Technical Report

Canadian Natural Alt-FEMP Performance Report

Project Area: Lloydminster and Bonnyville Region

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Executive Summary

In this report, Highwood Emissions Management (Highwood) and Canadian Natural Resources Limited (Canadian Natural) summarize Key Performance Indicators and key takeaways from two years of deployment of an Alternative Fugitive Emissions Management Program (Alt-FEMP) pilot in the Lloydminster region. The report includes the performance metric reporting requirements specified in the Alberta Energy Regulator (AER) Alt-FEMP[1] along with pertinent data analysis to enable and facilitate AER review of the Alt-FEMP pilot performance.

Background

Currently, all oil and gas operations based in Alberta outside the Peace River area must comply with the AER directive 060. Directive 060 requires all duty holders to possess and adhere to a documented fugitive emissions management program (FEMP) designed to reduce fugitive emissions and that contains all required elements.[2] The primary element of Base FEMP requirements is that the duty holder must conduct regular fugitive emissions surveys for all facilities excluding wells linked to the facility subtype code but not located at the same site, at the specified frequency (annual or triannual) based on the facility subtype code. The surveys are required to be conducted using an approved technology such as an Optical Gas Imaging (OGI) camera, or an organic vapour analyzer operated in accordance with EPA's Method 21.

In recent years there has been a surge of innovation in the development of methane measurement technology alternatives to more traditional methane measurement technologies such as OGI cameras. This diverse set of new methane measurement technologies (such as drones, mobile ground labs, satellites, aircraft, and continuous monitoring systems) can be leveraged to develop solutions tailored more closely to the needs of a duty holder. This can result in benefits such as improved emissions mitigation, reduced cost, better survey efficiency, and minimized risk to survey operators if the strengths of the alternative solutions are aligned with the oil and natural gas infrastructure requiring surveying.

To allow duty holders to leverage these new technologies, the AER has put in place a process for the review and approval of innovative and science-based alternatives to the required FEMP referred to as the Alt-FEMP. Duty holders who wish to use an Alt-FEMP can apply for full scale or alt-FEMP pilot programs, depending on the level of details available to support the application and the needs/wants of the duty holder. Both pilots and full-scale programs are approved for a pre-defined period and by the expiration date, the duty holder must submit a performance report to the AER evaluating the data collected, successes and limitations of the program.

Canadian Natural Resources Limited (Canadian Natural) Alt-FEMP Pilot

On 2020-03-02, Canadian Natural Resources Limited (Canadian Natural) applied for an Alt-FEMP pilot for part of its Lloydminster assets. The application was approved, and the Alt-FEMP came into effect in 2021. The original scope of the pilot program encompassed 1032 sites requiring annual surveys and 10 sites requiring triannual surveys under the original FEMP from the Canadian Natural Lloydminster area of operations.

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[1] "Alt-FEMP Performance Report Requirements." https://www.aer.ca/regulating-development/rules-and-directives/directives/alt-femp-performance-report-requirements
[2] Alberta Energy Regulator, "Directive 060: Upstream Petroleum Industry Flaring, Incinerating, and Venting."

The approved Canadian Natural Alt-FEMP pilot leveraged a combination of aircraft and mobile ground lab (truck) based alternative technologies to effectively survey facilities and detect fugitive emissions. Specifically, a combination of aerial screening using fixed wing aircraft equipped with Light Detection and Ranging (LiDAR) sensors (Bridger Photonics' Gas Mapping LiDAR™) and ground-based screening using trucks equipped with gas sensors and anemometers (PoMELO system) was used. All sites considered a part of the Alt-FEMP pilot were screened once per year with aerial Bridger screening and once per year with the ground, truck-based PoMELO screening. For aerial screening, if site-level emissions detected were above 500m^3/day methane, a follow-up PoMELO screening was scheduled. For any PoMELO screening (routine biannual or follow-up), if site-level emissions detected were above 500m^3 CH_4/day methane or the estimated fugitive emissions rates at the site were above 100m^3 CH_4/day, the crew completing the PoMELO screening would conduct a close range OGI survey of a portion of the site, guided by the PoMELO screening data. Any leaks detected during the close range OGI survey would then be tagged for repair. The principal benefit of this approach is that crews focus their time on surveying portions of facilities where there are fugitive emissions. Canadian Natural collected emissions measurement data from Brigder, PoMELO and OGI detection technologies throughout the course of the Alt-FEMP Pilot deployment, which will be explored here.

Summary of Key Performance Indicators

In 2021, a total of 1317 screenings (this is not counting PoMELO screenings scheduled as follow-up of aerial screenings) and 620 follow-ups with close-range methods were completed at sites within scope of the Lloydminster Alt-FEMP. From those screenings 459 follow-ups were triggered by PoMELO and 161 from Bridger. Those follow-up inspections resulted in a total of 780 fugitive emissions sources identified. An investigation into the detected leaks, broken down by component type, revealed that control valves were the highest single source of emissions contributing to 41% of the total detected emissions in 2021 (estimated using M015 emissions factors). Leaks from open-ended lines (e.g. missing caps) were not as frequent as control valves and connectors, but due to the large rate also had a significant contribution to total emissions in 2021. Annual emissions reductions were calculated to be 105.1 tonnes of CH_4 per site when calculated using PoMELO recorded emission rates (from comprehensive screenings and aerial follow-up) to estimate fugitive emissions. When interpreting this metric is important to account that in 2021 PoMELO quantification algorithm underwent significant updates to improve its accuracy, so it is expected that the most reliable metric for annual emissions were obtained from 2022 data (more details provided in section 3.3.1).

In 2022, a total of 1295 screening (without counting PoMELO screenings scheduled as follow-up of aerial screenings) and 421 follow-ups with close-range methods were completed. From those screenings 316 were triggered by PoMELO and 105 from Bridger. Those inspections resulted in a total of 860 fugitive emissions sources identified. Again, leaks in connectors and control valves represented most of the leaks tagged. From 2021 to 2022 the number of leaks from open-ended lines decreased considerably, and consequently the emissions coming from this source. Total annual emissions reductions were calculated to be 56.77 tonnes of CH_4 per site using PoMELO recorded emission rates, which exceed emissions reductions of 0.84 tonnes CH_4 per site estimated in the proposal stage, indicating the success of the pilot.

Predictive modelling

LDAR-Sim predictive modelling completed using Canadian Natural specific emissions profile forecasted an Alt-FEMP emissions reduction of 200 (± 15.6) tonnes per site per year as compared to 126 (± 5.6) tonnes per year for Base FEMP, supporting equivalent emissions reductions by Alt-FEMP. The results of this predictive modelling can be interpreted as how the Alt-FEMP would continue to perform against the Base FEMP should the Alt-FEMP pilot program continue unchanged.

Key takeaways:

- The Canadian Natural Alt-FEMP pilot enabled the company to develop a deeper understanding of Lloydminster assets emissions profiles, highlighting the most significant leak sources and components that should be closely monitored.
- Canadian Natural Alt-FEMP exceeded initial emission reduction prediction, achieving an estimated reduction of 56.77 tonnes of CH_4 per site in 2022 (metric calculated based on PoMELO rates).
- LDAR-Sim predictive modelling completed using a Canadian Natural specific emissions profile forecasted an emissions reduction of 200 (± 15.6) tonnes per site per year as compared to 126 (± 5.6) tonnes per year for Base FEMP highlighting the advantages of the new program proposed.
- Throughout the Canadian Natural Alt-FEMP pilot multiple improvements were performed to guarantee its success. Canadian Natural worked closely together with Bridger to improve report formats to guarantee more actionable insights. Examples of improvements are presentation of location level total emission roll-ups, integration of high-resolution imaging at the time of detection with public aerial imaging base maps, and individual location summary reports or presentation to field Operations personnel. PoMELO technology also had improvements during the pilot, mainly on its quantification algorithm, which allowed the reduction of required follow-ups without decreasing the number of sources tagged.

Glossary

The following key definitions are applied throughout this report. Further details on the framework which informed these definitions can be found in Fox, TA, et al. 2019[3]:

- **Technology**: A gas sensing instrument, optionally configured with a deployment platform and/or ancillary instruments (e.g., anemometers, positioning), that can be used to gather data on emissions.
- **Work practice**: A description of how a technology is used to collect information about emissions, including operating procedures (e.g., distance from source, measurement time, environmental envelopes for sure, production segments).
- **Method**: The combination of a technology, a work practice, and analytics for use in an LDAR Program.
- **Leak Detection and Repair Program (LDAR Program)**: An LDAR Program is the systematic implementation of one or more Methods across a collection of assets. The Program describes the Method, or combination of Methods, to be used for each facility, along with survey frequency, repair response, and reporting standards. Ultimately, it is the LDAR Program that results in emissions mitigation, not the Technologies or Methods in isolation. In this report, "LDAR Program" also specifies a Program based on traditional Technology (OGI) that satisfies the current regulatory requirements (ECCC).
- **Optical Gas Imaging (OGI)**: A common leak detection approach that uses thermal infrared cameras to visualize methane and various other organic gases. Common OGI cameras create images of a narrow range of the mid-IR spectrum (3.2− 3.4 μm wavelength) which methane and other light hydrocarbons actively absorb.
- **Alternative Leak Detection and Repair Program (Alt-LDAR Programs)**: An LDAR Program which incorporates an alternative, non-OGI methane detection Technology such as aerial flyovers. Alt-LDAR Programs typically also have an OGI Method. Occasionally, "Program" is used to indicate both LDAR and Alt-LDAR Programs.
- **Flagging**: Identifying that a site, or equipment group, is the source of an emission which must be followed up on.
- **Tagging**: Physically tagging the emission source component for repair. Typically done by follow-up inspection personnel.
- **"Screening" method:** Less an official term, screening Methods travel quickly and can survey many sites rapidly, typically at the loss of detection resolution. In simulation modelling, screening methods cannot localize leaks down to component level.

[3] Fox, TA, et al. 2019. A methane emissions reduction equivalence framework for alternative leak detection and repair programs. Elem Sci Anth, 7: 30. DOI: https://doi.org/10.1525/elementa.369

- **"Survey" / "Close-range" method:** Less an official term, surveys, or close-range methods can localize emissions down to the Component level. Screening methods are ultimately followed up by close range methods. For this report all close-range surveys were performed using OGI cameras.
- **Minimum Detection Limit (MDL)**: The smallest methane emission rate a particular Technology can detect assuming constant external conditions (wind speed, distance from Technology to emission, etc.).
- **Site-level emissions rate**: The total emission rate of a site.
- **Component-level emissions rate:** emission rates of unique leaks coming from equipment components such as valves and connections.

