RESEARCH ARTICLE

Methane venting from uncontrolled production storage tanks at conventional oil wells—Temporal variability, root causes, and implications for measurement

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Uncontrolled oil production storage tanks are important but poorly understood sources of methane (CH_4) emissions in the upstream oil and gas sector. This study reports and analyzes directly measured, temporally varying CH_4 emission rates, total gas vent rates, and vent gas CH_4 fractions from storage tanks at eight active upstream oil production sites in Alberta, Canada. Using a built-for-purpose optical mass flux meter (VentX) supplemented by an ultrasonic flow meter and quantitative optical gas imaging camera where possible, mean vent rates (whole gas) among tanks in the study ranged from 37 to 598 m^3/d; however, at some individual tanks, instantaneous flow rates could vary significantly from 0 to over 4,000 m^3/d for minutes at a time, while unsteady CH_4 volume fractions varied by up to 41% absolute. Root cause analysis revealed the limits of estimating vented emissions from oil production volumes using an assumed gas–oil ratio, especially in cases where produced gas from wells fully or partially bypasses separators. The analysis of the acquired data also demonstrated how 1-h duration vent measurements recommended in some regulations are insufficient to reliably estimate emissions from unsteady tanks. These two factors are the likely reason for significantly underreported vent rates in the present sample and are thought to be a key cause of the mismeasurement/underestimation of tank venting that has driven persistent gaps between bottom-up inventories and top-down measurements. Finally, detailed statistical analyses were completed to suggest minimum sampling durations and instrumentation requirements for direct measurements of tanks and minimum sample sizes for discrete ("snapshot") surveys of both individual tanks and multitank surveys under different scenarios. Results show that caution is warranted when interpreting snapshot measurements of individual tanks, but aggregate emissions of multiple tanks should be accurately measurable with readily achievable sample sizes. These results are expected to be especially valuable to ongoing efforts seeking to develop robust protocols for gas certification and measurement, reporting, and verification (MRV) of CH_4 emissions in the oil and gas sector.

Keywords: Storage tanks, Methane, Venting, Temporal variability, Sampling requirements, Root causes

1. Introduction

Rapid and sustained reductions in methane (CH_4) emissions are critical to limiting global warming and avoiding the worst impacts of climate change (Intergovernmental Panel on Climate Change, 2021). The oil and gas sector is a dominant source of CH_4 emissions in many parts of the world and a key focus of near-term mitigation efforts. Moreover, recent field studies have consistently observed much higher emissions than suggested in official national inventories across multiple jurisdictions including the United States (Alvarez et al., 2018; Robertson et al., 2020; Zhang et al., 2020; Chen et al., 2022), Canada (Chan et al., 2020; MacKay et al., 2021; Tyner and Johnson, 2021; Johnson et al., 2023a), and Mexico (Zavala-Araiza et al., 2021). One specific oil and gas sector source, production storage tanks, has been suggested as a key contributor to these discrepancies (Rutherford et al., 2021; Tyner and Johnson, 2021; Johnson et al., 2023a) while pointing at an area with significant mitigation potential. Recently, Johnson et al. (2023b) combined aerial measurements with on-site investigations to determine the origins of detected emissions, finding that both controlled and uncontrolled storage tanks were a significant contributor to oil and gas sector CH_4 emissions in British Columbia, Canada, despite regulations mandating three leak detection and repair (LDAR) surveys per year. However, in general, storage tank venting remains poorly understood, with most studies relying on qualitative observations using

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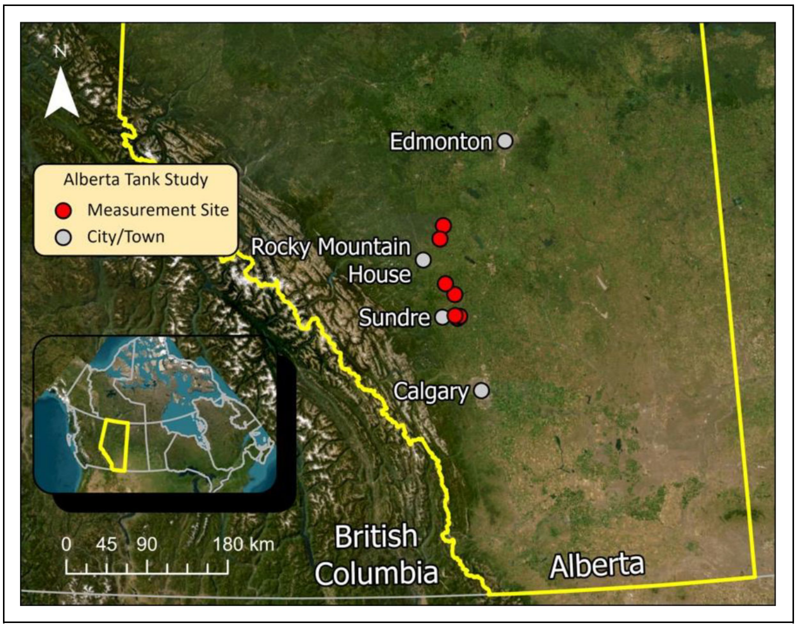

Figure 1. Map showing the approximate locations of the eight instrumented storage tanks (red circles) at operating single- and multiwell oil batteries.

optical gas imaging (OGI) cameras (Lyon et al., 2016; Mansfield et al., 2017; Englander et al., 2018; Lyman et al., 2019) rather than quantitative measurements. The lack of quantified tank measurements was underscored by Rutherford et al. (2021) who, given a lack of options in the literature, necessarily relied on data from a single tank venting study (Eastern Research Group, 2011) in their proposed update to the U.S. national inventory supplemented by flashing loss measurements from Hendler et al. (2009). These two studies were also geographically limited to the State of Texas. In particular, there is a dearth of continuous measurement data for tanks, which is a further gap considering studies highlighting potential uncertainties in relying on discrete (snapshot) measurements when quantifying intermittent sources (Schwietzke et al., 2017; Vaughn et al., 2018; Johnson et al., 2019; Alden et al., 2020; Riddick et al., 2020).

The objectives of this study were to (i) complete direct, on-site, time-resolved measurements of unsteady (timescales of seconds to hours) CH_4 and total gas (i.e., "whole gas," which includes all species in the vented gas) venting from uncontrolled oil storage tanks at upstream production sites, (ii) to investigate and better understand the characteristics and root causes of storage tank venting with a specific focus on vent variability and intermittency, and (iii) to complete statistical analysis to glean insights into measurement and sampling requirements to improve the accuracy of tank emissions estimates under different scenarios. Results of this work provide insight into the drivers of emissions, the limits of current estimation approaches based on gas–oil ratios (GORs), and the inadequacy of 1-h measurement guidelines in some current regulations. In addition, the results of the sample set of tanks are used to provide guidance on frequency response requirements for instrumentation used in tank measurements, on interpreting data from discrete measurements of individual tanks, and on conducting broader surveys of multiple tanks.

2. Methods

2.1. Study area

On-site, field measurements of CH_4 venting from eight liquid storage tanks were conducted over two separate campaigns in a region near Sundre and Rocky Mountain House, AB (see **Figure 1**): the first four from September 28 to October 8, 2021, and second sample of four from November 3 to 12, 2021. In collaboration with producers operating in these regions, viable measurement sites were identified by the field team as preferentially having a single uncontrolled production storage tank that was thought to be venting, with a well pad layout conducive to accessing the tank. Importantly, the tanks were preferentially chosen because they were known to be uncontrolled and venting, pursuant to the main goals of understanding the character of tank emissions, root causes, and potential implications for current measurement and estimation approaches. The candidate tanks were identified via a combination of operator knowledge, observations from the field team, and results of past aerial CH_4 surveys in these regions. As further detailed in the Supplemental Information (SI), these sites were a mix of single and multiwell oil batteries, all using conventional production methods. Seven of the eight sites operated with beam pumps (commonly called pump jacks), while one site with significant gas coproduction used a plunger lift system. These various encountered site configurations, each with an uncontrolled production tank, are found across oil producing regions of both Alberta and Saskatchewan; however, the relative frequency of each is not publicly known. All sites were actively producing during this study period, although one well's pump was turned off for maintenance midway through measurements as

