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Repeated leak detection and repair surveys reduce methane emissions over scale of years

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Abstract

Reducing methane emissions from the oil and gas industry is a critical climate action policy tool in Canada and the US. Optical gas imaging-based leak detection and repair (LDAR) surveys are commonly used to address fugitive methane emissions or leaks. Despite widespread use, there is little empirical measurement of the effectiveness of LDAR programs at reducing long-term leakage, especially over the scale of months to years. In this study, we measure the effectiveness of LDAR surveys by quantifying emissions at 36 unconventional liquids-rich natural gas facilities in Alberta, Canada. A representative subset of these 36 facilities were visited twice by the same detection team: an initial survey and a post-repair re-survey occurring ∼0.5–2 years after the initial survey. Overall, total emissions reduced by 44% after one LDAR survey, combining a reduction in fugitive emissions of 22% and vented emissions by 47%. Furthermore, >90% of the leaks found in the initial survey were not emitting in the re-survey, suggesting high repair effectiveness. However, fugitive emissions reduced by only 22% because of new leaks that occurred between the surveys. This indicates a need for frequent, effective, and low-cost LDAR surveys to target new leaks. The large reduction in vent emissions is associated with potentially stochastic changes to tank-related emissions, which contributed ∼45% of all emissions. Our data suggest a key role for tank-specific abatement strategies as an effective way to reduce oil and gas methane emissions. Finally, mitigation policies will also benefit from more definitive classification of leaks and vents.

Introduction

Methane emissions from the oil and gas industry are the largest anthropogenic source of methane in Canada, accounting for over 40% of total emissions in 2017 [1, p 3]. With methane having a global warming potential (GWP) significantly higher than carbon dioxide (CO_2), mitigating methane emissions is critical to achieve the Paris climate targets [2]. Furthermore, given the short atmospheric lifetime of methane, reducing emissions will result in an immediate reduction in radiative forcing. The sustainability of the natural gas industry, particularly considering growing liquefied natural gas (LNG) exports, will be further improved by reducing fugitive and vented methane emissions. Fugitive emissions or leaks refer to unintentional releases of methane, while vents refer to international releases. Finally, addressing methane emissions also reduces emissions of volatile organic

compounds from oil and gas operations, improving local air quality [3, 4].

Recent research on the discrepancy between official inventory estimates and measurements of methane emissions have raised concerns about the need for more effective methane regulations. Both ground-based and aerial-measurements in Alberta showed higher vented and total methane emissions compared to provincial regulatory estimates [5, 6]. Similarly, mobile measurements using truck-mounted sensor systems in British Columbia and Alberta have consistently shown that a majority of the emissions are dominated by a small number of high-emitting sites, often identified as 'super-emitters' [5, 7, 8]. This is not unique to oil and gas activity in Canada—measurements of methane emissions across different shale basins in the US demonstrate evidence of super-emitters, widespread underestimation compared to US EPA inventory, and significant spatial and temporal variability [9–12].

Recently, governments in the US and Canada have developed policies to reduce methane emissions from the oil and gas industry [13, 14]. These policies typically include a combination of absolute limits on venting and periodic leak detection and repair (LDAR) programs to detect and mitigate fugitive emissions or leaks [15, 16]. While many technologies have been recently developed to detect methane emissions, most regulatory LDAR programs require the use of optical gas imaging (OGI) systems for leak detection [17–19]. While OGI-based LDAR programs have been found to be effective in a survey of operators, there has been no systematic study of the effectiveness of repair process and the persistence of emissions reductions from one survey to the next in real-world operating conditions [20]. One recent study sought to understand the time evolution of emissions through year on year aerial OGI-based surveys, although it did not involve any intervening repair process [21].

In this work, we take the novel (to our knowledge) step to determine the effectiveness of LDAR programs by performing repeated detailed ground surveys at facilities using consistent measurement and tracking techniques over the course of 0.5–2 years. By completing two OGI-based LDAR surveys at well-pads and processing plants, an initial survey followed by a post-repair re-survey, we find that the repair process is highly effective—over 90% of leaks fixed after the initial survey do not re-appear. Our study identifies important dynamics underlying methane emissions at upstream production facilities that can help regulators develop targeted policies within the context of LDAR programs.