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1 Introduction

The Alberta Energy Regulator (AER) Directive 060 requires Alberta based oil and gas operations to adhere to a Fugitive Emissions Management Program (FEMP). A FEMP requires annual or triannual surveying of oil and gas sites, depending on the facility sub-type code, with an approved technology such as an Optical Gas Imaging (OGI) camera or an organic vapour analyzer operated in accordance with EPA's Method 21. Under section 8.10.6 of Directive 060, operators can apply to take part in an Alternative to Fugitive Emissions Management Program (Alt-FEMP) pilot. The Alt-FEMP pilot sees the use of innovative and science-based alternatives to the FEMP the operator would normally have to follow. Typically, Alt-FEMP programs involve the use of alternative monitoring technologies (aerial surveying, mobile ground labs, continuous monitoring, etc.) to screen for fugitive emissions which are ultimately localized with follow-up OGI surveys. If an Alt-FEMP is approved, the operator is required to submit a final performance report 60 days following the expiry of the approved Alt-FEMP. This performance report is reviewed by AER to determine if the Alt-FEMP was successful and, if not, determine the extent of any future study required.

On 2020-03-02, Canadian Natural Resources Limited (Canadian Natural) applied for an Alt-FEMP pilot for part of its Lloydminster assets. The application was approved, and the Alt-FEMP came into effect in 2021. The approved Alt-FEMP was based around aerial and ground-based screenings carried out by Bridger Photonics (Bridger) and PoMELO, respectively, which were then followed up by close range OGI surveys. Highwood Emissions Management (Highwood) and Canadian Natural have collaboratively prepared this performance report to summarize quantitative and qualitative learnings from the Lloydminster Alt-FEMP. The guiding questions of this Alt-FEMP performance report are based on AER guidance.[4] However, additional insights have also been detailed.

Highwood, using Canadian Natural provided data, led the quantitative investigation. Highwood compiled, cleaned, and analyzed the provided Bridger, PoMELO, and OGI collected data to understand fugitive emissions trends and assess alternative program performance. In addition, Highwood conducted simulation modelling using the Leak Detection and Repair Simulator (LDAR-Sim) to update modelling performed in the proposal/application stage.[5] The updated model is an important part of this report as it can be used to understand the pilot performance and as a decision-making tool to determine program continuity. The combination of data analysis and simulation modelling have allowed Highwood to prepare a comprehensive overview of the Lloydminster Alt-FEMP emissions mitigation performance.

Canadian Natural, as co-authors of this performance report, led the qualitative data summary. This process involved interviews with field operators to better understand the non-quantifiable aspects of Alt-FEMP performance. Typically, these learnings center around the "human" element of the Alt-FEMP and are also useful and meaningful.

This performance report will provide an overview of the Lloydminster Alt-FEMP work practices and scope as well as background on the resulting data and the tools used to analyze it. The performance report will first address the quantitative elements of the program, followed by the qualitative elements.

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[4] "Alt-FEMP Performance Report Requirements."https://www.aer.ca/regulating-development/rules-and-directives/directives/alt-femp-performance-report-requirements

[5] Fox, Thomas A., et al. "An agent-based model for estimating emissions reduction equivalence among leak detection and repair programs." *Journal of Cleaner Production* 282 (2021)

2 Lloydminster Alt-FEMP Performance Report Background

2.1 Alt-FEMP Methods and Scope

2.1.1 Methods Overview

The Lloydminster Alt-FEMP pilot was approved by the AER for the standard 2-year duration and commenced in 2021. It saw a combination of aerial screening by Bridger and ground, truck-based screening by PoMELO. Bridger is a Bozeman, Montana based methane detection technology company which specializes in aerial methane screening, primarily using fixed wing aircraft equipped with Light Detection and Ranging (LiDAR) sensors (fixed wing aircraft were used exclusively for this Alt-FEMP). PoMELO is based out of Calgary, Alberta and uses trucks equipped with gas sensors and anemometers. It should be noted that under the Lloydminster Alt-FEMP, PoMELO screenings involved the proprietary PoMELO gas sensing instruments mounted on equipment (trucks) owned by Canadian Natural and the instruments were operated by Canadian Natural employees who were trained on proper use by PoMELO staff. To ultimately localize a leak initially flagged by the Bridger and/or PoMELO screenings, close range OGI inspections were conducted, carried out by the same Canadian Natural crews responsible for operating the truck mounted PoMELO system (each PoMELO truck had an onboard OGI camera). For the remainder of this report, the method describing truck mounted screenings will be referred to as "PoMELO" and close-range follow-up OGI inspections will be referred to as "OGI".

The scope of the original Lloydminster Alt-FEMP application encompassed 1032 sites subject to annual surveys and 10 sites subject to triannual surveys.

The Lloydminster Alt-FEMP saw all encompassed sites screened biannually, once per year with Bridger and once per year with PoMELO. During a Bridger screening, all sites received a first flyover and locations with emissions detected in the original flight received a second flyover (typically less than 5 days apart) for persistence evaluation. Once all routine aerial scans were complete, the resultant data was processed by Bridger who create emission details reports which were sent to Canadian Natural. If a Bridger screening detected persistent (across the two screening days) site-level emission rates greater than 500m³/day methane, the site was flagged for follow-up by PoMELO.A PoMELO screening (regardless of whether it is a follow-up of a Bridger flag, or a comprehensive PoMELO screening) involves the PoMELO equipped truck driving around the site perimeter on the closest possible roads. During a PoMELO screening, measured site-level emission rates are processed live inside onboard equipment and interpreted by the Canadian Natural staff operating the PoMELO equipped truck. Using these measured site-level emission rates in conjunction with known routine emissions rates, onboard, live calculations are performed to inform the estimated fugitive emission rates encountered during the screening. If the total site-level emission rates are larger than 500m³/day methane or the estimated fugitive emissions rates are larger than 100 m³/day methane the site is again flagged for follow-up, this time with a close-range OGI inspection. The OGI inspection is performed by the crew operating the PoMELO equipped truck (the truck is parked and an OGI survey commences). While PoMELO and Bridger report site-level rates, they also provide guided estimates on localization, as a result, the OGI survey is targeted and site wide OGI surveys are not required. Figure 1 is a flowchart of the Canadian Natural Alt-FEMP work practice.

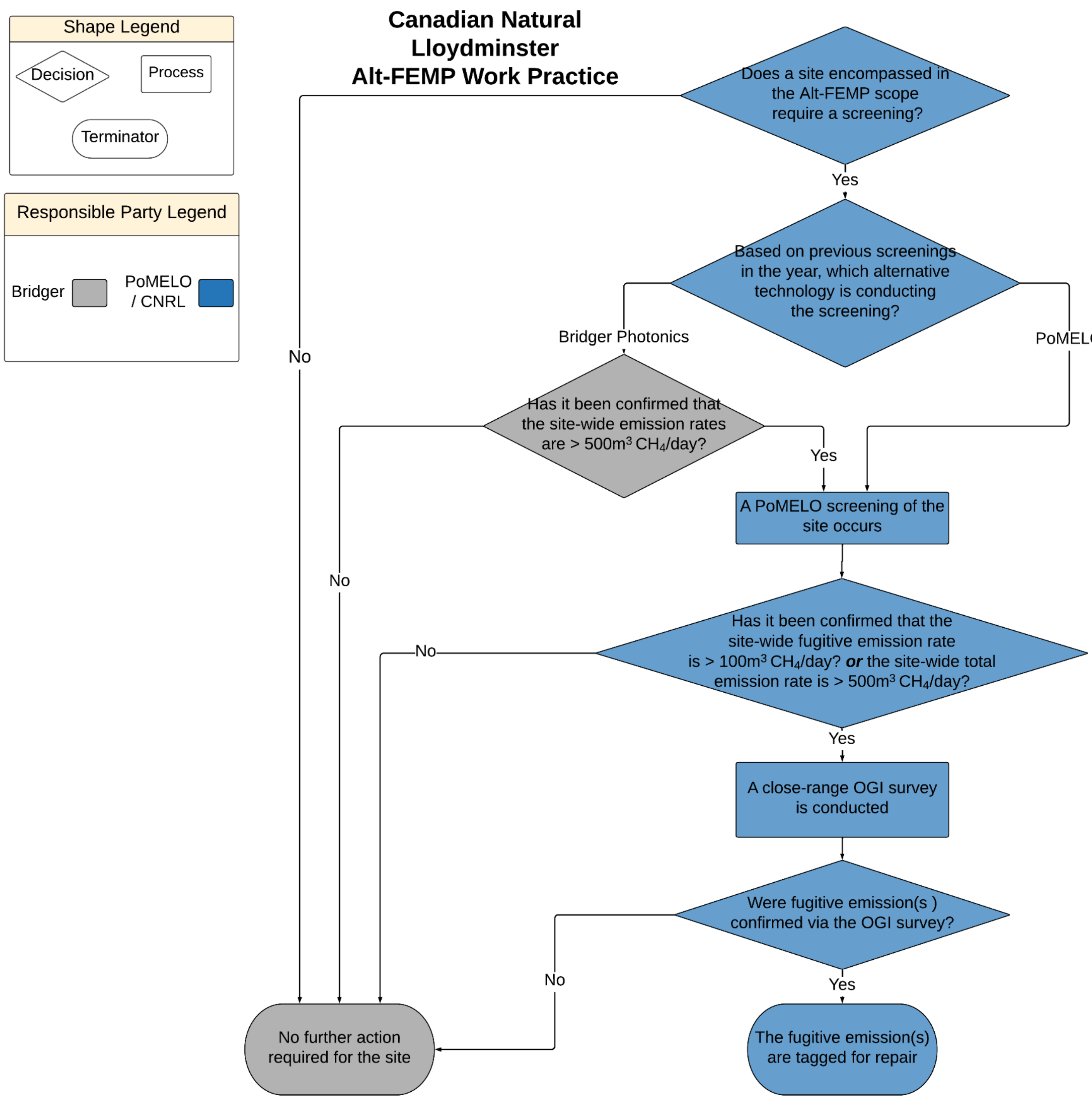

Figure 1: Flowchart depicting the Lloydminster Alt-FEMP work practices. The screening alerting thresholds of the Bridger and PoMELO methods is detailed. Details of repair processes are beyond the scope of this performance report and are not detailed.

2.1.2 Site Screening Dates

There were no rigorous screening date requirements throughout the Lloydminster Alt-FEMP. All screening dates are recorded and available in the supplemental data. For both years, Bridger screenings were performed in June and Pomelo saw the following spread of screenings:

- 2021 PoMELO Screenings: March to November
- 2022 PoMELO Screenings: January to September

2.2 Quantitative Data Analysis Background

2.2.1 Nature of the Provided Data

This section will summarize the “raw” (some internal Canadian Natural data cleaning was conducted before the data was shared with Highwood) data recorded by Canadian Natural during the Alt-FEMP pilot program and provided to Highwood for further cleaning and analysis. The data was provided in the form of Excel files, from these files, certain sheets and fields were deemed most relevant and used in data analysis. Figure 2 presents a hierarchy map of the Excel files, the relevant sheets, and the relevant fields provided by Canadian Natural for the Lloydminster Alt-FEMP and used in the quantitative data summary of this performance report.