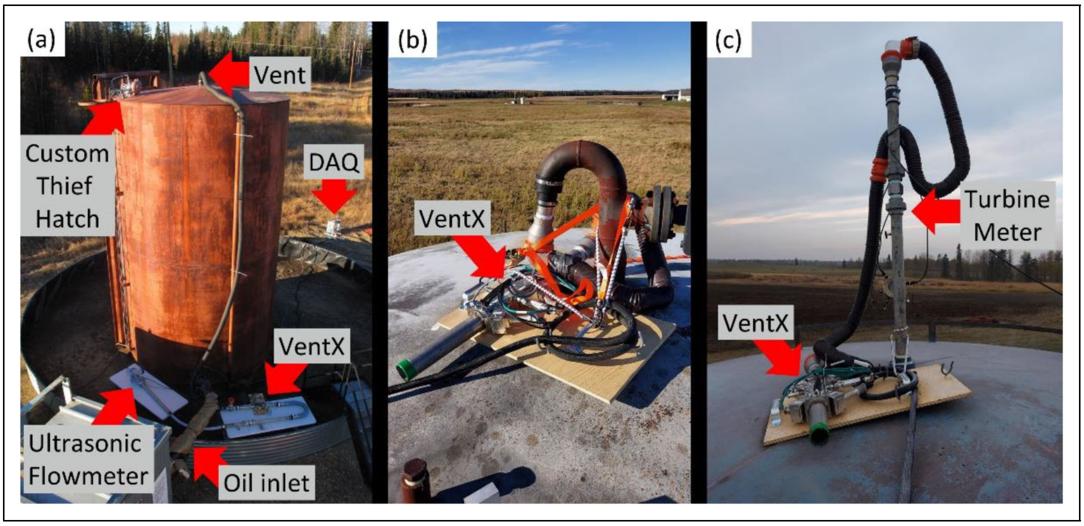

Figure 2. Images of equipment configurations for on-site tank measurements. (a) Measurement setup on a storage tank with the VentX and ultrasonic flow meter at ground level. The custom thief hatch was installed at this site. The data acquisition system is located in a safe area outside of the tank berm. (b) VentX installed on a tank top, with flexible hose to accommodate the gooseneck. (c) VentX and a turbine meter (the latter threaded into tank vent vertically) on tank top.

elaborated in Section 3.2.1. Total measurement time at each site varied from 4.2 to 68.8 h. While the present sample size is small and further on-site measurement studies building upon the approaches and analyses presented in this article should absolutely be pursued, to our knowledge, the presented results are the only source of high-fidelity temporal CH_4 emissions data for uncontrolled storage tanks available in the literature to inform improved regulations and guide measurement requirements for future studies.

2.2. Measurement methodology

Time-resolved CH_4 and total gas (whole gas) emission rates were measured by directly connecting to the vent outlet on each site's uncontrolled oil production storage tank using a VentX meter (Festa-Bianchet et al., 2022; Seymour et al., 2022). This instrument uses wavelength modulation spectroscopy with second harmonic detection targeting CH_4 absorption at 1,659 nm to simultaneously and nonintrusively measure both total vent flow rate (via Doppler shift) and CH_4 volume fraction (via selective absorption) at up to 2 Hz with an instantaneous CH_4 mass flow rate precision of $\pm$0.40 kg/h at 95% confidence in lab tests over a range of CH_4 fractions and total flow rates as detailed in Seymour et al. (2022). The VentX flow cell was specifically designed for low-pressure applications such as storage tank venting and features an unobstructed internal diameter of 52.5 mm. Due to the intermittent nature of tank venting and mixing of ambient air into the tank's vapor space, the ability to continuously monitor CH_4 content in the vented vapors is critical for accurate CH_4 emission rate quantification. As shown in **Figure 2**, the VentX meter was connected to the tank's atmospheric vent, either directly on the tank top (Sites A through D) or at ground level using a 9 m length of 100-mm ID flexible duct (Sites E through H). The latter method was preferred for simpler access to instrumentation, ease of collecting extractive samples, and improved safety by minimizing work performed at height. The ground-level flow measurements were further supplemented with an ultrasonic flow meter (Khrone, Optisonic 7300 C/i-Ex) at three of the four sites (space constraints precluded also installing it on the tank top). As further discussed in the SI (Section S1.6), at Site F, back pressure concerns during periodic spikes of high venting precluded use of the ultrasonic meter. This study shared resources, such as an articulated lift, with an independent industry-led study using turbine meters to measure the same storage tank vents. At certain sites, VentX measurements were therefore collected with a 2″ turbine meter installed in series, as shown in **Figure 2a** and **c**. Data collected during this separate study were not made available to the authors.

The packaging of the optoelectrical components of the VentX meter was further improved from the system described in Seymour et al. (2022) and used in recent field measurements of casing gas vents at heavy oil sites (Festa-Bianchet et al., 2023). Specifically, the laser diode, associated controllers, lock-in amplifiers, frequency generators, and data-acquisition hardware were integrated into a custom electronics board designed and manufactured by the Institut national d'optique (INO, Quebec City). This board was housed in a thermally controlled enclosure (nVent Hoffman, TE162024011), which was placed in a safe area and connected to the VentX flow cell using 30 m of fiber optic and electrical cabling. The enclosure also contained a fanless PC (Tangent, Rugged Mini E3) that controlled the VentX system, processed the demodulated signals from the INO board, acquired data from an external data acquisition system (Labjack, T7), and logged all results. Most importantly, the updated design permitted integration of a custom-instrumented thief hatch, which was installed when possible/permitted in place of the tank's original thief hatch to ensure an adequate seal. Consistent with these being uncontrolled atmospheric tanks with open gooseneck vents, the thief hatches at most sites either had failed gaskets or did not close properly, with most left open. Failed gaskets were replaced at sites where the custom thief hatch could not be installed. All tanks in the study also featured a small hole, approximately 1″–2″ in diameter, to allow for the operation of a level float. These holes were sealed to the best of the field team's ability by stuffing them with a rag or with tape. A handheld OGI camera (Teledyne FLIR, GFX320) was used at all sites to visibly inspect the entire tank to ensure that vent gas primarily flowed through the gooseneck vent and any secondary leaks or emission points were minimized.

The custom thief hatch was instrumented with a radar-level sensor to measure tank fill level and a gauge pressure sensor. At Sites G and H, a position sensor was also installed to log any potential openings of either the vacuum or pressure plate within the thief hatch, as well as a resistance temperature device to record the head space temperature inside the tank. All instruments on the thief hatch system were intrinsically safe and protected by appropriate isolation barriers to permit deployment in flammable gas environments. In addition, at Sites E through H, parallel attempts were made to measure venting rates using a QL320 quantitative OGI (QOGI) system consisting of the GFX320 camera ($f = 23$-mm lens) combined with a QL320 tablet. QOGI measurements were unsuccessful at Site F due to the lack of defined plume created by the pooling of vent gas inside the tank's berm as the gas rapidly exited the VentX flow cell. All QOGI measurements were made using a response factor for pure CH_4 (0.297) in the QL320 software (v. 1.4.1) to reflect an assumption that would be made during a QOGI survey, where gas composition was unknown. At six of the eight sites, extractive gas samples were taken using a hand pump for gas chromatography (GC) analysis by a third-party laboratory. These GC results (see Section S2 in the SI) confirmed the key capability of the VentX in tracking potentially variable CH_4 volume fraction of the emitted gas for accurate CH_4 emission quantification.

3. Results and discussion

3.1. Unsteady character of tank venting

Figure 3 shows temporally varying vent rate data for the eight instrumented storage tanks, with separate curves indicating total volumetric flow and measured CH_4 volume fraction in the vent stream. Also included in this figure are the CH_4 volume fractions from GC analysis of discrete gas samples taken at the indicated times (see SI Section S2 for all results) and industry reported site total vent rate (Petrinex, 2022). Mean rates are summarized in **Table 1** alongside a discussion of suspected root causes; further site details are provided in the SI. There are significant differences in the character of the emissions among sites: one half of sites (A, B, D, and H) showed continuous venting with some modest variation over the course of the measurement period, while the other half exhibited fluctuating vent rates relative to some nonzero base flow rate (Sites C and G) or variable plus intermittent venting that included periods of zero flow (Sites E and F). Data gaps in the plots are associated with periodic checking and cleaning of the windows in the VentX flow cell due to gas condensation or oil droplet deposition and/or occasional disconnection of the vent gas stream to either inspect for ice buildup or remove/install other instruments such as the turbine meter used in a separate industry-led field study. At Sites A and E, the vent line was also disconnected overnight at the requests of site operators. Only ultrasonic flow rate data were available for Site H as noted in the SI.