Methods

Leak detection and repair surveys

All LDAR surveys in this study were conducted by Davis Safety Consulting Ltd with personnel trained and certified in FLIR-camera based leak detection and thermography technologies. It was critical to have a trained and experienced crew perform the LDAR surveys because recent studies of survey crews showed that consistent leak detection results are achieved only when crews have experience conducting around 400 prior surveys [22]. All surveys were performed at facilities operated by Seven Generations Energy Ltd (henceforth 'the company') in the Montney basin in Northwest Alberta. Data collected as part of this study is publicly available through the Harvard dataverse repository and the supplementary material is available online at stacks.iop.org/ERL/15/034029/mmedia section [23].

The site-survey took place in two stages. In the first stage, a thermographer examines every component and equipment on site using a FLIR GF-320 infrared camera. A second crew member records details of each leak (location, type of leak, and other relevant parameters) electronically, and physically attaches a unique tag to the leaking component for identification. The facility manager is immediately notified of leaks that pose risk to life or property. In the second stage, leaks with tags have their volumetric flow rate quantified using a Bacharach Hi-Flow sampler. Leaks that are either inaccessible or pose safety concerns are not quantified—in this study emission rates from these leaks were estimated using literature values. Finally, the facility operator is supplied with reports that detail leak locations, quantified emission rates, as well as photos and videos of each leak. We do not get into the details of specific repairs undertaken by operators but only evaluate the changes to emissions in facilities that had undergone repairs. While such repair details—part replacement or maintenance—will affect the cost of the repair process, it is not material to the emissions reduction efficacy of LDAR programs.

The detection limit of FLIR technologies varies with weather conditions, temperature of the equipment, operator experience, and imaging distance [19, 24]. To account for daily changes in weather, the FLIR camera is qualitatively verified every day before starting the survey using a propane standard at a flow rate of 50–60 g h^{-1} from a ¼ inch orifice, with a background at ambient temperature (e.g. equipment or a wall). The distance at which this 'standard leak' is observed is set as the maximum imaging distance for that day. This calibration procedure aims to reduce variability in the detection limit of the camera with changing weather conditions, and to ensure that data across multiple days are more comparable. Hourly changes in weather are not as important if the general

outlook for the day (sunny, partially cloudy, etc) remains consistent [24].

Initial survey

The LDAR surveys were conducted every quarter in 2016 and 2017, such that all major facilities in the company's operating assets were surveyed once per year. Initial surveys covered 36 sites which consisted of 30 well pads and 6 processing plants. The 30 well pads consisted of 10 super-pads, 7 satellite pads, and 13 single well-sites. Super pads, which serve as gathering points for production from smaller satellite pads, also have limited processing equipment such as separators and dehydrators on site. Survey speed varied by the size of facilities: in one day (~10 h), about 4–6 satellite well-pads can be surveyed while larger super-pads and processing plants could take up to three days. The results of the LDAR survey from each of these sites were provided to the site manager within two weeks of the survey, with the expectation that re-survey may occur to evaluate the effectiveness of repair. Daily and monthly average production data were obtained from the company for all sites in order to calculate proportional loss rates. A total of 969 leaks and 686 vents were found in initial surveys, of which ~70% were directly quantified.

Re-survey

To check the effectiveness of repair procedures, 8 representative sites from the initial survey were chosen by the science team (APR, DRS, and ARB) to be re-surveyed using identical procedures described above. These sites were visited 6–13 months after the initial survey. The site managers at these sites were not informed *a priori* about the arrival of the survey crew to avoid last-minute interventions to reduce leakage. Post-survey, we worked with site managers to catalog all equipment or well changes that occurred at a site since the initial survey. This is critical to directly compare pre- and post-LDAR emissions at these sites and remove the influence of new equipment added between the two surveys as much as possible. A total of 130 leaks and 135 vents were found during the 8 re-survey site visits, of which 72% were directly quantified.

Emissions accounting (post-survey analysis)

Not all emissions detected by the OGI crew could be quantified by the Hi-Flow sampler because of access or safety issues. In order to develop a complete picture of site-level emissions based on bottom-up component-level surveys, we supplemented the non-quantified emissions using flow rate estimates based on the empirical LDAR dataset or literature surveys. For those component-types where partial measurements were available (see S.I. data spreadsheet), we assigned the average quantified emission rate for that component-type to the non-quantified emission sources, specific