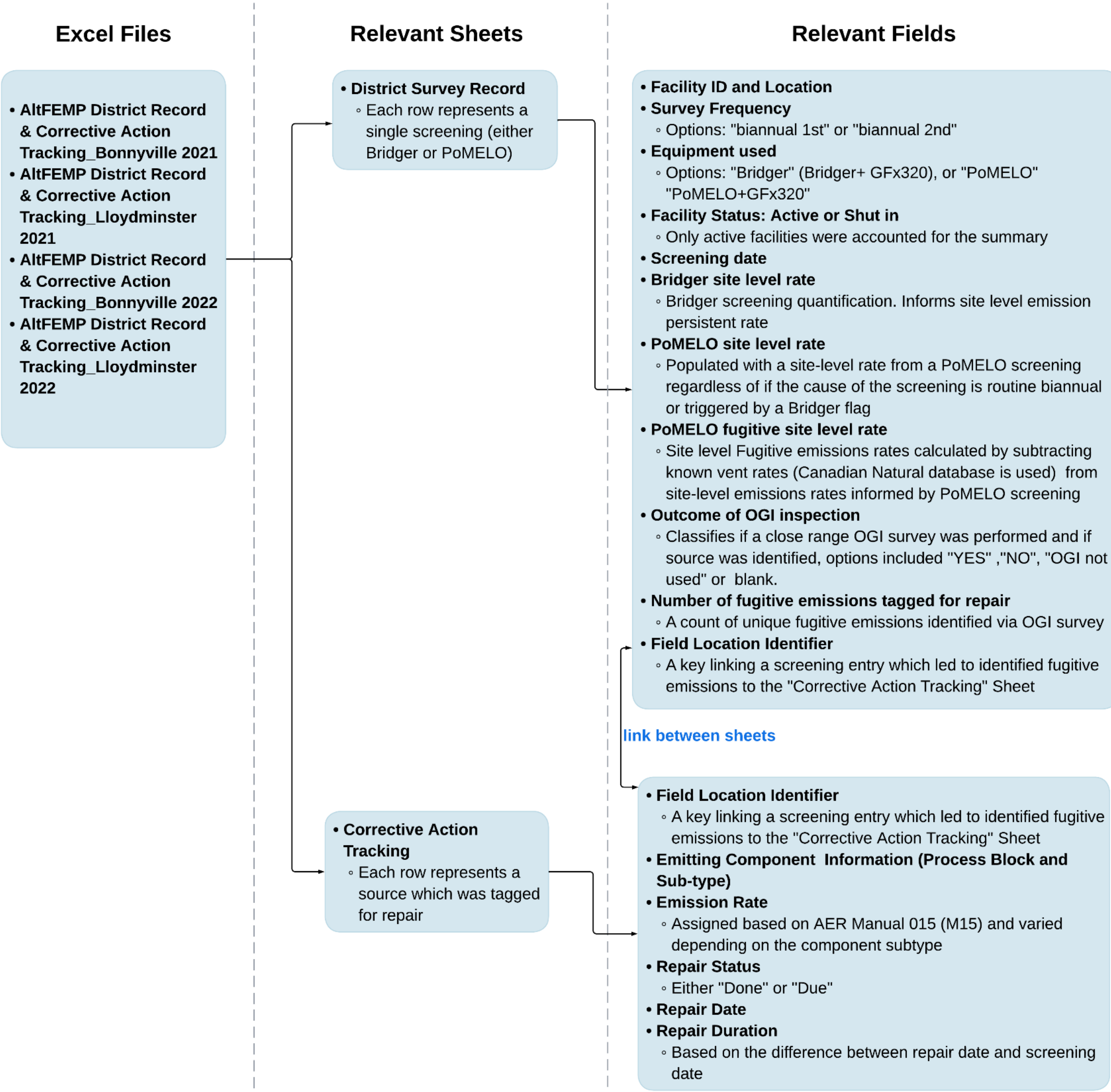

Figure 2: "Data hierarchy" of the provided Canadian Natural data. The Excel files provided as well as the relevant "sheets" and "fields" they contain are described. Under each relevant file, sheet, or field, the sub-bullet describes characteristics.

2.2.2 Tools used for Data Analytics

All data cleaning and analysis was conducted with Excel (some exploratory investigations were carried out with Python in a Jupyter Lab environment but those have since been translated to Excel). Selective filtering and pivot tables were used extensively. It should also be noted that analyzing the provided data was a highly collaborative process between Canadian Natural and Highwood with ample communication throughout the project.

2.2.3 Additional Files Attached to this Report

The following files are being submitted to the AER in addition to this performance report:

- Quantitative data analysis summary (An Excel file containing all quantitative analysis performance criteria required by the AER performance report guidelines):
  - "Quantitative Summary_Lyd.xls"
- The AER reporting template (Highwood transferred all Canadian Natural "raw" data to the official AER Alt-FEMP reporting template):
  - "AER_Screening and Follow-up Data_LYD.xls"

2.3 LDAR-Sim Modelling Background

As part of the emissions reduction summary, the AER has requested a comparison of annual emissions reduction with estimated emissions based on modelling. Additionally, a new modelling scenario incorporating a duty holder-specific emissions profile was requested. To meet these requirements Highwood used the Leak Detection and Repair Simulator (LDAR-Sim) as a modelling tool. A brief LDAR-Sim background and overview of relevant parameters will be provided in sections 2.3.1 and 2.3.2, respectively, while an overview of how Canadian Natural specific emissions profiles were incorporated in the model will be provided in section 2.3.3 and 2.3.4.

2.3.1 LDAR-Sim High-level Overview

LDAR-Sim is an open-source, agent-based numerical model developed at the University of Calgary used to predict emissions reduction effectiveness and costs of different LDAR programs and work practice configurations. LDAR-Sim works by building a "virtual world" of oil and gas infrastructure and emissions sources that is informed by empirical measurement data and historical environmental data. Different LDAR programs, which consist of unique methods (see glossary), are then applied to the virtual world to predict emissions reductions and compare performance amongst the programs. LDAR-Sim accounts for local environmental conditions and is built on actual site data. In this investigation, historical weather from Alberta and Canadian Natural Lloydminster Alt-FEMP site locations informed the modeled virtual world.

LDAR-Sim has over 100 parameters which allow for the fine tuning of the sites in the virtual world (the size and frequency of emissions they generate) and the performance/behaviour of the LDAR and Alt-LDAR programs and methods (minimum detection limit, travel speed, survey speed, operational weather envelopes, etc.). A full breakdown of LDAR-Sim operation and parameterization is outside the scope of this report; however, this section will describe the most relevant parameters to the Canadian Natural Alt-FEMP simulations.

Figure 3 presents a high-level overview of the processes which occur during each day of the simulation. While this flowchart provides a good overview of some processes, some additional functionality has been added to LDAR-Sim since its creation. Figure 3 is based on a previous version of LDAR-Sim and does not include travel time considerations used in the modelling detailed in this report.

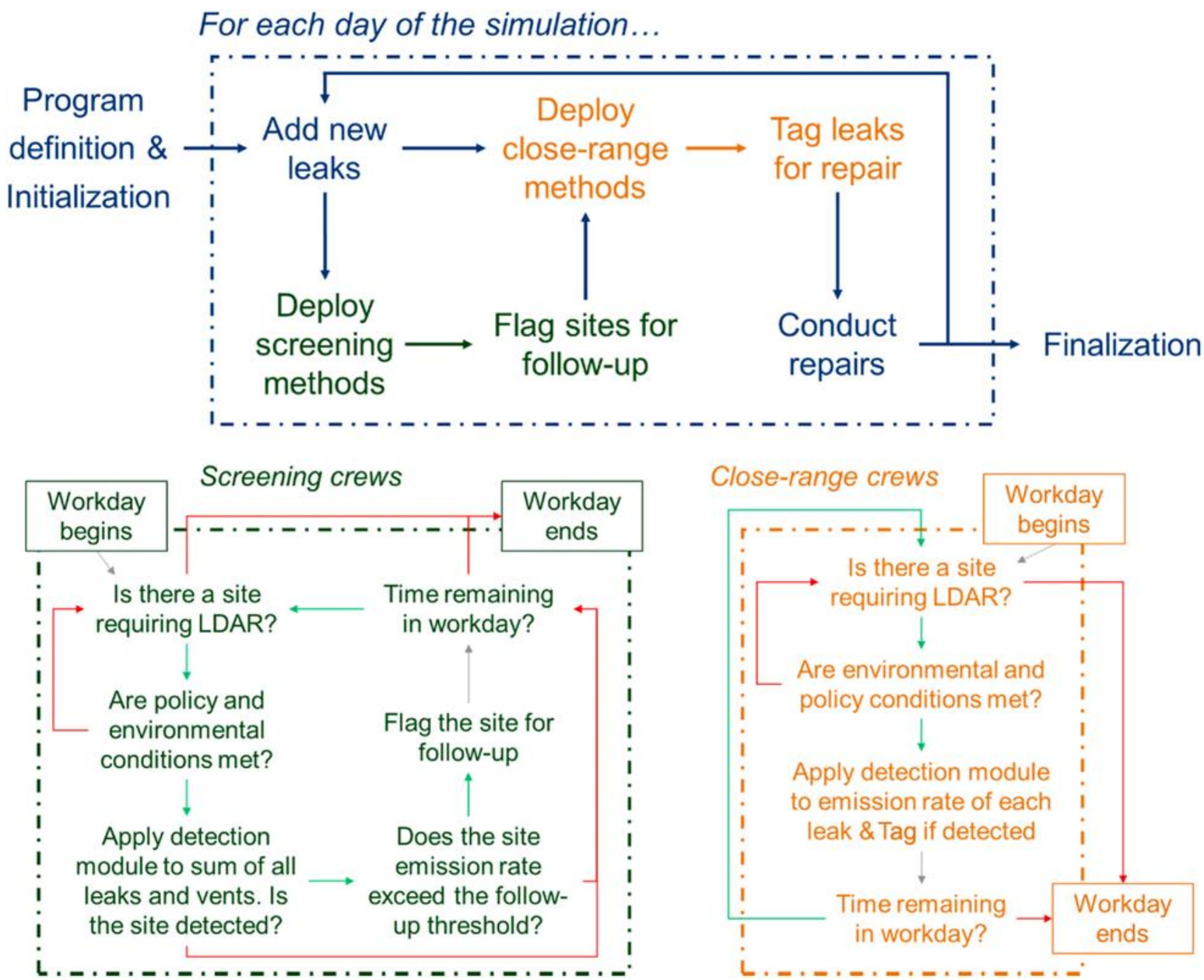

Figure 3: A detailed overview of the processes which occur in LDAR-Sim simulations each day of simulated time, modified from Fox et al. 2020. In the Alt-FEMP described by this report, screening methods (green text and arrows) will be represented by Bridger and PoMELO, while close-range Methods (orange text and arrows) are OGI crews. Red arrows represent 'no', green arrows are 'yes', and grey arrows are mandatory.