Measured CH_4 fractions in the vented gas stream also varied but were generally more stable than the corresponding total vent rates. However, the observed average CH_4 fractions differed greatly among the eight sampled storage tanks, spanning 22% to 76% CH_4. These two factors illustrate the importance of coupling site and/or tank-specific CH_4 fractions with any technology that only records total gas vent rates when reporting CH_4 or greenhouse gas emissions. The CH_4 fraction at sites with intermittent venting behavior (Sites C, E, F, and G) was generally more variable than at those with a more consistent outflow of gas (Sites A, B, D, and H). Additionally, sites with significant periods of zero outflow (Sites E and F) emitted gas with a lower CH_4 content than those with a mostly sustained outflow in between intermittent spikes (Sites C and G). This behavior is assumed to be linked to temperature-driven "breathing" of the tank. In the absence of a steady outflow of gas, cooling of the vapor in the headspace of the tank (which commonly occurs through diurnal temperature variations) will cause the tank to ingest air (American Petroleum Institute [API], 2021). In the subsequent periods of outflow, a mixed air/vapor stream with relatively lower CH_4 content is emitted. Further, fluctuations in the CH_4 fraction at sites with consistent outflow were found to be inversely linked to ambient temperature trends, presumably as colder temperatures led to lower volatile organic compound (VOC) vapor pressures as further discussed for Sites G and H in the SI.

The CH_4 volume fraction as measured by the VentX meter agreed well with the results of the GC analysis of the collected samples, including tracking changing CH_4 content over different days. Overall, the VentX meter underestimated CH_4 content when compared to the GC results by an average of −5.9% absolute (further discussed in Section S2 in the SI). While much of this difference is attributable to water vapor in the vent gas that is not quantified by the GC (Festa-Bianchet et al., 2023), additional vent gas species not present during calibration can also introduce uncertainty in the VentX reported CH_4 fraction (via secondary collision broadening, even though these species are not directly absorbing at the selected wavelength; Festa-Bianchet, 2023), such that uncertainties of up to −3.4 to +5.8% can be expected under present field conditions (see SI, Section S2). Most importantly, the results of **Figure 3** show how the CH_4 content of uncontrolled storage tank emissions not only varies among tanks/sites but can also vary in time, where the latter effect is most prominent for intermittently venting tanks.

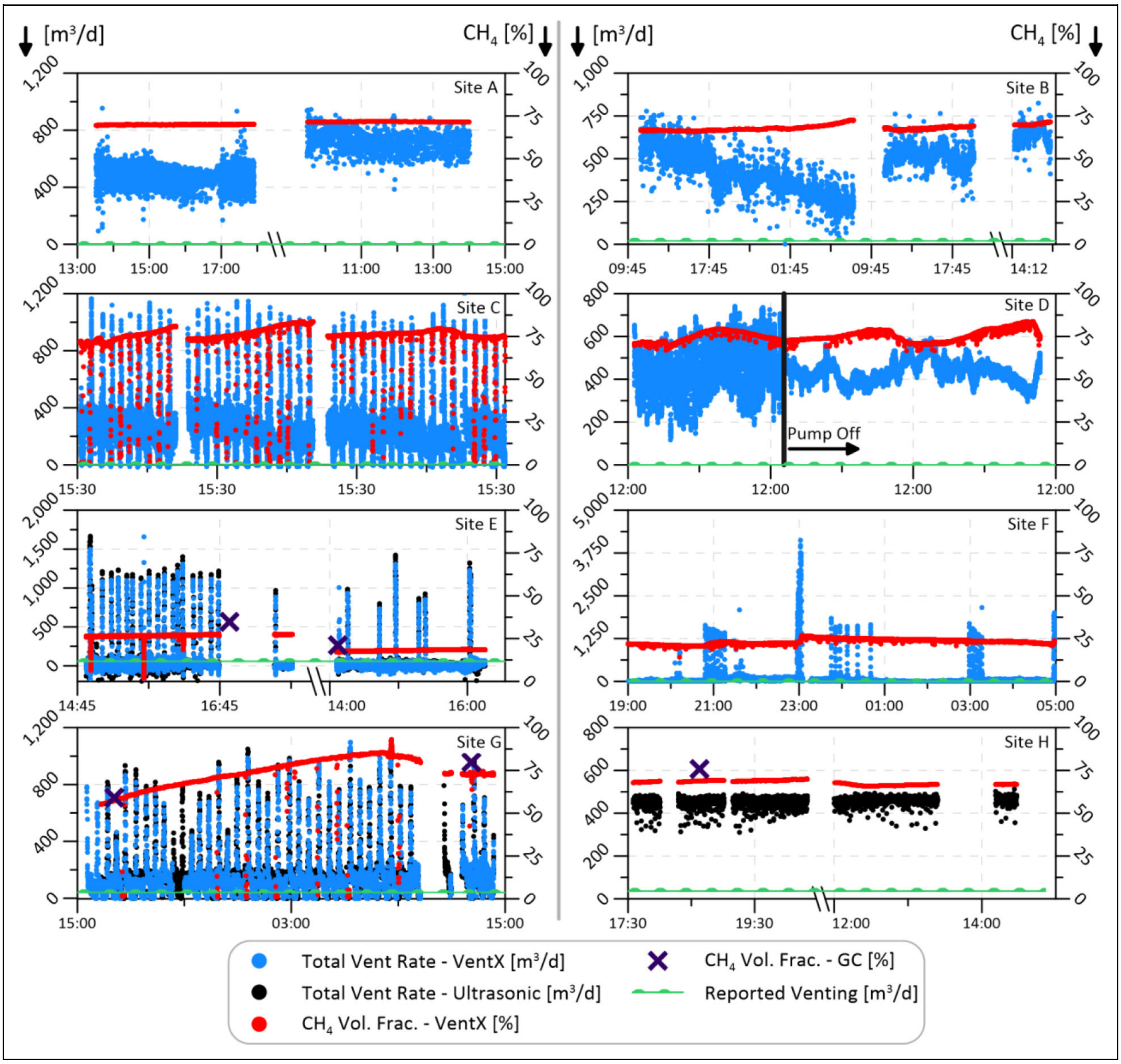

Figure 3. Time-resolved vent rates (whole gas) and methane fractions for the eight storage tanks at eight distinct sites. Also included are the gas chromatography results for methane in the extracted samples when these overlapped with the included measurement periods and site total reported vent volumes (Petrinex, 2022). Breaks in data correspond to intervals, where the flow cell windows were cleaned or where the vent line was temporarily disconnected. Additional measurement data of vent events during a plunger lift arrival for Site F are included in the SI, as well as expanded figures showing details of the venting patterns of each tank.

As elaborated in Section S3 of the SI, the QOGI software generally struggled to accurately resolve the vent plumes and failed to accurately measure vent rates. These difficulties may have been exacerbated by nonuniform backgrounds (e.g., mixture of storage tank wall, ground, and piping from this study's instruments or site infrastructure) and low thermal contrast between these backgrounds and the emitted gas, which was close to ambient temperature after residing in the storage tank. As shown in Section S1.8 of the SI, QOGI measurements at Site H (the most steadily venting tank) were slightly improved after the flowmeters and piping were rearranged to improve the visibility of the exit plume, but QOGI data were still highly scattered relative to direct measurements. Close analysis of Sites E and G suggests that intermittent spikes in the storage tank emission rate seen in the VentX or ultrasonic data were not accurately measured by the QOGI system. Overall, the lack of correlation between the QOGI estimated and directly measured vent rates presented in Section S3 of the SI suggests that QOGI is not accurate in the present application.