to each site-type. This method of using leak emissions factors is standard practice in methane emissions accounting. We only used data from the initial LDAR surveys to calculate emissions factors to better represent native emission rates pre-repair.
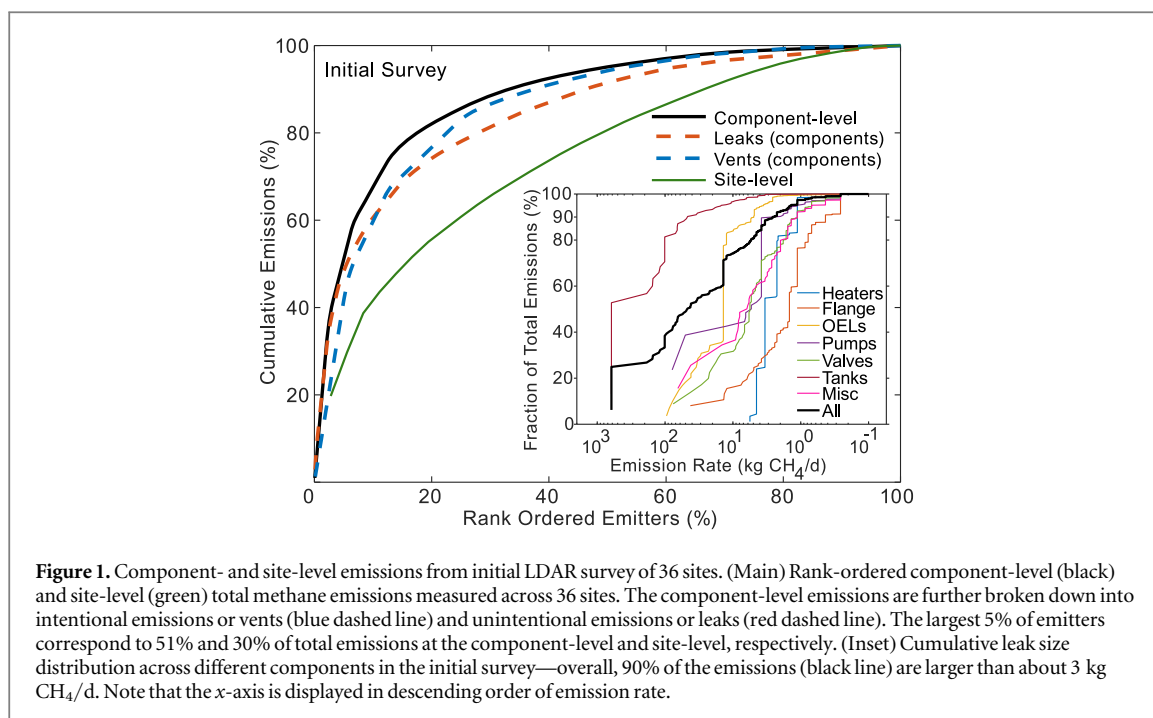
Tank emissions estimate

One type of emission—tank thief hatch and tank pressure release valve—lacked any quantification measurements in our study. This is because quantification using the Hi-Flow sampler cannot be used on tanks due to accessibility and safety issues. Assuming zero emissions from tanks because they were not quantified will lead to significant underestimation of emissions and introduce bias in the data. To solve this challenge, we develop custom emissions factors for tank-related emissions using data available from multiple peer-reviewed studies. First, we compiled a database of all peer-reviewed tank-related emissions measurements in the literature, disaggregated by site-type (e.g. well pads, processing plant, compressor station) and component (thief hatch, level controller, etc) [25–31]. Second, we develop emissions factors for tank emissions using this database for each site type—tanks on well-pads emit, on average, 30 kg CH_4/d, while those at processing plants emit 89 kg CH_4/d. These averages are used to estimate contribution of tanks to total site-level emissions. Third, we use non-parametric bootstrapping methods to estimate confidence intervals on tank emissions in this study, disaggregated by site type.

Throughout this study, measured volume flow rates have been converted to CH_4 mass flow rates assuming an average CH_4 mole fraction of 80.8% in the gas stream. This value represents the average methane composition at the company metering station, which receives gas from upstream well pads.

Results and discussion

Initial survey

Figure 1 shows the cumulative fraction of total emissions as a function of rank-ordered emitters at the component and site-level aggregation in the initial LDAR survey of 36 sites. As seen in many recent bottom-up studies of methane emission, we find that component-level emissions exhibit a highly skewed leak-size distribution—the top 5% of emitters contribute ~51% of total emissions [9]. Across all 36 sites in the initial survey, leaks and vents represented 15% and 85% of total emissions, respectively. There is no significant difference in the skewness of the size distributions of vents and leaks (see figure 1). The high fraction of emissions associated with vents is partly an artifact of classification—many jurisdictions in the US and Canada classify tank-related emissions as vents, even if the emission could be technically fixed (e.g. open thief hatch). If tanks do not contain a control