2.3.2 LDAR-Sim: Relevant Parameters

The most relevant parameters used to model the Canadian Natural Alt-FEMP pilot program and regulatory OGI are described in detail in Appendix A and Appendix B of this report. In the following list, a summarized version of important parameterizations to interpret simulation modelling results is provided:

- **Leak Production Rate (LPR):** The probability that a fugitive emission will arise at a given site on a given day. Highwood used leaks counts and known survey frequency available in the provided Canadian Natural data to calculate the LPR. This parameter will be covered in more details in section 2.3.3.
- **Leak Rate Distribution (LRD) / Leak Rates File**: This parameter dictates the simulated emission “size” as a rate. These rates can be randomly sampled from a lognormal distribution or from a leak file with known leak rates. Leak rates will be covered in more details in section 2.3.4.
- **Follow-up thresholds:** The emission rate required for a method to flag a site for follow-up. 500 m^3 CH_4/day total site-level emissions for Bridger and 100 m^3 CH_4/day fugitive site-level emissions *or* 500 m^3 CH_4/day total site-level emissions (fugitive + vents) for PoMELO.
- **Minimum Detection Limit**: The smallest methane emission rate a particular technology can detect. For OGI methods, the minimum detection was parameterized with a probability of detection (PoD) curve informed by Zimmerle et al. which accounts for operator experience and has a 95% PoD at an emission rate of 0.182 g/s.[6] Both screening methods (PoMELO and Bridger) were parametrized according to work practice thresholds.
- **Spatial coverage**: A representation of the average proportion of a site the method can effectively survey. For example, a value of 0.7 indicates that the method will find a leak 100% of the time in 70% of the site. In practice, every time a method goes to survey a new leak, a “weighted coin” is flipped representing spatial coverage. If the method “loses” the weighted coin flip, it will not detect that emission and will not be able to do so on subsequent screenings or surveys. The modelling conducted for this report assumed a coverage of 80% for comprehensive close-range surveys (OGI) and 90% for screening methods and follow-ups (PoMELO, Bridger and OGI follow-up). Screening methods were parametrized with higher spatial coverage for being able to detect sources that close-range surveys would typically miss. For example, aerial methods can flag elevated sources and ground-base survey can cover small leak rates that OGI would miss.
- **Temporal Coverage**: The probability that a method will detect a leak in a single survey. For the purposes of this Alt-FEMP performance report, this parameter was used to simulate how unfavourable wind conditions could affect Bridger and PoMELO screening performance. This parameter was set conservatively as 100% for close-range surveys (OGI). For screenings (PoMELO and Bridger), the effect of reducing temporal coverage from 100% to 75% was investigated.
- **Infrastructure:** The infrastructure file defines each unique Canadian Natural facility represented in simulation. Each row represents an individual facility and columns describe the facilities latitude,

[6] Zimmerle, Daniel, et al. "Detection limits of optical gas imaging for natural gas leak detection in realistic controlled conditions." Environmental science & technology 54.18 (2020).

longitude and required survey frequencies for different methods. For this report, the infrastructure file consisted of 690 facilities (676 that were subject to annual surveys and 14 facilities that were subject to triannual surveys under D060 FEMP) based on the scope of active facilities included in the program at the beginning of 2021.

2.3.3 Emissions Profile Details: Leak Production Rate

An LPR based on the data collected during the pilot was calculated using the following formula:

LPR = (# of leaks identified / # of inspections) / # of days in the frequency period

Where:

# of leaks identified: total number of fugitive sources tagged in 2022 (862 sources)

# of inspections: total number of screenings performed in 2022 (1295 screenings)

# of days in the frequency period: 180 days (all facilities received bi-annual surveys)

Note, only data from 2022 was used to calculate LPR to avoid noise stemming from when both companies (PoMELO and Canadian Natural) were still adjusting and improving the Alt-FEMP work-practice and quantification algorithms of the PoMELO and Bridger methods. Applying the values in the formula gives an LPR of 0.0037, which represents around 135 leaks every 100 sites per year.

2.3.4 Emissions Profile Details: Leak Rate Distribution

Peer reviewed literature of known leak rates typically show that leak sizes can be fit to a heavy tailed, lognormal distribution shape, indicating most leak populations are dominated by “small leaks”, with a small proportion of “large” and highly impactful leaks.[7,8,9] LDAR-Sim can generate leak rates by randomly sampling from a lognormal distribution (Section 2.3.2), so, the first step in incorporating provided Canadian Natural emissions data into the model was to attempt to fit provide emission rates to a lognormal distribution.

PoMELO site-level fugitive emissions measurements were used to create the lognormal distribution (a comparison investigation into PoMELO and Bridger site level rates was conducted and it was found they were consistently very similar). As individual, component scale leaks are required to build a leak rate distribution and PoMELO reports provided site-level emissions, component level leak rates were estimated by dividing site-level rates by the number of sources tagged during follow-up (Section 2.1.1).

The distribution based on Canadian Natural PoMELO site level emission rates is plotted in Figure 4 as a Cumulative Density Function (CDF) which aims to show the proportion of individual leak sizes. This plot can be interpreted as the y-axis values being the probability that a leak rate will take a value less than or equal to

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[7] Zavala-Araiza et al. “Reconciling Divergent Estimates of Oil and Gas Methane Emissions.” Proceedings of the National Academy of Sciences 112, no. 51 (December 22, 2015)
[8] Omara, et al. “Methane Emissions from Conventional and Unconventional Natural Gas Production Sites in the Marcellus Shale Basin.” Environmental Science & Technology 50, no. 4 (February 16, 2016)
[9] Ravikumar et al. “Repeated Leak Detection and Repair Surveys Reduce Methane Emissions over Scale of Years.” Environmental Research Letters 15, no. 3 (March 1, 2020)

the x-axis value. For example, for the Canadian Natural Lloydminster distribution we have 21% chance of leaks smaller than 1 kg CH_4/hr.

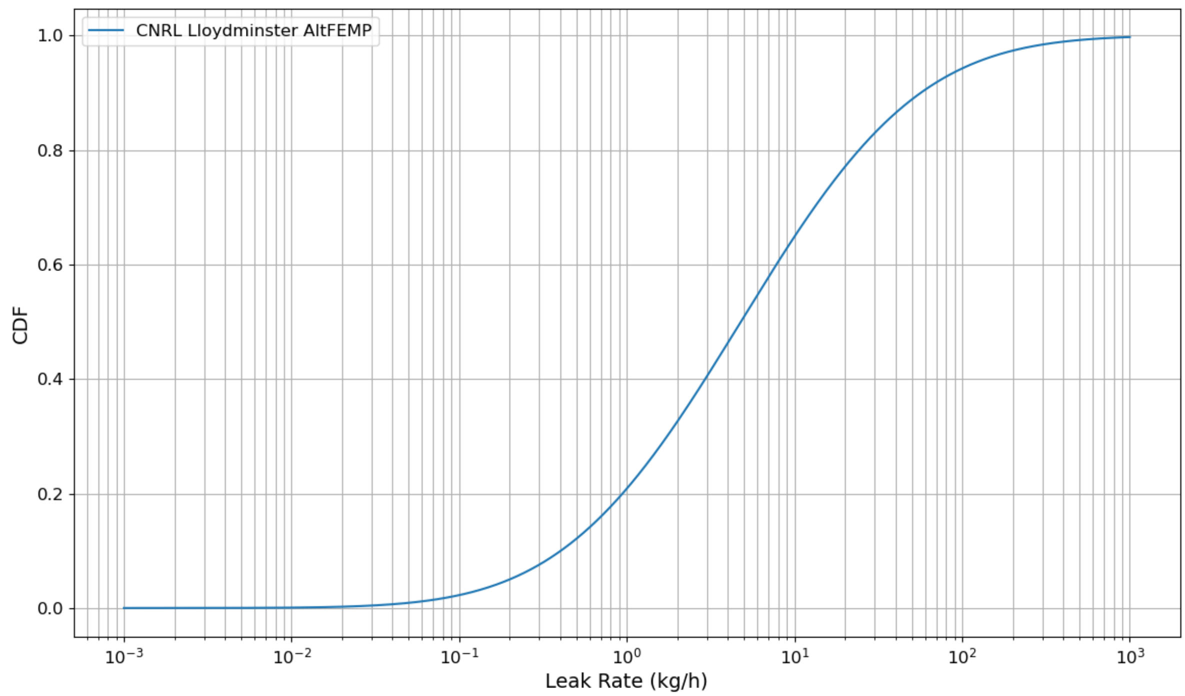

Figure 4. Cumulative density function (CDF) of Canadian Natural Lloydminster Alt-FEMP leak rates. The y-axis values are the probability a leak rate will take a value less than or equal to the x-axis value. For example, for the Canadian Natural Lloydminster distribution we have 21% chance of leaks smaller than 1 kg CH_4/hr.

3 Quantitative Data Summary (Screening and Survey Details)

3.1 Screening Summary

Table 1 and

Table 2 provide a quantitative summary of comprehensive, routine PoMELO and Bridger screenings performed under the Lloydminster Alt-FEMP in 2021 and 2022, respectively. While under the Alt-FEMP work practice (Section 2.1.1) sites flagged by Bridger are also screened by PoMELO, those additional screenings were considered an "initial follow-up" and not the main screening method, and for that reason these follow-up PoMELO screenings are not considered in the following tables.

An overview of the data sources which inform Table 1 and

Table 2, as well as any caveats and assumptions to the provided data follow:

- Number of screenings conducted: Count of total entries in the "Survey District Record" file for active sites. Constitutes all screenings performed throughout the year.
- Screenings flagged as emitting above threshold: Screening which measured site-level emissions above threshold. For PoMELO this means sites where site-level emissions (vents + fugitives) were

above 500 m^3/day or site-level fugitive emissions were above 100 m^3/day. For Bridger, this means sites where site-level emissions (vents + fugitives) were above 500 m^3/day. Note that this number does not reflect leaking sites as vent and fugitive rates are both considered.

- Screenings that triggered a follow-up: Screenings which ultimately led to a close-range OGI follow-up survey. Based on the District Survey Record Sheet and the associated field "Fugitive Emission found w/ OGI" (Figure 2). "Fugitive Emission found w/ OGI" was required to be YES or NO, as having either YES or NO implies the OGI survey was conducted. For most cases the "screenings flagged as emitting above threshold" count was lower than the "screenings that triggered a follow-up" count. This was due to PoMELO operators occasionally deciding to conduct an OGI follow-up inspections, even if the onboard quantification algorithm indicated this was not necessary (site or fugitive rates were below the follow-up threshold).
- Total number of fugitive sources: Number of fugitive emission sources tagged during close range OGI follow-up. Based on the District Survey Record Sheet (Figure 2).
- Average follow-up delay: It was assumed that the close-range OGI follow-up triggered by a site being flagged by PoMELO was instant as the same operators driving the PoMELO equipped truck would conduct the OGI survey.