3.2. Observed root causes of emissions

Table 1 summarizes the suspected root causes of emission for all eight storage tanks along with relevant measurement data. These root causes are of particular interest to operators seeking to mitigate their emissions and regulators considering policy options to drive reductions.

Table 1. Summary of measurement results and suspected root causes of emissions

Site	Measurement Duration[a] [h]	Mean CH_4 Volume Fraction [%]	Mean CH_4 Vent Rate During Measurement Period[b] [kg/h]	Mean Vent Rate (Whole Gas) During Measurement Period [m^3/d]	Total Measured Venting (Whole Gas) During Measurement Period [m^3]	Reported Total Site Venting (Whole Gas) During Month[c] [m^3]	Expected Average Monthly Site Vent Rate (Whole Gas) from Reporting[d] [m^3/d]	Best Guess Root Cause of Observed Venting
A	8.9	70.8	12 (11.96–12.00)	598	222.5	0.0	0.00	One of the two wells bypassing separator
B	36.5	68.5	9.2 (9.16–9.19)	473	719.8	600	20.1	Unknown
C	68.8	76.4	5.4 (5.39–5.43)	248	709.4	100	3.23	No separator
D	67.5	75.3	9.4 (9.41–9.43)[e]	443	1,246	0.0	0.00	No separator
E	4.2	22.3	0.28 (0.26–0.30)	40.8	7.1	1,700	58.3	Flashing losses after separator dump valve actuation
F	12.3	21.9	0.22 (0.13–0.32[f])	36.9[g]	49.8[h]	0.0	0.00	Gas entrainment during liquid unloading of plunger well
G	20.2	72.4	3.0 (3.01–3.06)	144	121.6	1,200	41.3	Bypassing separator
H	4.2	67.9	8.7 (8.69–8.77)	455	79.6	1,100	36.7	No separator

[a]Measurement duration represents the total hours of measurement data available for each site.

[b]The 95% confidence interval of the mean CH_4 vent rate during the measurement was calculated by adding in quadrature the precision of the mean over the recorded time series (calculated via a block bootstrap; Hall, 1985; Carlstein, 1986) using a block length of $n^{1/5}$ (Hall et al., 1995), where n is the number of data points in the time series for each tank and the VentX's calibration uncertainty of ± 0.0112 kg/h (derived from multiday flux data first reported in Seymour et al., 2022). For Site H, an ultrasonic flow meter uncertainty of ± 0.0397 kg/h was used, calculated by propagating the manufacturer specified maximum velocity error (± 15 mm/s) with the VentX's volume fraction calibration uncertainty (± 232 ppm) derived from the same data in Seymour et al. (2022).

[c]Reported vent volumes (available through the Petrinex [2022] reporting system) are for the month during which measurements occurred. If a storage tank was instrumented across 2 months (e.g., from September 30 to October 3 for Site B), the average reported volumes for the 2 months were used.

[d]Calculated as the total reported volume divided by the reported production hours.

[e]Includes data from when the beam pump was turned off. Mean methane vent rate was 9.68 kg/h (total gas vent rate of 455 m^3/d) when the pump was operating.

[f]Average vent rate for Site F was calculated by bootstrapping data measured during unloading events coupled with the frequency of these events as further explained in the main text below.

[g]Mean whole gas vent rate for Site F was based on mean whole gas emitted per liquid unloading event and 4-h cycle time.

[h]Includes gas volumes from partially recorded unloading events, which were not used to determine mean emission volume per unloading.

However, in general, attributing root causes can be notoriously difficult due to the many overlapping potential drivers of emissions, including traditional working, breathing, and flashing losses (U.S. Environmental Protection Agency [U.S. EPA], 2020), separator dump valve malfunctions (Lyon et al., 2016), liquid unloadings (Allen et al., 2015), or direct emission of gas bypassing the separator, all of which result in emissions from the same source (i.e., the tank's thief hatch or gooseneck). At six of the eight sites, CH_4 venting was related to the operation of the separator (Site E), partial (Site A) or complete (Site G) bypassing of the separator, or lack of a separator (Sites C, D, and H). A plunger lift system drove venting at Site F, and the source of venting at Site B could not be definitively determined.

In an ideal production scenario, all produced gas would be removed from the liquid stream at the separator, after which the gas could be conserved into pipelines, used for onsite fuel, or combusted. However, separators operate at elevated pressures to facilitate the flow of fluids from the separator, such that the pressurized oil leaving the separator and entering the storage tank will inevitably contain some amount of gas in solution (GIS). Once the oil reaches the atmospheric pressure storage tank, this dissolved gas will then "flash" into the tank's vapor space, displacing an equivalent volume of headspace gas out of the tank (U.S. EPA, 2020). These flashing losses are believed to be the cause of the regular spikes in instantaneous vent rate at Sites E and F. Emission rates from such sites are intermittent and tied to the frequency of dump valve actuation, which is itself tied to oil production rate. Further, a rare and difficult to identify failure mode of separators is a slow or stuck dump valve, which allows gas to flow directly to the tank while the liquid level in the separator is below the dump valve (Lyon et al., 2016). It is possible that the continuous venting from the storage tank at Site B, which did have a separator, was due to a stuck dump valve. Although working and breathing losses are an important contributor to VOC emissions, relative to other causes they are not thought to be a significant cause of CH_4 emissions (Lyon et al., 2016; API, 2021). See Section S2.1 of the SI for further discussion of the non-CH_4 species in the vented gas.

For the sites bypassing or operating without a liquid–gas separator, the root cause is relatively simple: gas produced by the well, either dissolved in solution or as a two-phase flow, is delivered directly to the production storage tank, where it is free to exit through the atmospheric vent. This simple configuration is more common at older single-well facilities or in certain plays where produced gas is not conserved and expected vent volumes are below regulated limits. Multiwell sites generally include a liquid–gas separator between the well and the production storage tank, such that the produced gas can be sent into a pipeline or handled on site if the well is isolated (e.g., used as fuel and/or destroyed). Closer inspection of repeated vent spikes from Sites C and G, where the former is operating without a separator and the latter bypassing it, was attributed to slugs of oil traveling between the well and tank, momentarily interrupting the steady vent of gas occurring between these spikes.

3.2.1. Apparent variability in GOR versus GIS

At upstream oil production sites, produced gas volumes are commonly estimated using a predetermined GOR value that is multiplied by oil production, which may be directly metered or measured after being offloaded from storage tanks into trucks and delivered for processing (Saskatchewan Ministry of Energy and Resources, 2020; API, 2021; Alberta Energy Regulator [AER], 2022). Vented volumes from tanks are then commonly estimated from this GOR-derived produced gas volume data (after accounting for any volumes of sales gas delivered from the site which is generally metered as it leaves the site and enters a pipeline) or using a GIS value of the oil entering the tank that is similarly multiplied by oil production. Closer analysis of the time-resolved CH_4 vent rate from the storage tank at Site C (simple site with no separator where a single beam pump delivers oil from the well directly to the tank) demonstrates the inherently unsteady drivers of tank venting and the challenges of estimating vent rates using GOR or GIS values. The observed vent rate at Site C followed a well-defined pattern, with regularly repeating spikes in vent rate between periods of constant venting. A similar venting pattern was seen from the storage tank of Site G, where the separator was bypassed. These spikes in vent rate are linked to the delivery of slugs of oil from the well to the tank and correspond with step increases in the tank fill level, as measured by the radar level sensor in the instrumented thief hatch (**Figure 4b**). Considering the entire period shown in **Figure 4a**, the measured total vent gas volume and total produced oil (estimated by the net change in tank fill) equate to a GOR of 397 m^3/m^3. Interestingly, the estimated GOR of 493 m^3/m^3 during the first 7 h (demarked by dashed black line in **Figure 4a**) is notably different from the 325 m^3/m^3 during the latter 6 h. This apparent variability in GOR is presumably because the vented gas is not only coming from GIS but also from the production of associated gas as a two-phase flow. Thus, there is a disconnect between produced oil volume and vent volume. Indeed, these GOR values are well above the threshold of 100 m^3/m^3 suggested by Peachey (2019) as indicative of a two-phase flow of oil and associated gas.