Figure 1. Component- and site-level emissions from initial LDAR survey of 36 sites. (Main) Rank-ordered component-level (black) and site-level (green) total methane emissions measured across 36 sites. The component-level emissions are further broken down into intentional emissions or vents (blue dashed line) and unintentional emissions or leaks (red dashed line). The largest 5% of emitters correspond to 51% and 30% of total emissions at the component-level and site-level, respectively. (Inset) Cumulative leak size distribution across different components in the initial survey—overall, 90% of the emissions (black line) are larger than about 3 kg CH_4/d. Note that the *x*-axis is displayed in descending order of emission rate.

equipment like a vapor recovery unit, tank-related emissions are classified as vents. Here, tank-related emissions contributed to 75% of all vented emissions, or 64% of total emissions. Of the total tank-related emissions, 78% or 949 kg CH_4/d can be attributed to emissions from level indicators, in line with recent findings that super-emitters are often caused by abnormal process conditions [32]. Tank-related emissions in this study are assigned by drawing from an empirical distribution of emissions from previously published studies (see Methods). Figure 1 also shows the cumulative fraction of emissions as a function of rank-ordered site-level data. Although less skewed than the component-level emission, the highest emitting top two facilities (5%, $n = 36$) contribute to 30% of total site-level emissions.

The inset of figure 1 shows the cumulative leak-size distribution as a function of emission rate disaggregated by major component types. Overall, 90% of emissions are from components emitting at least 3 kg CH_4 per day (kg CH_4/d), an order of magnitude smaller than a recent meta-analysis of methane emissions from US oil and gas operations [9]. However, the meta-analysis included emissions from compressor seals that are significantly larger than typical leaks. Excluding compressors, the 90% cut-off in the meta-analysis for leaks is about 4 kg CH_4/d, similar to results presented here. The mean and the median emission rates are 5.8 kg CH_4/d and 1.1 kg CH_4/d, respectively. However, there is significant variation across different component types—emissions from flanges exhibit some of the smallest rates, with a 90% cut-off at 0.6 kg CH_4/d, while tanks are the largest single emission source with a 90% cut-off at 25 kg CH_4/d. The mean emission rate from tank sources is 52 kg CH_4/d (95% C.I. [34, 89]), almost an order of
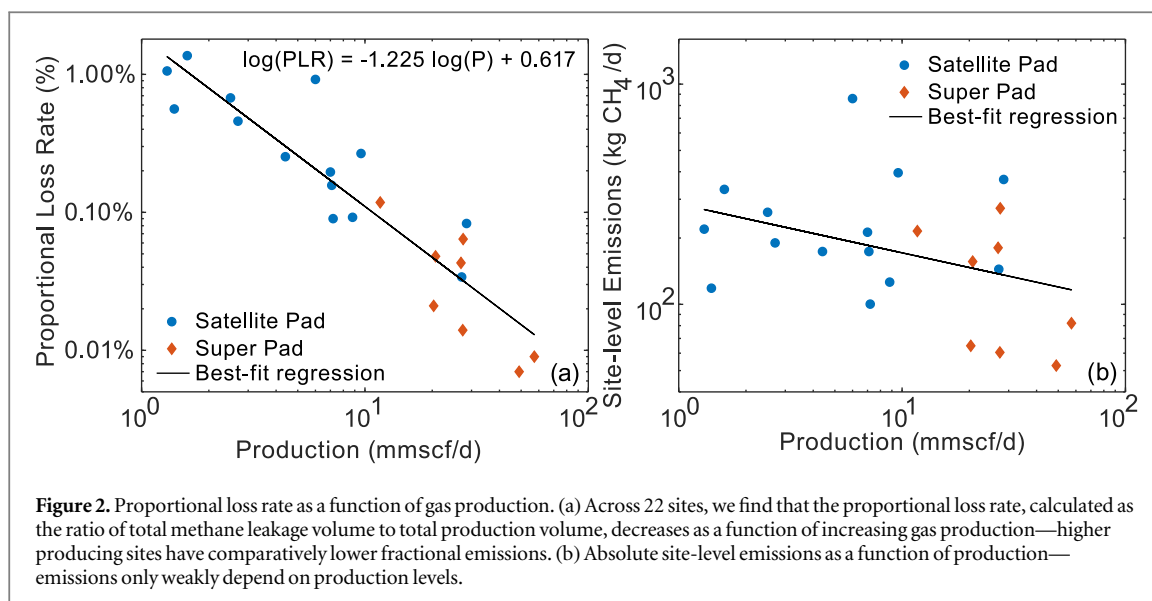
magnitude larger than the overall mean emission rate across all components. The outsized role of tanks in contributing to overall methane emissions at natural gas facilities has been a defining feature in many recent studies, and points to a critical need for tank-focused LDAR regulations [31].

