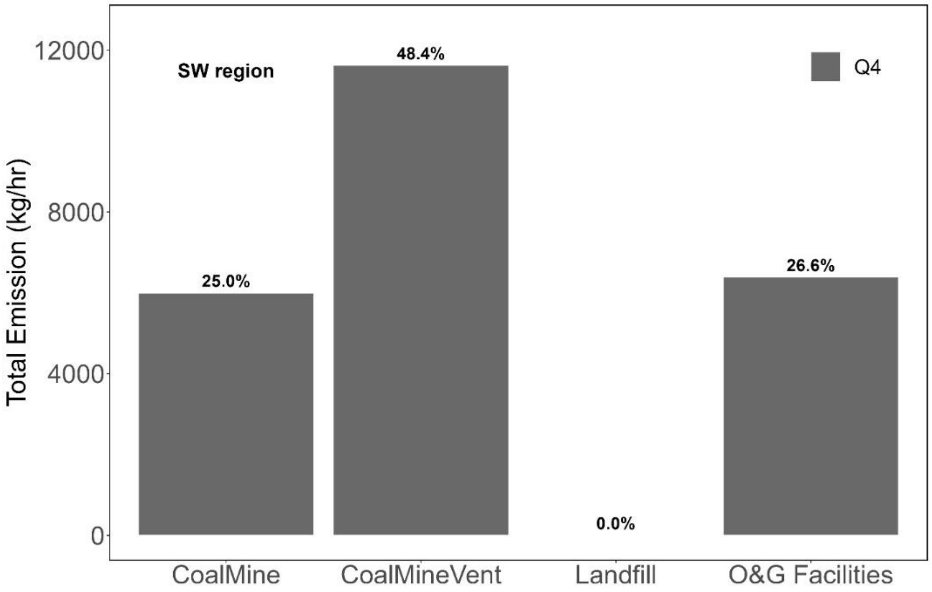

Figure 3-14: Total as-measured emissions by Bridger across the southwest pilot region showing relative contributions from different facility types in Q4 2023.

Figure 3-15 shows the total as-measured methane emissions from major facility types in the northeast pilot region in Q4 2023. The northeast pilot region does not have coal mines. Total emissions, across all facility types, are significantly lower in the northeast pilot region compared to the southwest pilot region. Similar to Q3 2023, landfills are the largest source of methane emission with a cumulative emission rate of about 600 kg/h contributing to 60% of total emissions. Oil and gas facilities contributed to 31% of total emissions in the northeast pilot region, with a cumulative emission rate of about 300 kg/h.

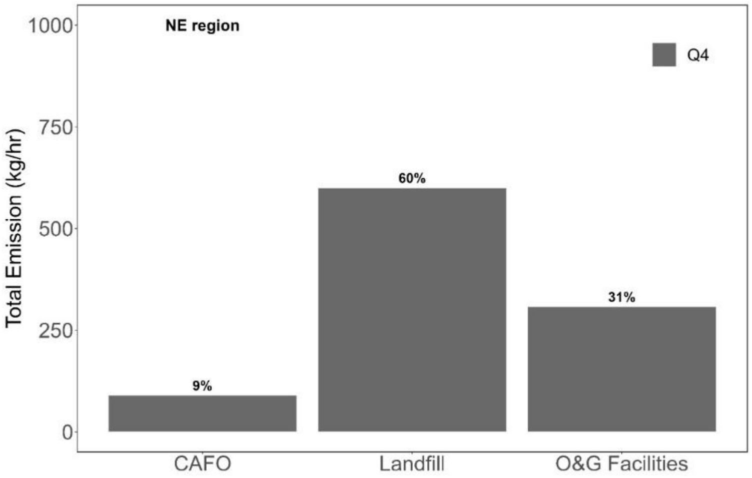

Figure 3-15: Total as-measured emissions by Bridger across the northeast pilot region showing relative contributions from different facility types in Q4 2023.