Table 1. Summary of screening performance metrics from the Lloydminster Alt-FEMP during **2021**

Performance Metric	PoMELO	Bridger	Total
Number of screenings conducted	655	662	1317
Screenings flagged as emitting above threshold	346	112	458
Screenings that triggered a follow-up*	459	161	620
Total number of fugitive emission sources	506	274	780
Sub-total number of fugitive emission sources in the Lloydminster operating area	270	216	487
Sub-total number of fugitive emission sources in the Bonnyville operating area	236	57	293
Average time between screening flag and follow-up survey	0	77	-

* Number of screenings that triggered a follow-up with close-range methods (OGI). For Bridger, this number refers to screenings that ultimately led to an OGI follow-up (the Bridger screening triggered a PoMELO follow-up which triggered an OGI follow-up).

Table 2. Summary of screening performance metrics from the Lloydminster Alt-FEMP during **2022**

Performance Metric	PoMELO	Bridger	Total
Number of sites-level screenings conducted	657	638	1295

Screenings flagged as emitting above threshold	187	43	230
Screenings that triggered a follow-up*	316	105	421
Total number of fugitive emission sources	662	200	862
Sub-total number of fugitive emission sources in the Lloydminster operating area	305	141	446
Sub-total number of fugitive emission sources in the Bonnyville operating area	357	59	416
Average time between screening flag and follow-up survey	0	64	-

* Number of screenings that triggered a follow-up with close-range methods (OGI). For Bridger, this number refers to screenings that ultimately led to an OGI follow-up (the Bridger screening triggered a PoMELO follow-up which triggered an OGI follow-up).

3.2 Follow-up Survey Summary

Table 3 and

Table 4 provide a quantitative summary of the close-range follow-up OGI inspections performed under the Lloydminster Alt-FEMP in 2021 and 2022, respectively. While under the Alt-FEMP work practice (Section 2.1.1) sites flagged by Bridger are initially followed-up by a PoMELO, these follow-ups are not detailed in Table 3 and

Table 4 unless this PoMELO screening ultimately led to a close-range OGI inspection.

All follow-up data presented in Table 3 and

Table 4 focuses on close range follow-up investigations conducted using OGI cameras. An overview of the data sources which inform the rows of Table 3 and

Table 4 follow:

- Number of follow-ups where a leak was found: Based on the District Survey Record Sheet (Figure 2). The field “Fugitive Emission Found w/ OGI?” is marked as YES.
- Number of follow-up where a vent was found: Based on the District Survey Record Sheet (Figure 2). The field “Fugitive Emission Found w/ OGI?” is marked as NO.
- Number of leaks repaired: Based on the Corrective Action Tracking Sheet (Figure 2). Is a count of repairs classified as DONE.
- Number of repairs delayed: Based on the Corrective Action Tracking Sheet (Figure 2). Is a count of repairs classified as DUE.
- Average time between leak detection and repair: Based on repair dates logged in the Corrective Action Tracking Sheet (Figure 2). Is average repair time (in days) for all repairs classified as DONE.

Table 3. Summary of follow-up survey performance metrics from the Lloydminster Alt-FEMP during **2021**. The table describes follow-up OGI investigations of biannual PoMELO and Bridger screenings. The values under the PoMELO column reflect OGI surveys triggered by PoMELO flagging sites during the routine biannual inspection. The values under the Bridger column reflect Bridger flags which ultimately led to an OGI follow-up investigation (Bridger flags will trigger a follow-up screening with PoMELO, occasionally this PoMELO follow-up screening deems OGI unnecessary, these cases do not count as a follow-up investigation of a Bridger screening). In other words, although PoMELO screenings are sometimes considered “follow-ups” under this Alt-FEMP work practice, they are not detailed in this report under the assumption that follow-up metrics are primarily concerned with OGI investigations.

Performance Metric	PoMELO	Bridger	Total
Screenings that triggered a follow-up	459	161	620
Number of follow-ups where a leak was found	237	113	350
Number of follow-ups where a vent was found	222	48	270
Total number of leak sources (unique fugitive emissions)	506	274	780
Number of leaks repaired	506	274	780
Number of repairs delayed	0	0	0
Average time between leak detection and repair (days)	19	22	-

Table 4. Summary of follow-up survey performance metrics from the Lloydminster Alt-FEMP during **2022**. The table describes follow-up OGI investigations of biannual PoMELO and Bridger screenings. The values under the PoMELO column reflect OGI surveys triggered by PoMELO flagging sites during the routine biannual inspection. The values under the Bridger column reflect Bridger flags which ultimately led to an OGI follow-up investigation (Bridger flags will trigger a follow-up screening with PoMELO, occasionally this PoMELO follow-up screening deems OGI unnecessary, these cases do not count as a follow-up investigation of a Bridger screening). In other words, although PoMELO screenings are sometimes considered “follow-ups” under this Alt-FEMP work practice, they are not detailed in this report under the assumption that follow-up metrics are primarily concerned with OGI investigations.

Performance Metric	PoMELO	Bridger	Total
Screenings that triggered a follow-up	316	105	421
Number of follow-up surveys where a leak was found	228	65	293
Number of follow-up surveys where a vent was found	88	40	128
Total number of leak sources (unique fugitive emissions)	662	200	862
Number of leaks repaired	657	180	837
Number of repairs delayed	5	20	25
Average time between leak detection and repair (days)	23	18	-

An overview of the caveats and assumptions regarding the data presented in Table 3 and

Table 4 follows:

- One of the performance metrics requested by the AER is the “Number of follow-up surveys where no leaks or vents were found”. This performance metric is not included in Table 3 or
- Table 4. Under the work practice of the Alt-FEMP described in this report, as the OGI survey is always conducted immediately after screening with PoMELO if it is necessary, it is exceedingly rare to conduct an OGI survey without very recent data indicating emissions on site, either fugitive, vented or both (the same crew who operates the PoMELO equipped truck will conduct an OGI survey if the live PoMELO data indicated is required, Section 2.1.1). The OGI crews operating out of the PoMELO truck is one of the strengths of this Alt-FEMP as the live PoMELO data can drastically reduce time consuming OGI surveys in which no emissions are found.
- The performance metrics requested by the AER includes the count of close range OGI surveys where a “vented emissions is found” and a “fugitive emissions is found”. Typically, an OGI survey will be triggered by site-level emissions which include both fugitive and vented emissions, but due to how data was logged it was difficult to classify sites where a mix of vents and fugitive emissions sources were present. Therefore, sites where fugitive emissions where tagged were classified as follow-ups where fugitive sources were present and follow-ups where no fugitive emissions were found were classified as follow-ups where vents were found. It may be beneficial in future data collection to log OGI surveys in which both venting and fugitive emissions are found.

3.2.1 Analysis of Fugitive Emission Trends by Component Type

One of the performance metrics the AER has suggested providing is the “Number of recurring leaks observed”. This is a nearly impossible metric to log without managing every component as a unique device. To allow an understanding of recurring emissions, a rigorous and consistent assumption around what constitutes “recurring” must be communicated across all operators completing close range surveys so they can cross reference past emissions and log them as recurring, or extremely rigorous data regarding the nature of each fugitive emission (i.e., very specific localization details, rates, etc.) must be logged and later parsed via data analysis. While not an explicit count of “recurring leaks”, the following investigation carried out by Highwood is an attempt to shed light on the component types in the Canadian Natural Alt-FEMP pilot program which are most frequently prone to fugitive emissions, potentially providing insight on where recurring leaks are most likely to occur.

Table 5 and Table 6 includes all fugitive sources tagged, described by component for 2021 and 2022, respectively. In the second column of both tables a count of leaks by component is informed and in the third and forth columns those are translated into percentage of leaks and percentage of emissions coming from specific components. Since PoMELO measurement does not provide component-level leak rates, the percentage of emissions was calculated considering rates estimated using emissions factors described on Table 32 from Manual 015.

Table 5. Fugitive leaks counts in 2021. The first column of the table consists of a count of leaks tagged that came from a specific component. The second and the third column described the % of leaks and the % of emissions coming from leaks from that

component. The percentage of emissions was calculated considering rates estimated using emissions factors described on Table 32 from Manual 015.

Component	# of leaks from component	% of leaks from component	% of emissions from component
Control Valve	373	48%	41%
Connector	312	40%	28%
Open-Ended line	34	4%	23%
Regulator	41	5%	3%
Pressure relief valve	6	1%	3%
Valve	12	2%	3%
Meter	2	0%	0%

Table 6. Fugitive leaks counts in 2022. The first column of the table consists of a count of leaks tagged that came from a specific component. The second and the third column described the % of leaks and the % of emissions coming from leaks from that component. The percentage of emissions was calculated considering rates estimated using emissions factors described on Table 32 from Manual 015.

Component	# of leaks from component	% of leaks from component	% of emissions from component
Control Valve	494	56%	58%
Connector	356	40%	34%
Open-Ended line	4	0%	3%
Pressure relief valve	4	0%	2%
Valve	8	1%	2%
Regulator	14	2%	1%
Pump seal	1	0%	0%
Meter	1	0%	0%

An overview of the data sources which inform the columns in

Table 5 and Table 6 follows:

- Component: Based on the field "*Emitting Component Sub-type*" in the "*Corrective Action Tracking*" sheet.
- # of leaks from component: A count of leaks in each category of "*Emitting Component Sub-type"* sources from "*Corrective Action Tracking*" sheet.
- % of leaks from component: Value based on the count of leaks in each category and total number of sources identified.
- % of emissions from component: Value calculated based on leak rates estimated using guidelines on Method 015. Initially annual emissions were grouped by component and then contribution by each source was calculated.

To compare leak data from 2021 and 2022 a bubble chart was plotted and is shown in Figure 5. Each bubble represents one component type, color coded by Alt-FEMP year, 2021 or 2022. The y-axis is the percentage of emissions coming from each component type, while the number of leaks from that component is shown by the bubble size. In 2021 and 2022 most emissions came from control valves, connectors, and open-ended lines. Open ended lines are not as frequent as the other components, but due to the high emissions rates coming from them, they considerably impact the total emissions. In addition, in 2021 leaks from open-ended lines represented only 4% of total leaks, but they contributed to 23% of total emissions. In 2022 the number of open-ended valves reduced considerably, which resulted in most emissions (>93%) coming from control valves and connectors only.