Figure 2(a) shows the site-level proportional loss rate as a function of gas production for 22 well-pads, calculated using the daily average production volume on the day of the initial LDAR survey. Only 22 of the 30 well pads are shown here because they were individually metered, allowing a proportional loss rate calculation. Using monthly average production volumes did not significantly alter the proportional loss rate. We find an inverse relationship between loss rates and production values in a log-log plot, with an R^2 coefficient of 0.82. Furthermore, separate data from satellite pads and super pads show that there may be emissions reductions advantages to aggregating production from many wells on larger pads. The average production normalized leakage rate for satellite pads and well sites is 0.21%, while that for super pads is 0.03%. These proportional loss rates are lower than many recent studies of methane emissions in Canada [6, 8].

Figure 2(b) shows the absolute methane leakage volumes as a function of production for the same set of sites in figure 2(a). There is only a weak inverse correlation between daily production volumes and emission rates compared to the proportional loss rate data.

While this only represents data from one specific operator, it speaks to recent debates over policy exception for low-producing wells [33]. Our data suggests that emission volumes are not proportional to production, and therefore regulations to limit methane emissions must consider both low- and high-producing wells. These findings reflect recent observations
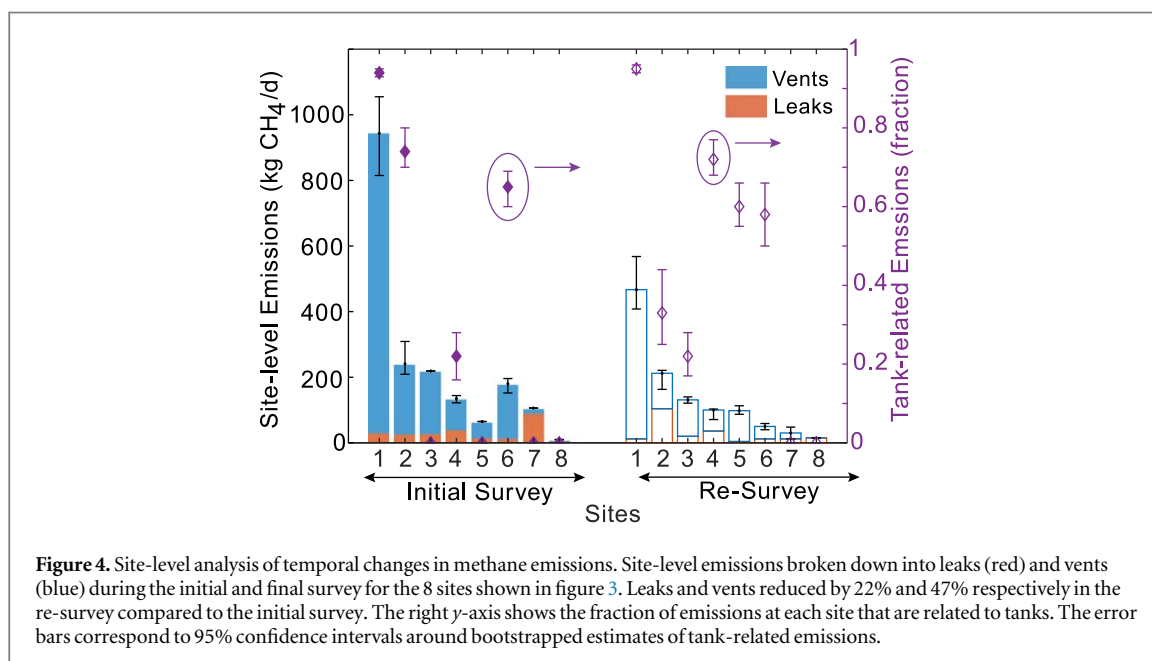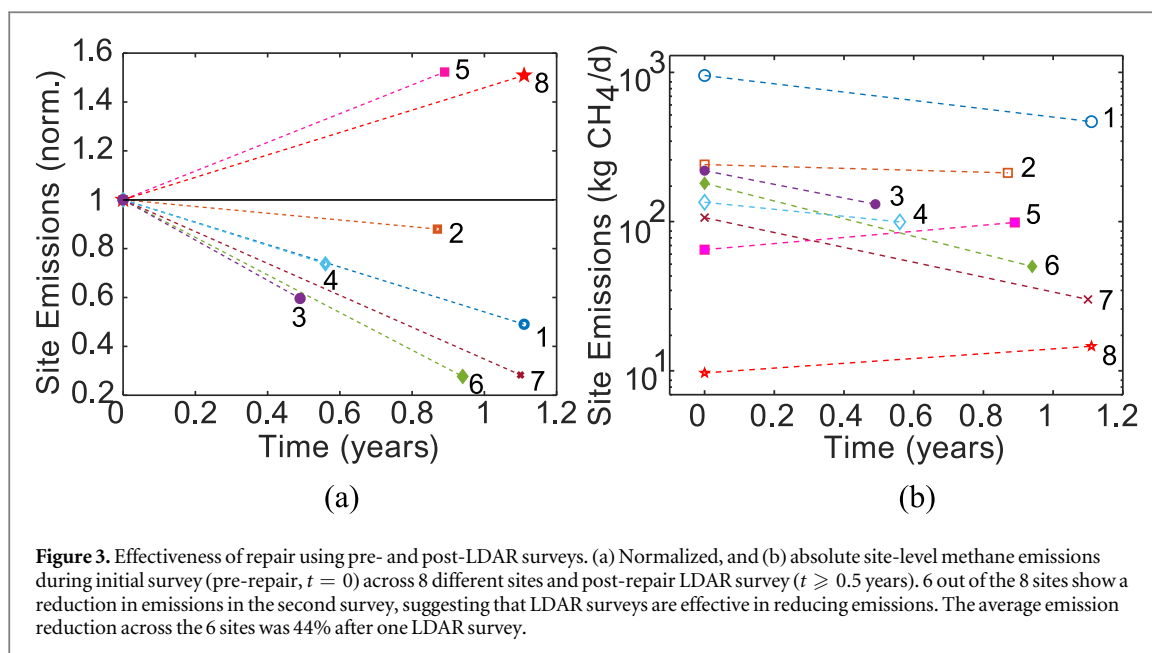
Figure 2. Proportional loss rate as a function of gas production. (a) Across 22 sites, we find that the proportional loss rate, calculated as the ratio of total methane leakage volume to total production volume, decreases as a function of increasing gas production—higher producing sites have comparatively lower fractional emissions. (b) Absolute site-level emissions as a function of production—emissions only weakly depend on production levels.