As a thought experiment, an estimated GOR due solely to GIS (denoted GIS-GOR) was calculated during the spikes in venting associated with oil arrival (i.e., integrating the cross-hatched region as shown for one example in **Figure 4b**). Averaged over the eight vents spike shown in **Figure 4a**, this calculated GIS-GOR was 98 m^3/m^3, which is less than one quarter of the apparent GOR during the total period of the figure and just within the expected range indicative of single-phase flow. This further underscores the challenge of using GOR to estimate vent volumes, where not only does GOR seem to change over the course of a single day, but vented gas driven by a combination of GIS and coproduction of associated gas is unlikely to be linearly correlated with oil production. This latter point is most strongly supported by the results of Site D (also a simple site with no separator), where the mean total vent rate from the storage tank only reduced from 455 to 436 m^3/d (from 9.6- to 9.3-kg/h CH_4) when oil production was stopped to regrease the well's pump.

3.2.2. Venting associated with a plunger lift system

Plunger lift systems, which use the natural pressure of the deposit to drive a plunger up to the surface, are sometimes used at gas wells to enable efficient removal of built-up liquids within the well bore. On a gas well, this removal process is a form of liquid unloading, which can

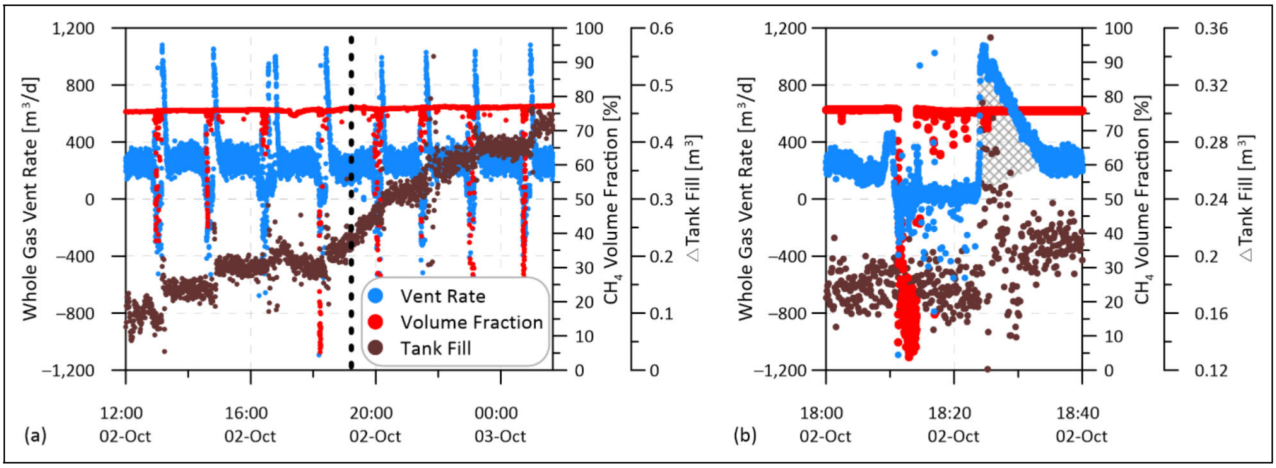

Figure 4. Analysis of directly measured gas–oil ratio (GOR) and gas in solution (GIS) during repeated spikes in venting. (a) Selection of flow rate data from Site C using the VentX meter, showing regular spikes in vent rate between periods of steady venting. These spikes repeated every 1 h and 43 min on average. Included in brown is the change in fill volume of the tank during this period, showing the sudden arrival of produced liquid coinciding with the spikes in venting. Dashed black line separates the included data into two periods for analysis of the GOR during each period. (b) Single spike in vent rate from (a). Cross-hatched area shows integrated volume of gas used in GIS estimate.

be an important driver of CH_4 emissions from gas wells (Allen et al., 2015). In the case of Site F, a plunger lift operating on a 4-h cycle was used to regularly bring both gas and oil up to a separator at the surface, where the gas was separated into a pipeline and the oil was diverted to the on-site storage tank. This unloading led to brief periods of high venting as any remaining dissolved gas in the oil (GIS) flashed out when the oil reached the atmospheric pressure tank. Five unloading events were measured by the VentX meter as plotted in **Figure 5a–e**. Although the interval between unloadings was regulated by the 4-h cycle controller, the temporal variation and emitted gas volume during each event differed. It was not possible to install the custom thief hatch system at this site, and as the flow rate reached its maximum during three of the measured events, some additional unquantified volume was released through the tank's hatch (note the clipped peaks in **Figure 5a, c**, and **e**).

A bootstrap analysis of the measured unloadings conservatively suggests a release of 3.2–9.3 m^3_{gas}/event, with a mean of 0.77–1.9 $m^3_{CH_4}$/event at 95% confidence, corresponding to a time-averaged CH_4 emission rate of 0.13–0.32 kg/h. However, without quantification of the contribution of additional leakage through the thief hatch during periods of highest instantaneous vent rates, these results serve rather as a confirmation of the variability in plunger lift liquid unloading emissions. This was previously observed by Allen et al. (2015), who measured a range of 1.6–244.1 $m^3_{CH_4}$/event over 295 individual events at 25 wells with automatic plunger lifts, with a mean of 14.2–59.5 $m^3_{CH_4}$/event at 95% confidence. This is the basis for the single-valued liquid unloading emission factor of 36 $m^3_{CH_4}$/event currently suggested for level 3 reporting under OGMP 2.0 for wells with >100 events/year (OGMP2.0, 2022). This emission factor is likely to notably overestimate emissions from the tank at Site F, which highlights the importance of direct measurement for sources that have potential to be highly variable. Also, the underlying thermal mass meter measurements in Allen et al. (2015) were composition-corrected (via a simple scaling by thermal conductivity) assuming the vented gas matched the reported composition of gas at the well (mean CH_4 content of 84%), whereas the present data (**Figure 3** and as tabulated in Section S2 of the SI) show that the vented gas from the tank can be quite different. While the OGMP 2.0 recommendations for Level 4 measurement of liquid unloadings suggest that techniques "for determining CH_4 content can be employed" (OGMP2.0, 2022), there is no further guidance provided on where this gas can be measured or caution on how the composition might vary temporally. More generally, there is a clear need for further measurement studies of CH_4 emitted during liquid unloadings and the present results can hopefully be useful as a guide for designing future measurement campaigns.

4. Implications for measurement and reporting

4.1. Current reporting based on GOR or 1-h measurements likely inaccurate

The preceding analysis illustrates the challenges in accurately measuring CH_4 venting from uncontrolled storage tanks in which the vent rate is generally unsteady, the CH_4 content can vary, and there can be multiple factors driving emissions and influencing emission rates. These challenges have parallel impacts on reporting efforts, with several recent studies (Rutherford et al., 2021; Tyner and Johnson, 2021; Johnson et al., 2023b) suggesting actual emissions from tanks are much higher than suggested in current bottom-up inventories. This supposition is directly supported by the present measurements, as shown in **Figure 6**, which compares the mean emission rates from the eight storage tanks to their corresponding *site*-total reported emissions for the corresponding month (Petrinex, 2022). At seven of the eight sites, the mean measured