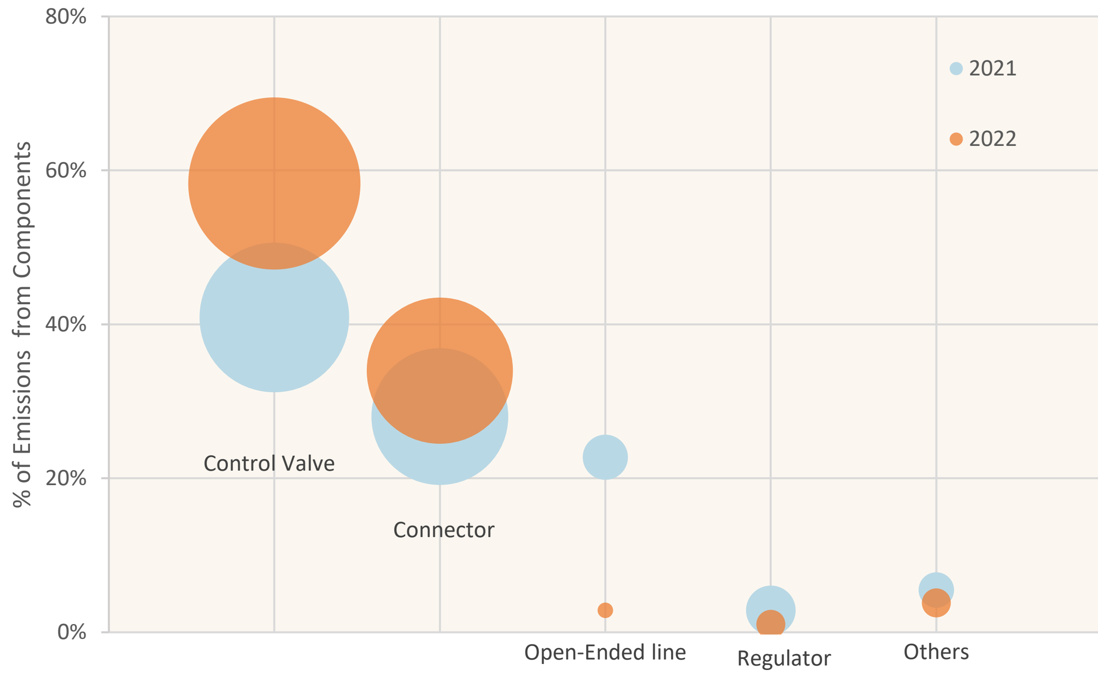

Figure 5. Comparison of emission contribution by component during Al-FEMP pilot in 2021 and 2022. Y-axis represents % of emissions coming from each component and bubble sizes indicates component count.

3.3 Emissions Reduction Summary

Section 3.3 will present investigations into the calculated and modeled emissions and emissions mitigation of the Lloydminster Alt-FEMP pilot program. Section 3.3.1 presents high-level look at emissions reductions from an assumed baseline emission. Section 3.3.2 presents modelling with LDAR-Sim which heavily draws from available Canadian Natural data and can be viewed as a "future looking" investigation into ongoing Lloydminster Alt-FEMP performance. Finally, Section 3.3.3 is a discussion of the discrepancy in the modeled emissions reduction put forth in the Alt-FEMP application package with the actual emissions reductions calculated in Section 3.3.1 and modeled in Section 3.3.2.

3.3.1 Annual Emissions Reductions from an Assumed Baseline

An investigation into annual emissions and emissions reductions was first undertaken using available leak data and assumptions around leak duration. The approach described here is calculation based and does not employ simulation modelling. Tagged leaks (those which were ultimately localized with an OGI inspection after a Bridger and/or PoMELO screening) during the Alt-FEMP pilot in 2021 and 2022 and their associated characteristics (component, rate, etc.) were used for these calculations. Total emissions and emissions mitigation per year were calculated by the following formulas:

$$\text{Annual Emissions [kg CH}_4\text{]} = \sum_i (\text{leak rate [kg CH}_4\text{ .}hr^{-1}] * \text{leak duration [hr]})_i$$

$$\text{Annual Mitigation [kg CH}_4\text{]} = Baseline\ \ Emissions\ \text{[kg CH}_4\text{ .}year^{-1}] - AltFEMP\ Emissions\ \text{[kg CH}_4\text{ .}year^{-1}]$$

These formulas were used to estimate emissions reductions of the Alt-FEMP by calculating an annual emissions baseline assuming a scenario in which no LDAR was performed across the span of the Alt-FEMP pilot and comparing this baseline against the formulas applied to the Lloydminster Alt-FEMP work practices (bi-annual screenings).

Leak duration is an important consideration. In practice, leak duration is almost always unknown, so AER Manual 015 guidelines were followed to estimate leak durations. These guidelines indicate that leak duration should be estimated as half the time between the previous survey at the same facility ID.[10] Since under the Lloydminster Alt-FEMP work practice (Section 2.1.1) all facilities included in the pilot program received bi-annual inspections, estimated leak duration when calculating annual emissions/mitigation under the Alt-FEMP, was a quarter of year (2190 hours). Conversely, to calculate the annual emissions baseline, it was assumed that all leaks would be propagated for one year, emitting for 365 days (8760 hours).

In addition to leak durations, leak rates must be assumed. To explore the differences between Manual 015 leak rate estimates and PoMELO emission measurements, two methods of assuming individual leak rates were used:

- **Method 1 (PoMELO Measured Rates)**: Method 1 assumes leak rates by using the provided site-level leak rates measured by PoMELO screenings (routine screening and follow-ups). Site-level fugitive emissions were reported in m^3/day. Rates were converted considering a gas density of 0.6787 and methane volumetric concentration of 0.95. Leak rates were drawn from the column "PoMELO fugitive site-level rates" from "District Survey Record" (Figure 2). For this method, screening rates from inspections where one or more fugitive sources were confirmed were used.
- **Method 2 (Manual 015):** For this quantification each leak tagged was assigned an emission rate based on emissions factors from Table 32 from AER Manual 015. Leak rates were drawn from "Corrective Action Tracking", where all components tagged for repair were listed. Since all new sources created in the "District Survey Record" generate a new leak in the "Corrective Action Tracking" we were able to ensure that the same sources were considered in both methods. (Details about the nature of the provided data are described in the section 2.2.1).

Table 7 summarizes annual emissions and Table 8 summarizes annual emissions reductions for sites encompassed in the Lloydminster Alt-FEMP in 2021. Both tables contain emissions estimates calculated using both Method 1 (using PoMELO rates) and Method 2 (M015 rates).

Table 7. Average annual emissions per site obtained from Alt-FEMP program data from 2021 calculated by Method 1 (using PoMELO rates) and Method 2 (M015 rates). For both methods Alt-FEMP emissions and baseline (scenario in which no LDAR is performed) values are informed.

Operating Area	Average Annual Emissions (tonnes CH_4 per site)

[10] Manual 015: Estimating Methane Emissions (https://static.aer.ca/prd/documents/manuals/Manual015.pdf)

	Method 1 (PoMELO rates)		Method 2 (M015 rates)	
	Alt-FEMP	Baseline	Alt-FEMP	Baseline
Lloydminster	48.75	195.00	0.44	2.00
Bonnyville	13.01	52.06	0.52	1.68
Weighted Region Average[1]	**35.03**	**140.10**	**0.47**	**1.88**

[1] This metric represents average annual emissions for the Lloydminster and Bonnyville regions. Lloydminster and Bonnyville have different site counts, so a weighted average was applied considering site counts for each operating area.

Table 8. Average annual emissions reductions per site obtained from Alt-FEMP program data from 2021 calculated by Method 1 (using PoMELO rates) and Method 2 (M015 rates).

	Average Annual Emissions Reductions (tonnes CH_4 per site)[2]	
Operating Area	Method 1 (PoMELO rates)	Method 2 (M015 rates)
Lloydminster	146.25	1.56
Bonnyville	39.04	1.16
Weighted Region Average[1]	**105.08**	**1.41**

[1] This metric represents average annual emissions for the Lloydminster and Bonnyville regions. Lloydminster and Bonnyville have different site counts, so a weighted average was applied considering site counts for each operating area.

[2] Lloydminster emissions came from 497 sources and Bonnyville emissions came from 293 sources. More details available in Table 1 and Table 3 (Section 3.1 and 3.2)

Table 9 summarizes annual emissions and Table 10 summarizes annual emissions reductions for sites encompassed in the Lloydminster Alt-FEMP in 2022. Again, both tables contain emissions estimates calculated using both Method 1 (using PoMELO rates) and Method 2 (M015 rates).

Table 9. Average annual emissions per site obtained from Alt-FEMP program data from 2022 calculated by Method 1 (using PoMELO rates) and Method 2 (M015 rates). For both methods Alt-FEMP emissions and baseline (scenario in which no LDAR is performed) values are informed.

	Average Annual Emissions (tonnes CH_4 per site)			
	Method 1 (PoMELO rates)		Method 2 (M015 rates)	
Operating Area	Alt-FEMP	Baseline	Alt-FEMP	Baseline
Lloydminster	7.49	29.94	0.40	1.60
Bonnyville	36.69	146.78	0.55	2.19
Weighted Region Average[1]	**18.90**	**75.58**	**0.46**	**1.83**

[1] This metric represents average annual emissions for the Lloydminster and Bonnyville regions. Lloydminster and Bonnyville have different site counts, so a weighted average was applied considering site counts for each operating area.

Table 10. Average annual emissions reductions per site obtained from Alt-FEMP program data from 2022 calculated by Method 1 (using PoMELO rates) and Method 2 (M015 rates).

	Average Annual Emissions Reductions (tonnes CH_4 per site)[2]	
Operating Area	Method 1 (PoMELO rates)	Method 2 (M015 rates)
Lloydminster	22.46	1.20
Bonnyville	110.08	1.64
Weighted Region Average[1]	**56.69**	**1.37**

[1] Represents the average annual emissions for the Lloydminster and Bonnyville regions. Lloydminster and Bonnyville have different site counts, so a weighted average was applied considering site counts for each operating area.

[2] For Lloydminster emissions came from 446 sources and for Bonnyville emissions came from 416 sources. More details available in Table 2 and Table 4 (Section 3.1 and 3.2)

For both years, emissions estimated by Method 1 (PoMELO) were significantly higher than emissions estimated by Method 2 (Manual 015), however, as the rates used under Method 1 (PoMELO) are direct measurements of Canadian Natural sites, Highwood concludes these rates and the resultant calculations are a more accurate representation of emissions at the sites in the scope of the Lloydminster Alt-FEMP. One remaining source of uncertainty to be aware of is that PoMELO site-wide fugitive emission rates are estimated by subtracting known, scheduled routine emissions from site-level measurements, therefore, if there is an unexpected variation in routine emissions, this unexpected variation will directly impact fugitive emissions estimates.

It is also important to highlight the significant difference observed between emissions calculated using PoMELO rates from 2021 to 2022. 2021 PoMELO emissions are almost two times higher than those in 2022, even with a similar number of leaks being reported. The main cause of this divergence can be explained as an update in the quantification algorithm used by PoMELO which happened from 2021 to 2022. This update considerably increased the confidence in emission rates reported.