elsewhere–Omara *et al* also found that site-level proportional loss rate from low producing sites is higher than at high producing sites [34]. Future studies with larger sample sizes could help to establish the contribution of methane emissions from low producing wells.

The relatively low proportional loss rates reported here can be attributed to several factors. One, the loss rates calculated in this study are limited to pad-level emissions and do not include emissions from gathering and boosting stations. Two, the reported loss rates do not include methane slip from compressors or emissions from episodic events like liquids unloading which are typically not measured as part of LDAR surveys but have been shown to be a significant source of methane emissions in the literature [30, 35]. Three, the combination of newer equipment (all sites have been developed since 2014), a liquids-rich reservoir, and a sustainability-focused company operating practices result in lower emissions than is typically observed. For example, the company has a voluntary LDAR program to reduce methane emissions from its operations and uses instrument-air driven pneumatic systems instead of natural gas whenever feasible. Therefore, the low proportional loss rates observed here is likely not representative of all operators. This also indicates that it is possible for oil and gas operations to have leakage significantly lower than 1% even under a voluntary mitigation plan. Yet, evidence from many recent studies show methane emissions larger than reported or official inventory estimates [5, 6]. It suggests that there might be significant differences in methane emissions across operators—a hypothesis with major implications for emissions policy. Future studies should explore the impact of institutional practices on environmental outcomes.

Figure 3(a) shows normalized methane emissions at 8 selected facilities where a post-repair re-survey was conducted. The initial survey dates and emission rates for the 8 facilities, while occurring over a period

of one year, has been normalized to start at time, $t = 0$. The post-repair survey date is scaled similarly. Because all operators were given the results from the initial survey and were informed of potential re-survey, we expect all 8 sites to have undergone some level of repair. In 2 of the 8 sites where re-surveys were conducted, additional equipment was installed between the initial and post-repair survey (site #2 and site #5). For this analysis, whenever possible, we removed those emissions associated with the newer equipment that were not present during the initial survey while calculating the post-repair re-survey emissions.