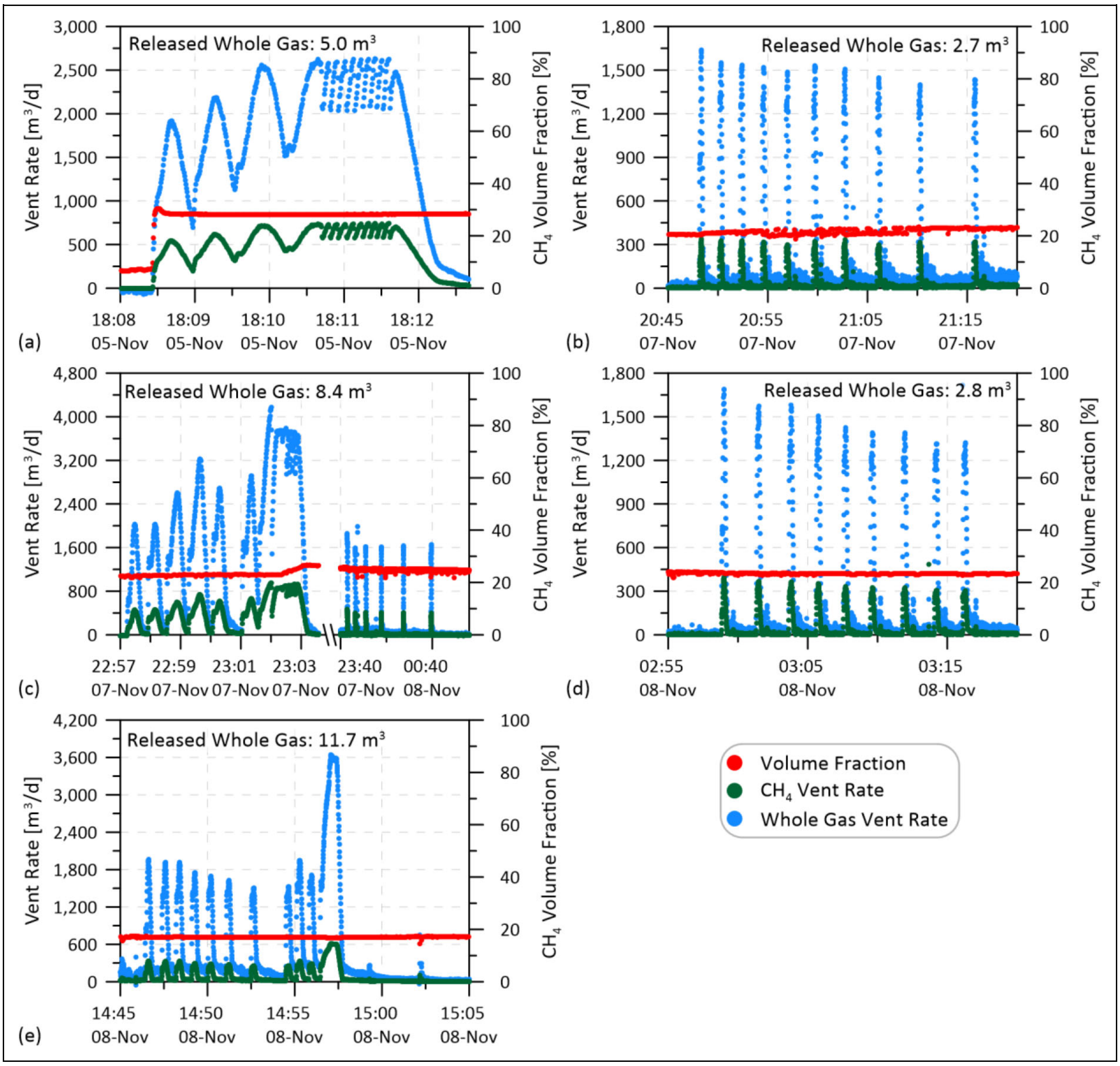

Figure 5. Five examples of storage tank venting after the arrival of the plunger at a plunger lift oil and gas well. Plots show temporary high vent rates of gas with low methane content due to dilution with ambient air. The clipped peaks at in examples (a), (c), and (e) suggest some additional venting was occurring through the existing thief hatch at these points. All data acquired using the VentX meter. Whole gas vent rate refers to total volumetric output during each arrival event, including other nonmethane species and any previously ingested ambient air.

vent rate was notably higher than the expected mean vent rate implied by the monthly reported site total venting and operating hours, and the combined mean rate of all eight sites was 122 times that expected from the reported data. Moreover, as per **Table 1**, at five sites, the measured volume of gas emitted from the storage tank during the on-site sampling period exceeded the monthly reported venting volumes for the entire site. However, considering the apparent root causes of emissions at these sites, these differences may simply reflect the limits of estimation methodologies under current regulations.

In Alberta, Directive 17 specifies that vent sources of less than 500 m^3/d can be estimated using either a GOR or a 1-h measurement (AER, 2022). Based on the present measurements, all sites except Site A (598 m^3/d) would fall below this threshold, but given that Directive 17 allows these same approaches to be used in determining the applicability of the 500-m^3/d threshold, it is likely that reporting for all sites in the present sample is similarly derived. The use of GOR to estimate venting is common in many regulations, including those in New York (2022), New Mexico (2021), and Colorado (State of Colorado, 2015). Critically, Section 4.3.5.4 of Directive 17 also states that while GOR may be determined via a 24-h measurement of produced oil and gas volumes, GOR values can instead be estimated from a laboratory analysis of a pressurized oil sample (either through pressure–volume–temperature analysis or modeling based on compositional analysis of the sample), from empirical relations (including a "rule-of-thumb" ratio of gas volume per m^3 of oil per kPa of pressure drop), or from process simulators (Canadian Association of Petroleum Producers, 2002); these

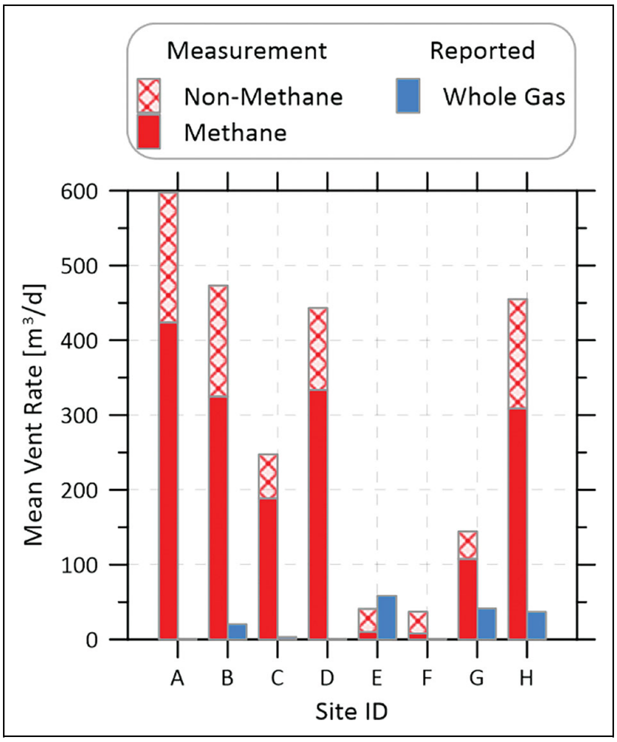

Figure 6. Mean measured emission rates from the eight production storage tanks compared with expected average site-total vent rates from reported data. Solid red fill is methane portion of the total measured vent stream and cross-hatch is nonmethane portion; blue bar is the expected vent rate from reported data calculated as site total reported vent volume for the month(s) of the field measurements divided by total reported production hours for the same month(s) from Petrinex (2022). See Section S2.1 of SI for further discussion of the nonmethane species in the vented gas.

various methodologies mirror those suggested by the API (2021) to estimate flashing losses. These latter approaches intrinsically assume that GOR equals GIS. Notably, GOR values obtained from pressurized liquid samples during the planning stages of a well have been linked to chronic emissions over the life of the well from undersized equipment incapable of handling all flashing emissions (United States of America and State of Colorado v. Noble Energy, 2015; Southern Petroleum Laboratories, 2018).

As detailed in the analysis of Site C above, for any site operating without a separator or allowing some portion of associated gas to bypass a separator, using GIS to calculate vent rates in place of GOR would necessarily miss additional associated gas volumes. Noting that the measured vent volumes and reported oil production at Sites A–D, G, and H all exceed the 100 m^3/m^3 level indicative of two-phase flow (see Section S1.9 of the SI), underestimation if using GIS in place of GOR could potentially explain the discrepancies between measured and reported data in **Figure 6**. By contrast, the measured tank venting at Site E (with an apparent GOR of 11.4 m^3/m^3) was found to be slightly below reported total site venting as would be expected. Although use of a 1-h measurement instead of a GIS measurement would likely provide better estimates, the analysis of the present time-resolved data suggests that estimated emission rates could still range from 1% to 224% of the true rate at the seven nonplunger lift sites (see Section S5 of SI) depending on when the measurement was taken. In the extreme, a measurement taken between plunger lift events at Site F could even lead to an estimate of zero venting as reported, or up to 433% of the measured mean if an unloading event is captured. Thus, it is entirely possible that the discrepancies in **Figure 6** reflect the limitations of current regulated estimation approaches rather than noncompliance by operators.