Combining both the southwest and the northeast region, Figure 3-16 shows the difference in equipment-level leaker emission factor between AMI and non-AMI oil and gas sites in Q4 2023. We did not find any statistically significant difference in the leaker emission factor between AMI and non-AMI facilities, similar to observations in Q2 and Q3 2023. Similar to Q3 2023, we observe a higher leaker emission factor associated with the 'other' category for non-AMI facilities compared to AMI facilities. This is likely because we were not able to correct Bridger's classification through operational information resulting in a higher number of equipment in this category. Furthermore, we observe higher leaker emission factor for separators at non-AMI facilities compared to AMI facilities. Given the small sample size, the uncertainty on this leaker emission factor is high, and therefore is not statistically significant from the leaker emission factor for separators at AMI facilities.

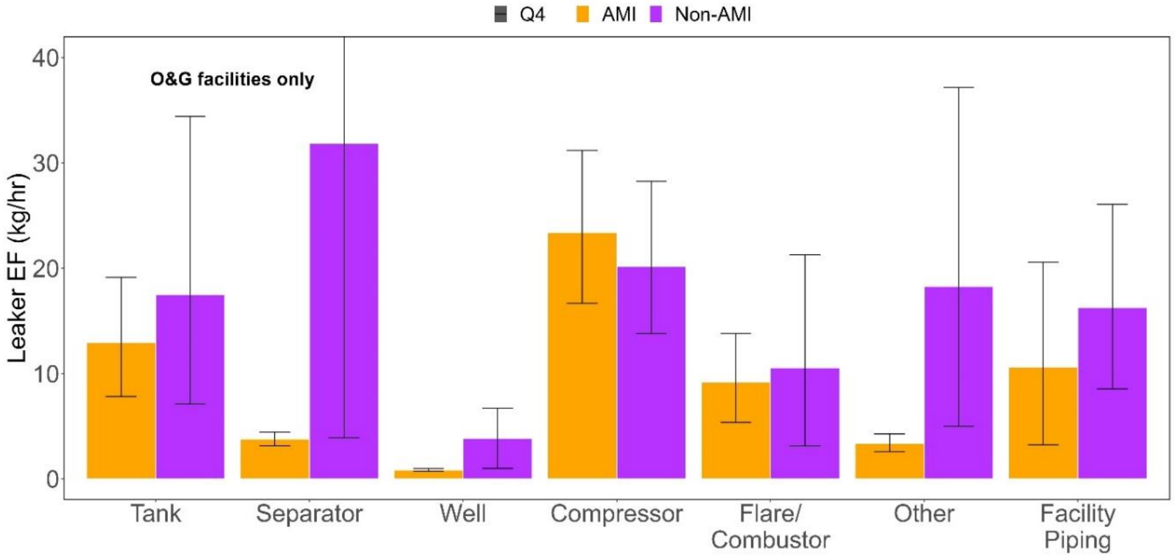

Figure 3-16: Equipment-level leaker emission factor for AMI and non-AMI facilities across both southwest and northeast pilot region in Q4 2023.

Table 3-5 shows the difference in equipment-level emitter statistics between AMI and non-AMI companies by aggregating data from both the southwest and northeast pilot regions. There is no statistically significant difference in the fraction of emitting equipment between AMI and non-AMI companies.

Table 3-5: Equipment-level emitter statistics for AMI and non-AMI facilities across both southwest and northeast pilot region in Q4 2023.

Equipment Type	Equipment Count		% Equip. Emitting	
	AMI	Non-AMI	AMI	Non-AMI
Tank	1522	500	5%	3%
Separator	2660	940	3%	5%
Well	1582	681	<1%	<1%
Compressor	159	69	47%	55%
Flare/Combustor	174	59	11%	14%
Other	27	27	-	-

Equipment Type	Equipment Count		% Equip. Emitting	
	AMI	Non-AMI	AMI	Non-AMI
Facility Piping	15	15	-	-

Figure 3-17 shows the rank-ordered cumulative distribution of equipment-level emissions across all oil and gas facilities (AMI and non-AMI) and aggregating both the southwest and northeast pilot regions. Equipment-level emissions are highly skewed where a small fraction of emitters contribute to the majority of emissions. During Q4 measurements, over 50% of emissions can be attributed to equipment emitting at least 61 kg/h, similar to Q3 2023. Tanks and compressors are the likely equipment to be emitting over this limit. 10 emitters are classified as large release events, emitting over 100 kg/h in Q4 – four of these large emitters were from tanks.