While keeping assumptions in mind is important, the provided results in Table 7 to Table 10 communicate effectiveness of the Lloydminster Alt-FEMP with regards to emissions reductions.

3.3.2 LDAR-Sim I Modelled Emissions Reductions

To expand on the calculations carried out in Section 3.3.1, simulation modelling with LDAR-Sim was also conducted to model performance of the Alt-FEMP against FEMP OGI inspections should the trends observed thus far in the pilot program continue. The simulation modelling used Canadian Natural leak rates

(Figure 4) and replicated Alt-FEMP and FEMP work practices (biannual screenings of all sites or annual to triannual OGI surveys of all sites, respectively).

Simulation modelling results are shown in a series of visualizations created by the LDAR-Sim software. These visualizations show the emissions and emissions reductions of 3 LDAR programs (see glossary):

- P_none: A program in which no formal LDAR is applied to the sites. Under this program it is assumed that all leaks exist for 365 days before being "naturally repaired" (i.e., retrofits, operator walkthroughs, etc.)
- P_Regulatory_OGI: A program designed to represent base-FEMP LDAR requirements defined by Directive 060 of the sites encompassed in the scope of the Lloydminster Alt-FEMP. Under this program, all sites in simulation receive an accurate number of OGI surveys.
- P_ALT_FEMP: A program designed to replicate the Lloydminster Alt-FEMP work practice (Figure 1). Each site receives the correct number of screenings (Bridger and PoMELO) its "real-life counterpart" would.

Figure 6 is a series of box plots showing emissions under each modeled program. Under the assumptions used for this modelling, a typical site would emit on average 364 tonnes of methane per year in the absence of a FEMP program (P_none). In contrast, a typical site under the Canadian Natural Alt-FEMP program (P_ALT_FEMP) emitted, on average, 163 tonnes of methane per year, representing an emissions reduction of 55%.

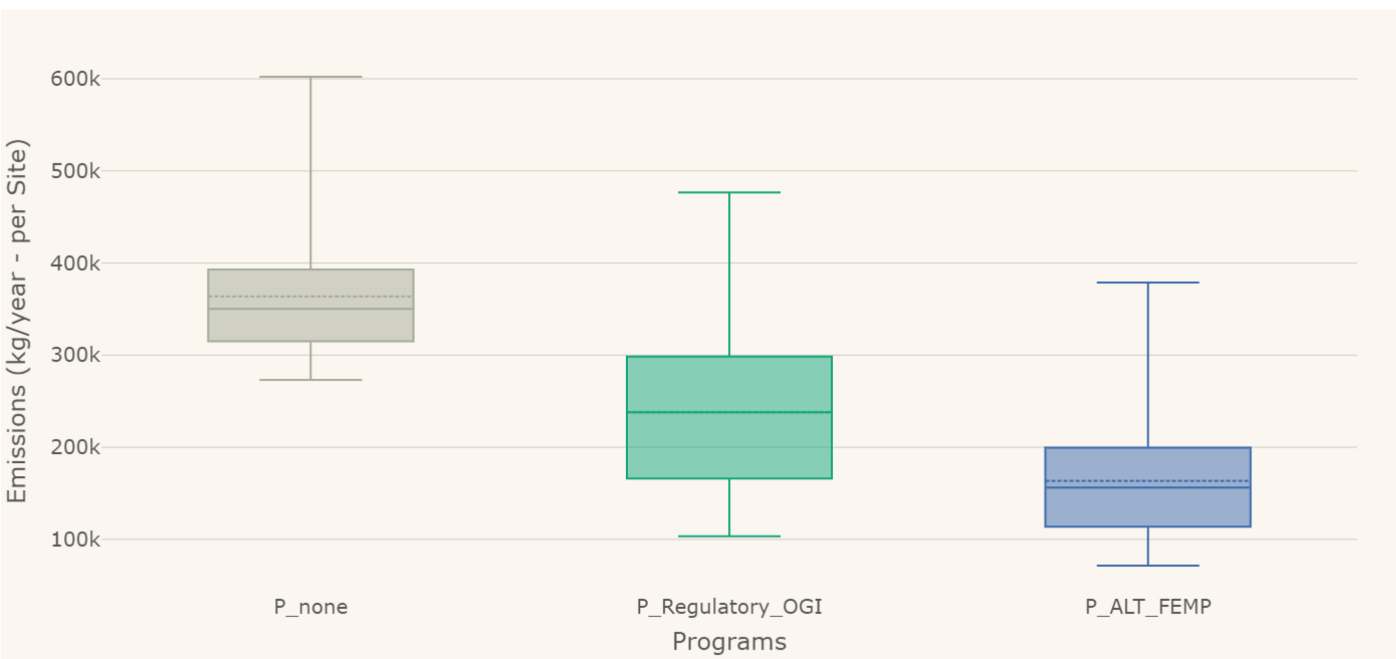

Figure 6. Box plots of average emissions in kg CH_4 per site per year (averaged across all Alt-FEMP sites in simulation). Comparison of programs based on the Canadian Natural Lloydminster Alt-FEMP (P_ ALT_FEMP), base FEMP routine OGI inspections defined by Directive 060 (P_Regulatory_OGI) and annual emissions in the absence of an LDAR program (P_none). On average, the Alt-FEMP program leads to greater emissions reductions than the D060 OGI-based program.

Figure 7 is a bar chart of average emissions reductions. When mitigation of the Base FEMP (P_Regulatory_OGI) and the Alt-FEMP program are compared (P_ALT_FEMP) we see the Alt-FEMP program mitigated 200 tonnes of methane per year per site, compared to 126 tonnes mitigated under the FEMP program. The additional mitigation by the Alt-FEMP program is observed because leaks are tagged faster, reducing its duration and consequently overall emissions.

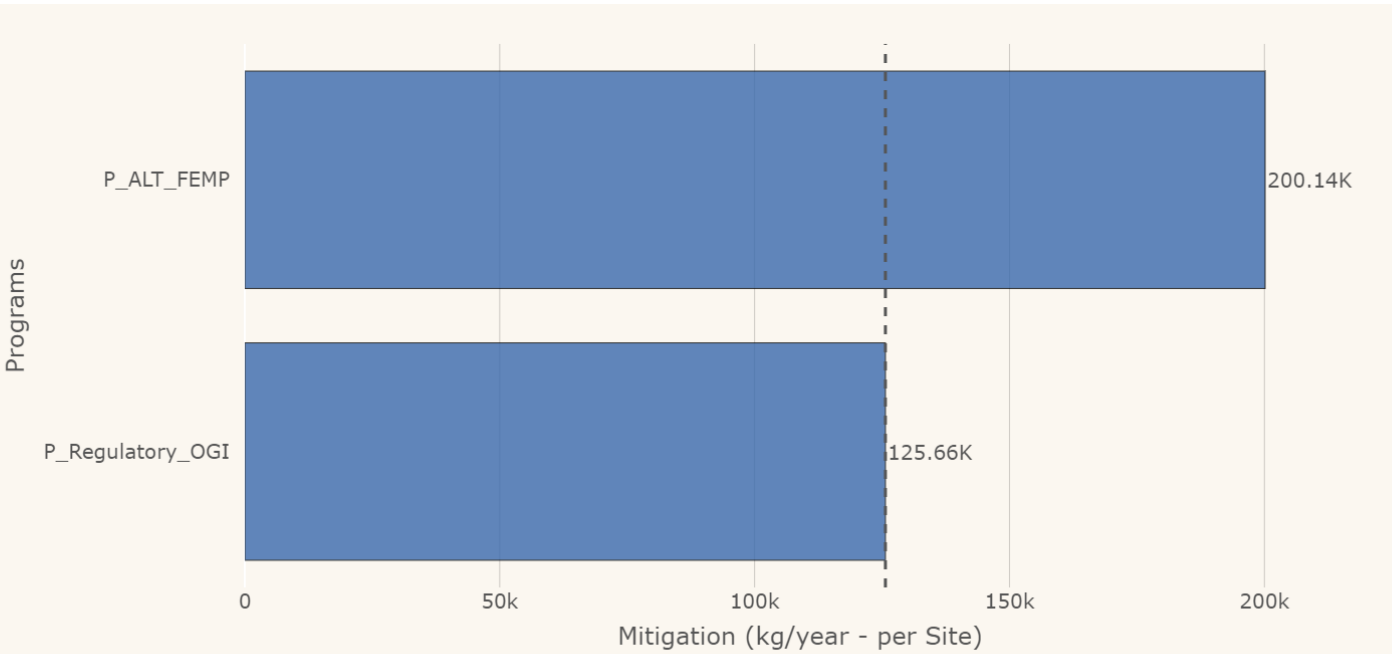

Figure 7. Average emissions mitigation in Kg CH_4 per site per year (averaged across all Alt-FEMP sites in simulation). Comparison of programs based on the Canadian Natural Lloydminster Alt-FEMP (P_ ALT_FEMP) and base FEMP routine OGI inspections defined by Directive 060 (P_Regulatory_OGI) On average, the Alt-FEMP program sees an increase in mitigation of 74,480 Kg CH_4 per year per site.

Figure 8 is a timeseries of average daily emissions per site in kg methane for each modeled program. The cyclicity seen in the timeseries of the Base FEMP (P_Regulatory_OGI) and Alt-FEMP (P_CNRL_Alt-FEMP) programs is due to the required screening/survey frequency of the sites under each program and is a useful indicator of why the Alt-FEMP leads to increased mitigation. In the Lloydminster area, most sites require annual surveys under FEMP programs, however, under the Alt-FEMP program all sites are visited twice a year. When a timeseries is “climbing”, emissions at the sites are “pooling” (leaks are being generated and added to the simulation with no mitigation efforts). When a timeseries starts to “fall” surveys have been performed and the leaks identified are being repaired. As the sites are surveyed more frequently under the Alt-FEMP program, leaks have less time to “pool” and the cyclicity from rise to fall is indicative of biannual surveys.

It is also worth noting that in modelling the Alt-FEMP program, the first screening of the year is performed by PoMELO and the second is performed by Bridger. For the first screening, due to the smaller threshold (100m^3/day) more sites are flagged for follow-up and more emissions are mitigated. This behavior is observable in the Alt-FEMP timeseries, when comparing the emissions drop for the first and second screening of the year. While the effect of the PoMELO screening is more immediately noticeable, the Bridger screening is still capable of finding large leaks which can have a marked impact on overall mitigation.