4.2. Sampling considerations for short-duration measurements of individual tanks and multitank surveys

The continuous vent rate data from the eight storage tanks can be used to infer the impact of source variability and intermittency on the precision of 1 to *N* discrete short-duration (snapshot) measurements that may be obtained using techniques such as aerial surveys, ground vehicle-based surveys, or other remote observations. Emission rates that would theoretically be observed using an idealized discrete measurement technology (i.e., ignoring potential further complications of instrument error and minimum detection limits—equivalent to assuming vent rates are above the minimum detection limit of the simulated snapshot technique and measurement error is random and averaged out over multiple passes) were simulated using a bootstrap sampling approach by randomly sampling the continuous flow rate data from **Figure 3** with replacement. This procedure also necessarily assumes that the observed storage tank venting is an ergodic process (i.e., the time average emissions are equivalently calculable from a sufficiently large set of random samples) and that its behavior in the long term is well described by the time period of our samples. As such, these results do not address abnormal emissions due to infrequent causes such as operational malfunctions. Although different discrete technologies interrogate the underlying emission source in different ways (e.g., transecting the plume, imaging a fully formed plume, etc.), all can be assumed to remotely interact with a plume that at any moment represents an ensemble of streaklines generated over a preceding time interval. In practice, this means a plume has an inherent averaging effect that through turbulent diffusion would continue to smooth out source fluctuations as it advects further from the release point. This effect can be represented by a simple moving average of the directly measured instantaneous vent rate data. For the present analysis, a moving average of span $\tau = 10$ s is chosen to represent the detectable/observable near-field time history of a typical CH_4 plume by aerial technologies under common source rate and wind conditions encountered during recent surveys. Additional scenarios presented in the SI demonstrate that shorter or longer assumed τ have negligible influence on the analysis.

Figure 7a shows the results of this analysis for two example sites, C and D from **Figure 3**. The shaded spread

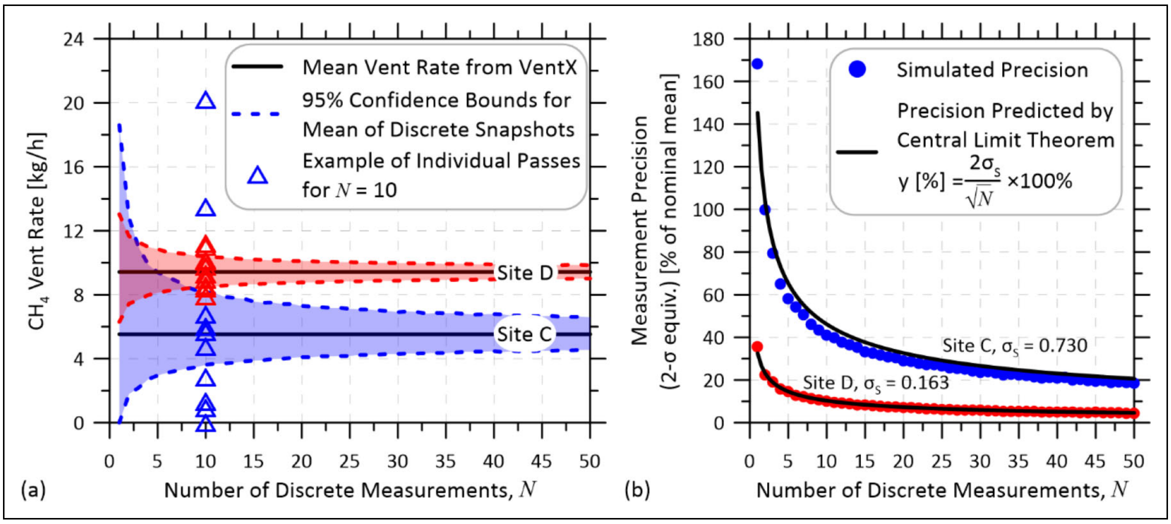

Figure 7. Example convergence plots for repeated discrete ("snapshot") measurements of the tanks at Sites C and D. (a) 95% confidence intervals on the mean emission rate for simulated discrete ("snapshot") measurements of a specified number of measurement passes *N*. Example bootstrap sample set of $N = 10$ discrete measurements is shown for both tanks. (b) Expected measurement precision after a specified number of discrete measurement passes plotted as a percentage of the mean rate for Sites C and D overlaid with the precision predicted by the central limit theorem given the measured standard deviation of the VentX data. Results in this figure assume turbulent diffusion in the plume imparts a moving average with span $\tau = 10$ s on the directly measured vent rate data; Section S4 of the SI shows that shorter and longer values of τ have negligible impact on the analysis. In both plots, vent rates are assumed to be above minimum detection limits of the simulated snapshot technique and no additional measurement error is considered (equivalent to assuming measurement error is random and averaged out over multiple passes).

between the dashed blue and red lines in **Figure 7a** shows the 95% confidence bounds on the range of estimated emission rates that would be expected when making between $N = 1$ and 50 measurement passes over Sites C and D, respectively. Also superimposed on **Figure 7a** is an example resampling set representing 10 measurement passes (i.e., one set from the 8,000 bootstrap samples for the case where $N = 10$) for the measured tank at each site. The larger spread in inferred emission rates for Site C than D is a direct result of the higher temporal variability in the unsteady vent rate, as shown in **Figure 3**. Because venting at Site C was both variable and intermittent, a single measurement pass could be expected to report values between 0 and 18.6 kg/h, equivalent to −100% and +236% of the mean from the VentX measurements. By contrast, a single measurement pass over Site D (whose vent rate was variable but not intermittent) would be expected to measure values between 6.3 and 13.0 kg/h or within −33% and +38% of the true source rate (9.42 kg/h). However, as expected, in both cases, the measurement precision improves as the number of measurement passes is increased. This is more clearly shown in **Figure 7b**, which represents the asymmetric confidence bounds as a 2σ-equivalent relative precision error (i.e., half the range of dashed lines in **Figure 7a** divided by the true mean and expressed as a percentage). Also drawn is the predicted measurement precision from the central limit theorem of the form $y = \frac{2\sigma_s}{\sqrt{N}}$, where σ_s is the sample standard deviation of each vent's original data set normalized by the mean rate. Thus, despite the asymmetric, and for Site C, intermittent, distributions of instantaneous vent rates, even for a small number of passes the measurement precision still reduces with the square root of samples size consistent with the central limit theorem.

This analysis was extended to all tanks in the present survey, and the results considering the same $\tau = 10$ s plume averaging time are summarized in **Figure 8** with additional (similar) scenarios with longer and shorter τ included in the SI. Directly related to the differing temporal variability in vent rates among tanks (**Figure 3**), the required number of measurement passes to achieve a target level of precision varies significantly. For example, a ±20% or better precision can be expected after just a single pass at Site H, but could take more than 1,400 passes to achieve at Site F (the highly intermittent plunger lift site). As expected, in all cases, the precision error decreases with one over the square root of sample size, which on log–log axes appear as lines with a slope of −0.5. Thus, although it is not possible to provide a single-valued guidance on the required number of discrete measurements to accurately estimate the emission rate from any one specific production storage tank, the statistical analysis of individual measurement passes obtained in any discrete measurement campaign can provide sufficient information to quantify the precision of that particular measurement.