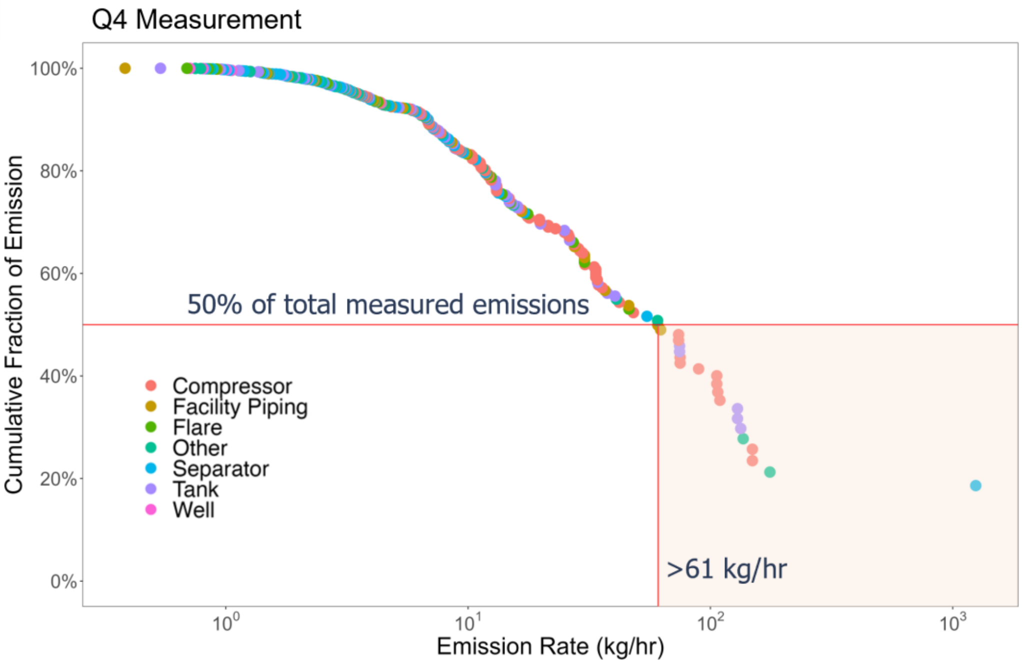

Figure 3-17: Rank ordered cumulative distribution of equipment-level, as-measured methane emissions estimate across both the northeast and southwest pilot regions. 50% of emissions can be attributed to equipment emitting at least 61 kg/h.

Figure 3-18 shows a summary of individual large release events detected by Bridger in Q4 2023. Large release events are defined as those detections by Bridger with an instantaneous methane emission rate over 100 kg/h. In Q4 2023, 27 events were classified as large release events, of which 16 were from coal mines or coal mine vents, 1 was from a landfill, and the remaining 10 were from oil and gas facilities. This is the highest number of events classified as large release events across the three surveys in 2023. Furthermore, Q4 2023 also saw some of the highest individual emitters with one coal mine vent emitting over 7000 kg/h. A single coal mine had 12 individual emitters, each of which were over 100 kg/h, with a cumulative emission of 6000 kg/h. Of the 10 oil and gas facilities, all but one individual emission event was less than 200 kg/h, similar to observations in Q2 2023. Four compressors and three tanks had emission events larger than 100 kg/h, while one separator at a non-AMI facility exhibited an instantaneous emission rate of over 1000 kg/h.