Overall, emissions reduced by 44% across all 8 facilities between the first and second LDAR survey. Incidentally, this emissions reduction is similar to US EPA and Environment and Climate Change Canada's (ECCC) modelling assumption that an annual OGI-based LDAR survey will reduce emissions by 40% [16]. 6 of the 8 sites re-surveyed saw average emissions reductions of 46% (304 to 165 kg CH_4/d/site), while 2 of the 8 sites (site #5 and site #8) saw emissions increase by an average of 52% (37 to 57 kg CH_4/d/site). The emissions increase on site #5 could be due to uncertainty associated with attributing emissions to only part of the site that was not expanded between the two surveys. The overall emission reductions of 44% between initial survey and post-repair re-survey is a combination of an average *decrease* in leaks of 22% (274 to 214 kg CH_4/d) and vents of 47% (1625 to 888 kg CH_4/d). In the initial survey at our 8 sites, leaks and vents contributed to about 15% and 85% of total emissions, respectively. This is similar to leak-vent split observed in the overall population ($n = 36$), the skewness being an artifact of classifying tank-related emissions as vents (see figure 1). In the post-repair re-survey, leak and vents contributed to 19% and 81% of total emissions, respectively. Figure 3(b) shows the absolute emissions levels at the 8 sites where a post-repair re-survey was conducted in log-scale. The initial

Figure 3. Effectiveness of repair using pre- and post-LDAR surveys. (a) Normalized, and (b) absolute site-level methane emissions during initial survey (pre-repair, $t = 0$) across 8 different sites and post-repair LDAR survey ($t \geqslant 0.5$ years). 6 out of the 8 sites show a reduction in emissions in the second survey, suggesting that LDAR surveys are effective in reducing emissions. The average emission reduction across the 6 sites was 44% after one LDAR survey.

Figure 4. Site-level analysis of temporal changes in methane emissions. Site-level emissions broken down into leaks (red) and vents (blue) during the initial and final survey for the 8 sites shown in figure 3. Leaks and vents reduced by 22% and 47% respectively in the re-survey compared to the initial survey. The right *y*-axis shows the fraction of emissions at each site that are related to tanks. The error bars correspond to 95% confidence intervals around bootstrapped estimates of tank-related emissions.

emissions across the 8 facilities span about two orders of magnitude, indicating that site-level emissions are similarly skewed to that of component-level emissions (see figure 1).

The effectiveness of LDAR surveys in reducing emissions can be studied by tracking leaks and vents from the initial survey during the re-visit. Figure 4 shows the site-level analysis of temporal changes in leaks and vents between the initial survey and the re-survey, along with emissions contribution from tank-related sources. The error bars correspond to 95% confidence intervals, with the uncertainty associated with bootstrapping estimates of tank-related emissions (see methods). It does not include uncertainty associated with the Hi-Flow sampler measurements for other components, as the error (5%) is significantly

lower than that derived from tank bootstrapped emissions. Sites that did not have any tank-related emissions do not have any error associated with the bootstrap process. Across the 8 facilities shown here, 93% of the leaks corresponding to 90% of fugitive emissions observed in the initial survey were fixed before the re-survey, indicating a high degree of repair follow-through (i.e. tagged leaks were generally fixed). We find that leaks that were fixed did not re-appear and leaks that were not fixed were still present during the re-survey, demonstrating a high level of leak persistence confirming prior observations [21]. However, overall emissions tagged as leaks only reduced by 22% in the re-survey compared to the initial survey. This suggests that while repair processes can be effective in reducing emissions, frequent LDAR surveys might be

necessary for long-term emissions management. Combined with the skewed nature of the leak size distribution (see figure 1), solutions to leak mitigation will require frequent surveys with low-cost and rapid leak detection technologies [36]. In the case of upstream production facilities, this suggests a potential role for cheap fixed sensors, fence-line truck-based monitoring, or aerial surveys using planes and satellites [37].

Leaks only comprise 15% of the overall methane emissions across 36 facilities because tank-related emissions, as the largest single contributor, are classified as vents. By contrast, vented emissions were reduced by 47% during the re-survey, despite near-zero repair after the initial survey—only two emission points classified as vents were fixed by the operator. It is possible that the operator could have improved oversight of tank related emissions based on the findings from the initial survey and reduced the frequency of occurrence of abnormal process conditions such as open thief hatches—this possibility cannot be verified experimentally. Outside of any direct intervention by the operator to reduce emissions, there are other potential causes for the reduction in tank-related emissions. One, tank-related emissions are often intermittent and could have resulted in lower vent emissions during the re-survey purely by chance. Two, emissions from water, chemical, or other storage tanks depend on liquid-level and other process and operation characteristics that might have been different between the survey periods. Three, seasonal equipment like catadyne heaters which vent methane only operate in the winter when needed to prevent chemical lines from freezing. These are further discussed below.