Also shown in red is the expected measurement precision of the total aggregated emission rate for a survey consisting of one or more passes over all eight tanks. Encouragingly, despite the presence of highly intermittent sources in the sample, a precision of ±20% on the total mean emission rate is achieved in just three passes of each source. Extending this analysis further, the estimated error

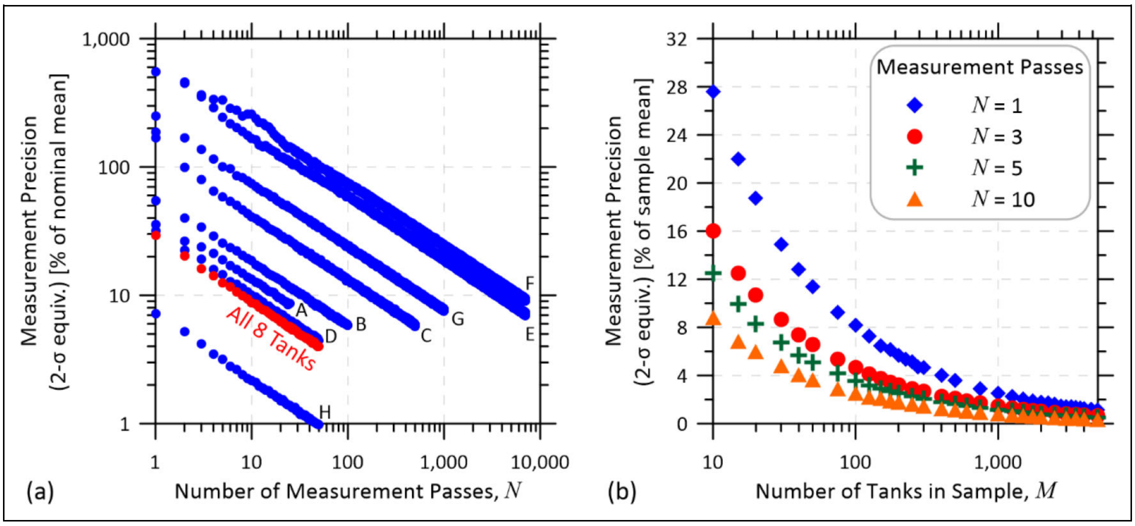

Figure 8. Convergence plots for simulated repeated discrete ("snapshot") measurements of all tanks in the study (each with *N* measurement passes) and for larger scale surveys of *M* tanks. (a) Simulated measurement precision when using a discrete ("snapshot") measurement technique versus number of measurement passes for all eight storage tank sources. The result in red is the precision on the sample average when sampling all eight sites for each given number of measurement passes. (b) Simulated measurement precision from a hypothetical survey of *M* tanks when using a discrete measurement technique that entails *N* measurement passes per source. Results in this figure assume turbulent diffusion in the plume imparts a moving average with span $\tau = 10$ s on the directly measured vent rate data; Section S4 of the SI shows that shorter or longer values of τ have negligible impact on the analysis. In both plots, vent rates are assumed to be above minimum detection limits of the simulated snapshot technique and no additional measurement error is considered (equivalent to assuming measurement error is random and averaged out over multiple passes).

of short-duration measurements on larger sample sizes was calculated by bootstrapping samples of up to 5,000 tanks comprised of random combinations (with replacement) of the eight instrumented tanks. These results are shown in **Figure 8b** for different survey scenarios that include 1, 3, 5, or 10 passes of each tank in the sample. As an example, considering an aerial survey making 3 passes per tank (consistent with the mean of 3.1 passes per source in recent surveys; Johnson et al., 2023a; Johnson et al., 2023b), the present analysis suggests a remote survey of as few as 25 variable and intermittent tanks should be sufficient to quantify the aggregated emission rate within $\pm 10\%$ at 95% confidence. A sample of 88 tanks should be sufficient to quantify total emissions within $\pm 5\%$ at 95% confidence. While these insights necessarily assume tanks within a population are well-represented by random combinations of the storage tanks included in this study, they provide valuable guidance on the design of future surveys and further support the results of independent analysis of source intermittency effects in Johnson et al. (2023a).

4.3. Recommendations

The preceding results and analyses support several recommendations to improve the accuracy of tank vent measurements and GHG reporting, to support robust emission surveys and monitoring protocols, and ultimately to enable more efficient regulations and operational decisions to reduce CH_4 emissions from production storage tanks. First, the use of GIS measurements to estimate vented gas volumes should be limited to wells operating with a separator, where it can be reasonably assumed that the vented gas is driven by flashing from the liquid delivered to the tank. Venting estimates for wells producing gas and oil directly to their storage tank should instead be measurement based. Additionally, the continued venting after the well was turned off at Site D illustrates how vent volumes may not always be well-correlated with produced oil volumes, suggesting that some GOR-based estimates can be similarly problematic. While current regulations in Alberta already indicate that the use of a GOR should be limited to cases where "gas volume estimates will vary in conjunction with oil volumes" (AER, 2022), no guidance is provided on how to distinguish between the two scenarios. Selective direct continuous or time-averaged measurements can provide this necessary information with the parallel benefit of enabling accurate GOR or measurement-based estimates where appropriate.

Second, when making direct measurements of tank venting, the detailed analysis of minimum sampling durations shown in Section S5 of the SI suggests that the current Alberta-recommended minimum measurement duration should be increased from 1 to 24 h (consistent with the duration of GOR measurements in current regulations in Alberta and Utah [AER, 2022; Utah, 2022], and the required measurement duration for storage tank emissions in the State of Texas [2015]) to ensure $\lesssim 10\%$ measurement precision can be expected at least 95% of the time. Alternatively, if the employed direct measurement technique provides similar time-resolved data to that presented here, then starting from an initial minimum sample duration of 1-h, concurrent statistical analysis of the real-time measured data could be used to determine convergence within a target level of precision (i.e., stopping time) in conjunction with common-sense consideration of any relevant site operating characteristics such as the frequency of plunger lift actuations. This latter approach (when feasible) would ensure that a measurement will be accurate considering the specific characteristics of the tank being measured.

Third, meters used to measure vented emissions from storage tanks should be capable of responding to the intermittent venting spikes as seen at Sites C, E, F, and G, or risk underestimating the average emission rate. The shortest duration spikes observed in this study occurred at Site E and had an average total duration of about 26 s. As further confirmed by spectral analysis of the temporal vent data, this suggests that a suitable meter for this application should have a frequency response of at least 0.1 Hz and in the case of nontotalizing meters, a recording resolution of at least 0.5 Hz (i.e., 2-s integration time).

Fourth, from an emissions perspective, for wells that are already conserving produced gas, venting can be reduced by minimizing the separator operating pressure where possible and hence the amount of gas remaining in solution with the oil that subsequently gets released in the atmospheric pressure tank. Use of dual stage separators (Hendler et al., 2009) or vapor recovery towers (U.S. EPA, 2007) can further reduce gas emitted from tanks with the added benefit of enhanced gas conservation. Correspondingly, noting the much lower venting rates from tanks operating with versus without separators in the present sample, the latter scenario should be avoided wherever possible. Assuming that in these cases the economic feasibility of gas conservation has already been explored and ruled out consistent with current Alberta regulations (AER, 2021), the present data suggest that significant mitigation potential could still exist via use of combustors to destroy CH_4.

Finally, future studies using discrete sampling approaches to measure tanks via aerial surveys, vehicle-based techniques, or other remote approaches should be cognizant of the influence of tank vent rate variability and intermittency on required sample sizes. In the extremes from the present data, individual tanks could require between just 1 and more than 1,000 discrete measurements to accurately resolve the mean. Statistical analysis is thus especially critical when interpreting measurements for individual tanks. However, more encouragingly, the presented bootstrap analyses demonstrate that in larger surveys of multiple tanks/facilities, precision in the total emission rate of better than 5% should easily be achieved for sample sets larger than 100 (although depending on the chosen technology, quantification uncertainty and detection sensitivity can still be additional important factors). This result is especially important for developing protocols for measurement, monitoring, and verification (MRV) under programs such as OGMP 2.0 (OGMP2.0, 2022). Adoption of each of these recommendations should significantly improve the accuracy of vent reporting from tanks, enable identification of key mitigation opportunities, and ultimately help close a key and persistent gap between bottom-up inventories and measurements.

Data accessibility statement

In addition to data included in the SI (.pdf), anonymized measurement data are posted on the Carleton University Dataverse under doi:10.5683/SP3/YJBP0E.

Supplemental files

The supplemental files for this article can be found as follows:

Supplemental Information.pdf

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Competing interests

The authors have no competing interests to declare.

Author contributions

Conception and design: MRJ, SAF-B.

Acquisition of data: SAF-B, ZRM.

Analysis and interpretation of data: SAF-B, MRJ.

Drafted and revised article: SAF-B, MRJ.

Approved submitted version: SAF-B, ZRM, MRJ.

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