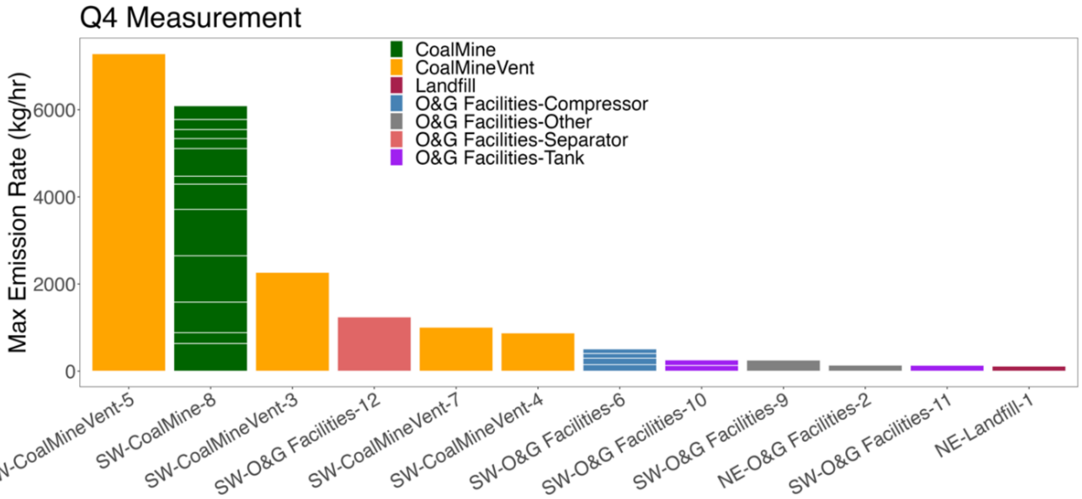

Figure 3-18: Emissions rates and site types associated with large release events (events with instantaneous emission rate > 100 kg/h) in Q4 2023.

3.4 ChampionX Mass-Balance Measurements

ChampionX conducted both regional mass balance measurements in the northeast and southwest pilot boxes and raster scans to identify hotspots.

Figure 3-19 shows total methane emissions in the northeast pilot region as measured by Bridger disaggregated by major facility types in Q2 and Q3, and the three mass-balance estimates by ChampionX in Q3. Total regional emissions as measured by ChampionX varied from about 1600 kg/h to over 2700 kg/h, with an average of 2000 kg/h. The uncertainty on this estimate is about 45% (i.e., 2000 ± 900 kg/h). The sum of all Bridger measurements in Q3 2023 is about 1500 kg/h, which is statistically similar to ChampionX estimates. However, a few caveats are noted: (1) Bridger and ChampionX measurements were not concurrent, so they did not sample the same state of emissions across all facilities; (2) Bridger did not measure all emissions from the pilot region and therefore represents a minimum bound for comparisons with regional mass balance measurements; and (3) careful extrapolation algorithms need to be developed to estimate regional emissions from facility-level Bridger emissions estimates.

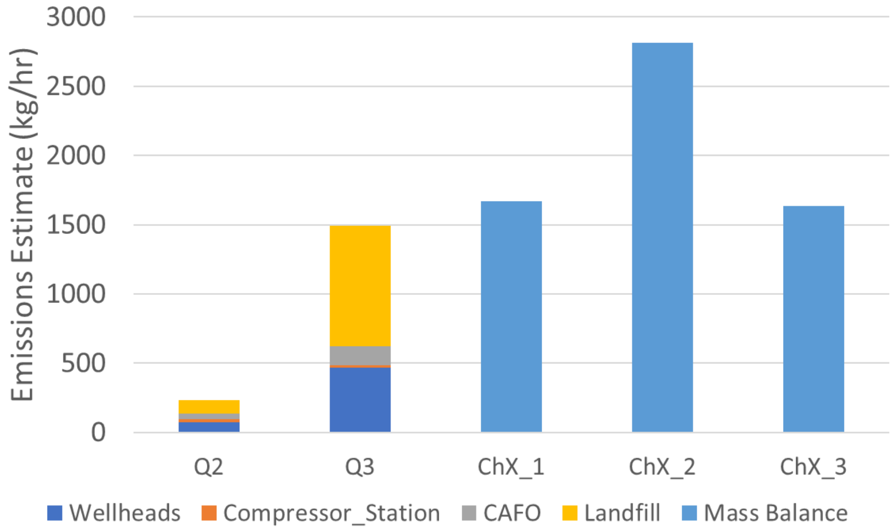

Figure 3-19: Total methane emissions estimates in the northeast pilot region as measured by Bridger Photonics disaggregated by major site types in Q2 and Q3 2023, and regional mass balance emissions estimates during the three measurements by ChampionX.