Figure 4 also shows the contribution of tank-related emissions to total emissions at the 8 facilities where post-repair re-survey was completed. The error bars on the fraction of tank-related emissions correspond to 95% confidence intervals calculated at the site-level. Tank-related emissions contributed 64% of the total emissions and 75% of vented emissions (1215 kg CH_4/d, 95% C.I. [1017, 1423]) in the initial survey. In the post-repair re-survey, tank-related emissions contributed to 64% of total emissions and 80% of vented emissions (692 kg CH_4/d, 95% C.I. [561, 869]). Vented emission reduced from a total of 1621 kg CH_4/d (95% C.I. [1423, 1829]) during the initial survey to 863 kg CH_4/d (95% C.I. [732, 1040]) in the post-repair re-survey, a reduction of 47%. Analyzing the underlying component-level emissions points to important insights for future mitigation. Of the 17 tank-related emissions in the initial survey, 12 were specifically from tank-level indicators. During the re-survey, 12 tank-related emissions were found, only one of which was from a tank-level indicator. On average, this reduction in the number of emissions from tank-level indicators between the two surveys reduced vented emissions by approximately 934 kg CH_4/d.

Emissions from tank-level indicators are dependent on several factors such as liquid level in the tanks, and ambient temperature, and is independent of any LDAR program. After tank-level indicators, the biggest source of tank-related emissions is thief hatches, accounting for 8% and 28% in the initial survey and post-repair re-survey, respectively. This has two important implications for methane emissions reductions—one, periodic snap-shot measurements may show significant variation in emissions when emissions are dominated by tanks, and two, routine emissions measurements may mask the effectiveness of the repair process in reducing leaks if stochastic tank-related vents are not explicitly considered in analysis. More work is necessary to understand the time evolution of tank-related emissions at oil and gas facilities.

Tanks are one of the largest sources of methane emissions and a targeted and frequent LDAR survey specific to tanks would be critical to effective emissions reductions, even at the expense of LDAR on other equipment. In this context, the state of Colorado provides an example of targeted regulation to reduce tank-related methane emissions [38]. High emissions from tank level indicators and thief hatches point to a need for improving routine maintenance procedures outside of regulatory programs.

In this paper, we presented the first quantitative study of the effectiveness of leak detection and repair programs in methane emissions mitigation at oil and gas facilities, which relies on detailed site visits to quantify emissions before and after LDAR-associated repairs occur. We re-emphasize that this study is limited to facilities of a single operator, and the results presented here cannot be extrapolated to other regions or other operators.

Our analysis of methane emissions provides further evidence to bolster prior observations elsewhere—that emissions distributions are skewed with the top 5% of emitters contributing to about 51% of total emissions, and that tank-related emissions comprise a large fraction of total emissions. Furthermore, our re-visit of selected sites following repair provides critical data that can influence future methane mitigation policies. We find that leaks are persistent and LDAR programs are effective—reducing leaks by 90% between surveys. However, despite high repair efficacy, leak related emissions only reduced by 22% between the two surveys, indicating the need for rapid, low-cost, and frequent LDAR surveys. More importantly, regulators and operators should focus their efforts on reducing vent-related emissions. In this context, further clarity on the classification of emissions as leaks and vents will aid the repair process and effectiveness of LDAR programs. In this study, vented emissions reduced by 47% between the two surveys, the majority of which can be attributed to lower tank-related emissions in the post-repair re-survey. Finally, we find that tank-related emissions contribute almost

two-thirds of total emissions and points to the need for targeted inspection of tanks.

Given the limited sample size in our study, we call for a more expanded investigation of the effectiveness of LDAR programs in reducing methane emissions. In addition, details of the leak repair process such as average time to fix leaks, fraction of leaking components requiring replacements or work stops, time to repair, and associated costs are still relatively unknown and require further analysis. Future studies that track pre- and post-LDAR emissions would be critical to help regulators develop targeted policies that would be cost-effective and efficient in addressing methane emissions.

Acknowledgments

Author contributions

APR, DRS, and ARB designed the research question and developed appropriate methodologies and field protocols. APR and DRS oversaw the field campaign, participated in leak detection surveys, and performed all associated data analysis. RL, JB, AB, YN, SZ, and XB provided periodic feedback on data collection and analysis throughout the course of the study. All authors assisted with writing and editing the manuscript.

Data availability statement

Any data that support the findings of this study are included within the article (as supplementary information) and publicly available at the Harvard dataverse repository [23].

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