Figure 3-20 shows total methane emissions in the southwest pilot region as measured by Bridger disaggregated by major facility types in Q2 and Q3, and the three mass-balance estimates by ChampionX in Q3. Because of the large size of the southwest pilot region, ChampionX split the flights into two sub-regions, each shown by a different color. Similar to the northeast region, the regional emissions estimate as measured by ChampionX varied by day of measurement, from 30,000 kg/h to nearly 45,000 kg/h. However, unlike the northeast region, ChampionX measured an average emission of 22,500 ± 6,000 kg/h, which is three times larger than the sum of all Bridger measurements. The difference between ChampionX and aggregated Bridger measurements are statistically significant. This discrepancy could be attributed to several reasons: (1) coal mines are the largest source of methane emissions in the region, with Bridger measuring individual sources that were larger than 6000 kg/h. Furthermore, these same coal mine emissions were highly variable. Thus, it is likely that a large fraction of the discrepancy could be associated with methane emissions from coal mines; (2) Unknown sources including coal mine vents that were not available in public databases and were not included in the measurements for Bridger would have been included in the regional mass balance measurements by ChampionX. Indeed, three sources that were found by ChampionX during the raster scan flight were not known to the study team; (3) conventional wells in the region were not directly measured by Bridger. Although each well is likely to emit low volumes of methane, they can cumulatively contribute to a large fraction of total emissions [24]. Effective reconciliation of regional emissions in the southwest pilot region would require more careful and comprehensive assessment of activity and emissions data in the region. Like before, careful extrapolation algorithms need to be developed to estimate regional emissions from facility-level Bridger emissions estimates.

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[24] Omara et al. (2022). Methane emissions from US low production oil and natural gas well sites. *Nat. Commun.* 13, 2085.

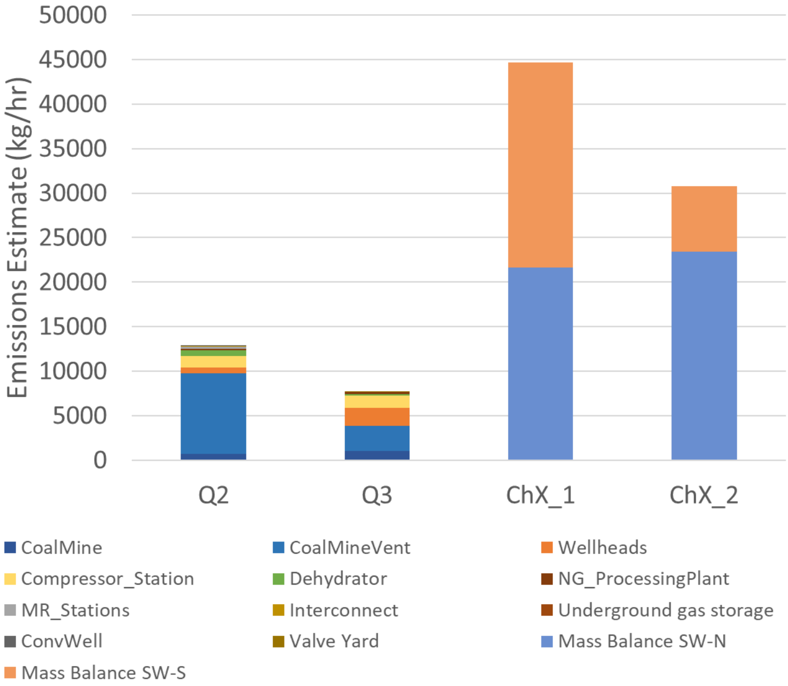


Figure 3-20: Total methane emissions estimates in the southwest pilot region as measured by Bridger Photonics disaggregated by major site types in Q2 and Q3 2023, and regional mass balance emissions estimates during the two measurements by ChampionX. Because of the large size of the pilot region, ChampionX divided the region into two sub-regions that were measured independently.

3.5 Measurement Informed Inventory Model

A measurement-informed inventory (MII) model was developed to account for the frequency and duration of intermittent emission events observed at oil and gas facilities. The MII model incorporates three types of emissions estimates:

a. Measured emissions – Emissions measured by Bridger Photonics, accounting for the frequency and duration of emissions, disaggregated by major equipment type.

b. Below detection threshold emissions – Emissions that are below the detection threshold of the measuring instrument and can be obtained with statistical models or operational data such as leak detection and repair programs.

c. One-time emission events: Emission events that are the result of unique operations such as maintenance activities or events that may have been missed by Bridger at the time of measurement (e.g., liquids unloading event) are included in this category.

Publicly available data or modeled emissions (e.g., below detection threshold emissions) specific to the Appalachian Basin are used to parameterize the MII model. This basin-specific MII model can be further refined by incorporating operational data through root cause analysis, maintenance logs, LDAR records, or other information.

Figure 3-21 presents a case study of the use of the MII model in developing measurement-informed emissions estimates. In this case study, an upstream production site with 3 wells, 6 separators, and 3 tanks was found to have a tank emission of 760 standard cubic feet per hour

(760) as estimated by Bridger measurements or about 32 metric tonnes (mt) for the three-month period between surveys. No emissions were found on the wellheads or the separators. However, basin-wide measurements enable us to develop estimates of the frequency of emissions – in this example, we estimated that only 5% of tanks are emitting at any given time. Similarly, 1% of wells and 4% of separators were also found emitting across the pilot measurement region, even if this specific site did not have any measurable emissions from wells and separators. However, they would exhibit non-zero emissions over the course of three months (time between quarterly surveys).

The basin-specific MII model uses the frequency of emissions from each equipment to scale Bridger's snapshot measurement data. Accounting for the 5% emitter frequency significantly reduces tank emissions over the three-month period. In addition, a basin-wide average number of liquids unloading events that were not directly measured by Bridger was included, resulting in an addition of 0.25 mt of emissions to this site. Finally, using GHGRP data to simulate below detection threshold emissions further added another 1.8 mt of emissions to the site. Overall, the basin-specific MII model help convert an instantaneous measurement of 32 mt for the three-month period to 4.5 mt.

The basin-specific MII model can be further refined using operational data. For this facility, the AMI member provided information about this site including the type of tank (uncontrolled), number of maintenance or other one-time activities, and records of LDAR surveys. This helped further refine a basin-specific MII estimate of 4.5 mt to an operator specific MII estimate of 3 mt.

Thus, an instantaneous measurement equivalent to 32 mt is estimated to be 3 mt, average over the 3-month period between two consecutive surveys. The significant change in total emissions can be attributed to accurate accounting of the frequency and duration of intermittent emissions events, and incorporating emissions that were not directly measured by the technology.

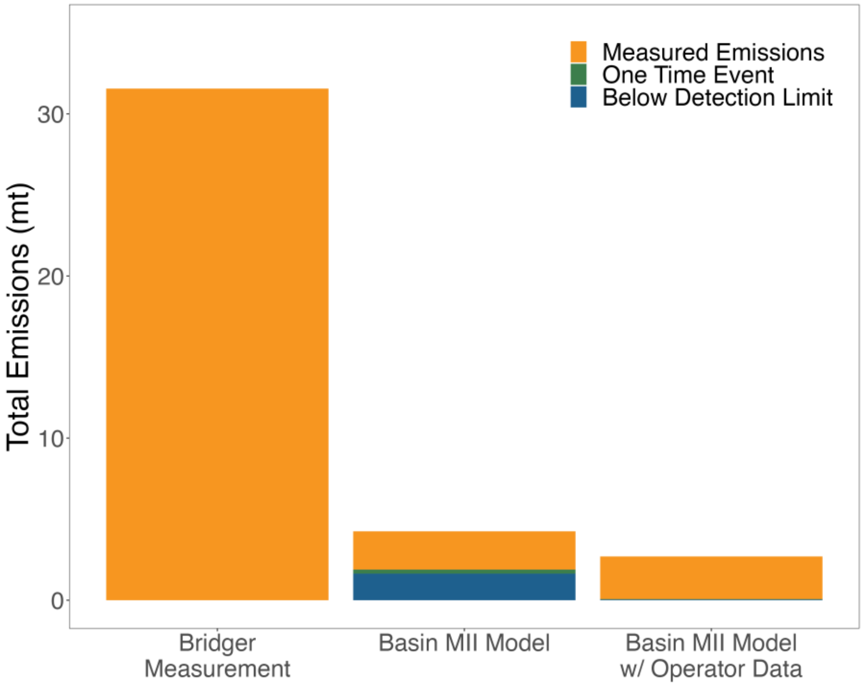


Figure 3-21: Case study of the use of measurement informed inventory (MII) model: Bridger measured an emission equivalent to 32 metric tonnes from a tank at this site (left). Accounting for the frequency of emission events and incorporating basin-wide modeled results for typical one-time events and below detection threshold emissions gives a basin-specific MII of about 4.5 mt. Further refining this number through operational data provided by the AMI member resulted in an operator specific MII of about 3 mt.

4.0 Lessons from the 2023 Campaign

The AMI pilot program was the first comprehensive, large-scale, multi-technology methane emissions measurement and reconciliation campaign in the Appalachian Basin. The pilot program in 2023 helped identify critical elements for a successful methane measurement and mitigation program. This section discusses some of the lessons from the 2023 campaign and how that informs campaigns in 2024 and beyond.

4.1 Importance of Operational Data

Operational data provided by AMI member companies have been crucial to interpreting measurement data. Many of the detailed analyses to develop measurement-informed inventories or reconcile top-down and bottom-up measurements would not be possible without an accurate accounting of operational information including a record of maintenance activities, ground-based leak detection and repair surveys, root cause analysis, and verification of measurement reports. In 2023, operational data was used to develop models such as the measurement-informed inventory model and served as inputs to the MAES model to describe emissions under ‘normal’ operating conditions for midstream facilities. This assists in reconciling measurements with inventory estimates as snapshot methane emissions data can be accurately scaled and extrapolated to develop annualized emissions estimates. Furthermore, operational data and root cause analysis were critical in developing duration estimates for large release events. The proposed updates to the EPA subpart-W greenhouse gas reporting program places a strong emphasis on duration information for large emissions – operational data provides an effective proxy to determine emissions duration. Finally, operational information in the form of identifying and correcting errors made by measurement systems related to equipment or operator-level attribution and identifying emissions sources that are classified as ‘other’ have significantly improved QA/QC procedures associated with measurements.

Recommendation: Expanding, streamlining, and standardizing operational data requests will be critical to enabling accurate interpretation of snapshot measurements and enable reconciliation with emissions inventories.

4.2 Directed Use of Mass-Balance Measurements

The AMI pilot program deployed two types of mass balance measurements with ChampionX. The first type included traditional regional mass balance measurements where ChampionX would conduct large perimeter methane concentration measurements to estimate regional emissions.

Regional mass balance measurements are critical to reconciling facility-level emissions estimates provided by Bridger with regional emissions estimates from ChampionX. During the pilot phase, we were able to reconcile Bridger and ChampionX estimates in the northeast pilot region, but it proved more challenging in the southwest region. Several factors contributed to this challenge including: the presence of unknown large emissions sources (e.g., coal mines), potential emissions from extensive gathering pipeline network, and a lack of availability of comprehensive activity data in the region. Future measurements should also focus on gathering improved activity data for reconciliation exercises.

The second type of measurement was a raster scan over each pilot region, followed by detailed spiral mass balance measurements on select high-emitting sources as identified by the raster scan. The goal of the raster scan was to identify unknown sources of emissions in the region – for example, several coal mines are not specified in public databases and yet are found to be emitting methane. Although ChampionX found three sources that were not previously identified by Bridger measurements, they did not identify or spiral 9 sites that are likely to have large release events as identified by Bridger. Thus, ChampionX is not able to consistently identify large sources of emissions in the region through a raster scan. This is likely because of a combination of temporal variation in emissions, scale of measurement, and technological challenges.

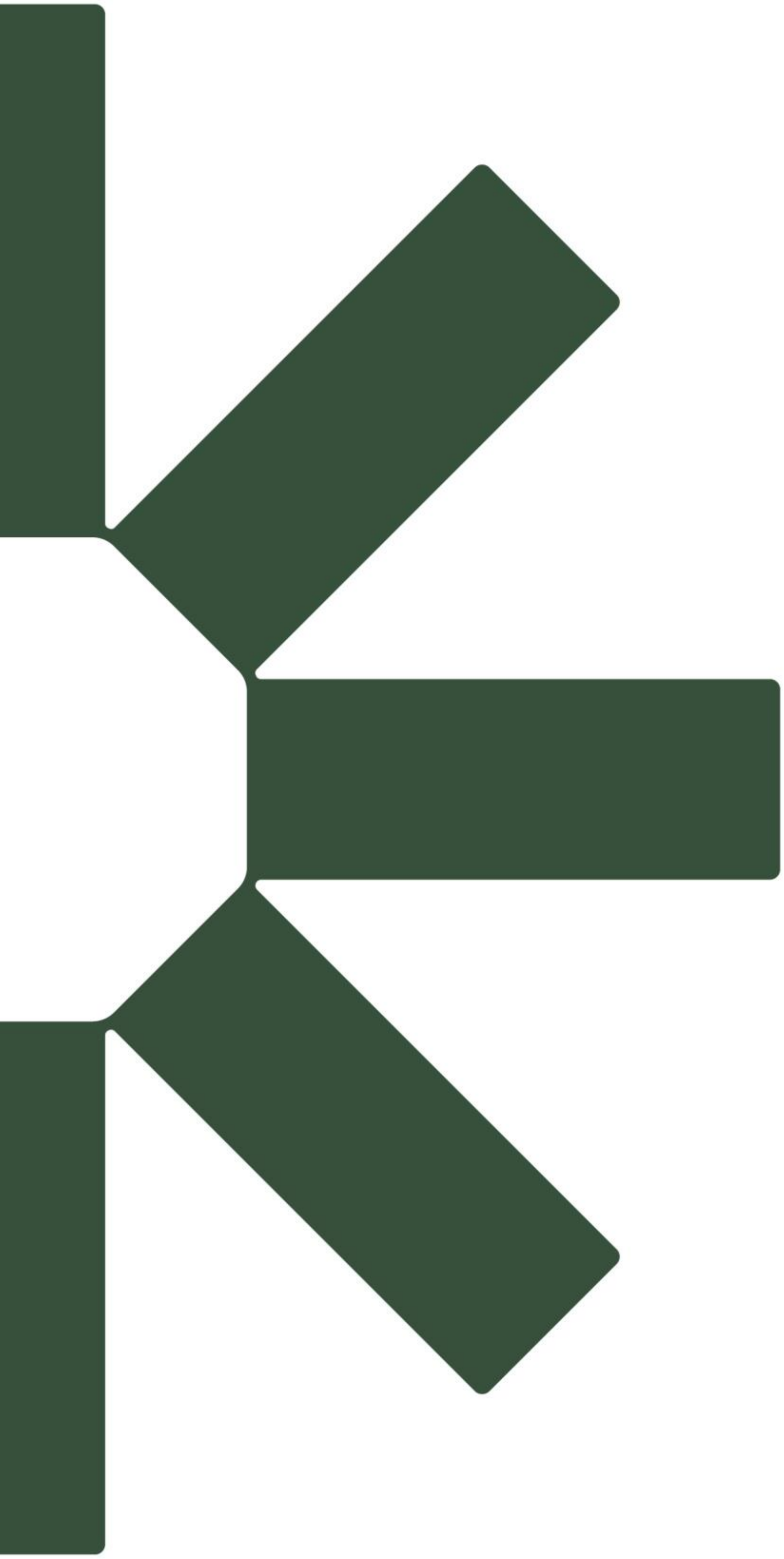
Recommendation: Continue regional mass balance flights, along with parallel efforts to improve activity data in the southwest pilot region. We do not recommend raster scans at this time because of significant uncertainty in identifying unknown large methane emissions. Future technological development may warrant revisiting this decision.

4.3 Use of Satellite Measurements

Satellite measurements were not used as part of the analysis for the 2023 pilot campaign. However, new satellites with high spatial resolution (~300 m) are likely to be launched in 2024 including from the Environmental Defense Fund (EDF) and Carbon Mapper. Data from these satellites can provide independent, top-down methane emissions data that can be reconciled with periodic aerial measurements conducted by Bridger. Inclusion of satellite data has several advantages:

1. A major challenge with satellite detection of methane emissions is attribution to various sources. This is further complicated in the Appalachian Basin because of the variety and magnitude of sources seen in the 2023 pilot campaign – coal mines and coal mine vents are located next to oil and gas facilities. Given that coal mines are a significant source of large release events, misattribution of satellite data could inadvertently suggest high oil and gas methane emissions in the region. Helping satellite developers improve their attribution capability using ground-based emissions information collected by AMI will be a mutually beneficial exercise.
2. Satellites provide increased coverage (albeit at lower resolution compared to aerial surveys) over the Appalachian Basin with revisits times less than one week which can improve detection and estimation of the duration of large release events, compared to quarterly aerial surveys.
3. Satellite technologies are rapidly improving both in their spatial resolution and minimum detection threshold. Thus, it is imperative that AMI develops an underlying framework to access satellite data in the future.

Recommendation: Attempt to coordinate with entities that are launching satellites targeting methane emissions from oil and gas operations and develop a framework to enable AMI to make the best use of future advances in satellite technology.



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