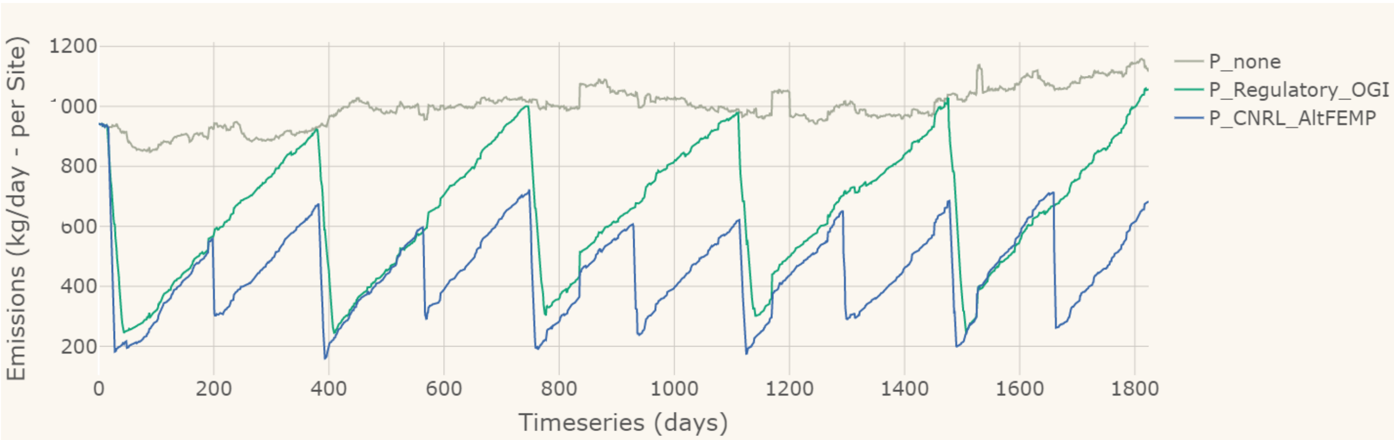

Figure 8. Timeseries of average emissions in kg CH_4 per site per day (averaged across all Alt-FEMP sites in simulation). Comparison of programs based on the Canadian Natural Lloydminster Alt-FEMP (P_ ALT_FEMP), base FEMP routine OGI inspections defined by Directive 060 (P_Regulatory_OGI) and annual emissions in the absence of an LDAR program (P_none). The cyclicity of the various time series is indicative of the dominant annual survey/screening requirements of the modeled programs with the Alt-FEMP (P_ ALT_FEMP) program showing biannual cyclicity and the base FEMP program (P_Regulatory_OGI) showing annual cyclicity as most sites have this requirement (as opposed to triannual).

Sensitivity Analysis

One important parameter that can impact both PoMELO and Bridger is the impact of wind direction and speed. For example, higher wind speeds can lead to decreased detection capabilities as methane plumes become more rapidly dispersed. While LDAR-Sim does incorporate weather conditions, wind direction is not considered and speed only goes down to average daily speed level granularity. To explore the impact of unfavourable wind conditions during a PoMELO or Bridger screening a sensitivity analysis using the LDAR-Sim temporal coverage parameter (Section 2.3.2) was performed.

In Figure 9 temporal coverage for the screening methods used in the Alt-FEMP program was varied from 50% to 100% (noted by the final value in the program names). A value of 50% indicates there is a 50% chance the wind will be unfavourable to a point the screening technology cannot detect an emission during a screening. A value of 100% indicates the wind is never unfavourable. It should be noted that the regulatory OGI programs temporal coverage was conservatively left at 100%, while in practice, wind can affect OGI performance. Figure 9 shows that even when wind is considered unfavourable during 50% of screenings, the Alt-FEMP program still outperforms the Directive 060 informed base FEMP OGI-based program.

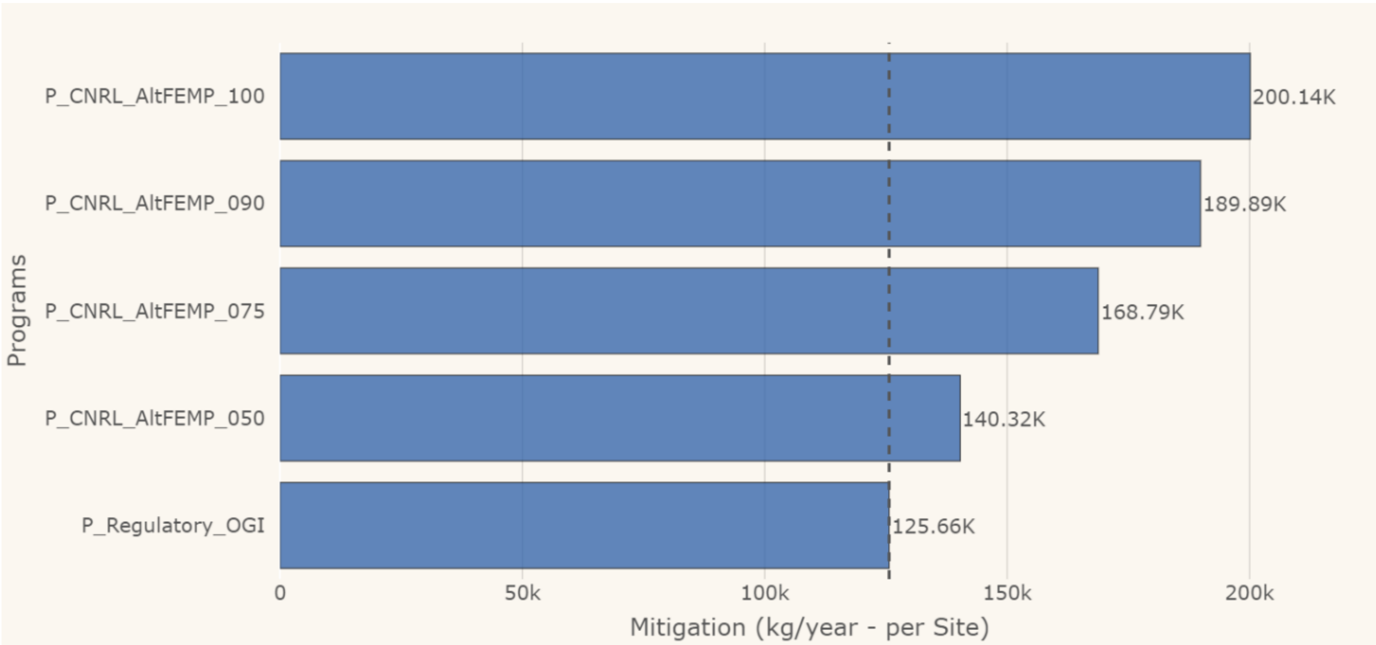

Figure 9. Updated model emissions mitigation of CNRL Alt-FEMP programs with screening methods with coverages ranging from 100% to 50% (P_CNRL_AltFEMP_*XXX*) and a program based on routine OGI inspections defined by D060 (P_Regulatory_OGI).

3.3.3 Analysis of Discrepancies Between Estimated and Modelled Emission Results

In the original Lloydminster Alt-FEMP application submitted, a third-party consultant estimated the proposed Alt-FEMP would lead to total mitigation of 1,283,140 m^3 CH_4 / year considering the 1,042 sites originally in scope. Converting this value to kg CH_4 /year and normalizing by the number of sites this translates in an average annual reduction of 0.84 tonnes of CH_4/year/ site. Comparing this number with mitigation calculated in this report (57 tonnes of CH_4 / year/ site) we can conclude that actual performance exceeded estimated reductions. The largest factor in this discrepancy is the incorporation of region-specific leak rates and leak occurrence.

Furthermore, when leak rates and leak production rates were incorporated in the updated model, we estimated that reduction could be as high as 200 tonnes of CH_4/year/ site (Figure 7). Highwood concludes emissions reductions of the Alt-FEMP program are the most rigorous results presented in this report. Modelling incorporated known emission rates, peer-reviewed detection capabilities, and accurate time delays as well as the inherent randomness of LDAR programs.

The model results presented can be continuously updated to see how the Alt-FEMP will perform looking forward as new data becomes available.

4 Qualitative Data Summary

4.1 Technology limitations

4.1.1 Bridger Screening with Gas Mapping LiDAR (GML)

The following are generalized potential limitations of Gas Mapping LiDAR (GML) and are not specific to this past project:

- **First Environmental Constraint:** The GML's industry leading sensitivity has a wide range of operation and allows data acquisition on ground wind speeds from 0-40 kph. However, there is technology deployment limitations when winds speeds fall out of this range. GML is an active (i.e. laser-based) sensor and as a result can detect emissions in shadows and cloudy or low-light conditions (i.e. no daytime hour limitations).
- **Second Environmental Constraint:** Surveys are not conducted when there is significant water on facilities or when the ground is covered in snow. Bridger anticipates overcoming the snow restriction for the next sensor generation. Currently the Generation 2 sensor is being tested for use in Canadian operations.

Gas Mapping LiDAR™ performance is statistical in nature. Bridger was involved in a fully blinded controlled methane release study with active oil and gas facilities.[11] That study found that Bridger's detection sensitivity was 0.56 kg CH_4/hr per m/s wind with an offset of 0.31 kg CH_4/hr for a 50% probability of detection. For the production sector Bridger's stated sensitivity is 2.8 kg CH_4/hr (150 scfh) with 95% probability of detection under all operational conditions. Additionally, in the fully blind study, Bridger was able to quantify the controlled releases with a bias of only -8% and only +/-31% standard deviation (1-sigma) using on-site wind data. Bridger was able to achieve these results even under very challenging survey conditions: (a) wet, muddy ground, (b) flying at the top of our operational flight altitude range, and (c) turbulent wind conditions. A more recent blind release study found Bridger's detection sensitivity with a 90% probability of detection of 0.41 (kg/h)/(m/s) wind speed at 675' above ground level (AGL). [12] Both studies were performed using generation 1.0 of GML. Bridger's Gen 2 GML sensors, which are being used in Canada, have improved detection sensitivity. The probability of detection curve for generation 2.0 GML is forthcoming in 2023.

None of the limitations above have impacted Canadian Natural's Alt-FMEP data quality.

4.1.2 PoMELO screening

The following are generalized potential limitations of PoMELO:

- **Environmental constraints:** Severe weather such as extreme cold, snowfall, blowing snow, rain, lightening, and other conditions which make driving dangerous limited the use of PoMELO.
- **Annual Servicing:** Required annual servicing can introduce some limited downtime to operations.
- **Difficulty of localizing leak to source with OGI cameras:** PoMELO detection limit is below OGI in most conditions, resulting in some situations where emissions could be detected with PoMELO but not localized by OGI.

[11] *Johnson, M. R., Tyner, D. R. & Szekeres, A. J. Blinded evaluation of airborne methane source detection using Bridger Photonics LiDAR. Remote Sens Environ 259, (2021).*
[12] *Bell, C. et al. Single-blind determination of methane detection limits and quantification accuracy using aircraft-based LiDAR. Elementa: Science of the Anthropocene 10, (2022).*

- **Efficiency and Safety:** PoMELO is a vehicle-based system. Extended drive time between pilot sites limited the efficiency of PoMELO surveys.
- **Quantification based work practice:** Emissions quantifications from PoMELO inherently had some error which reduced OGI follow-up efficiency in some cases.

4.2 Successes of the Alt-FEMP

Methods were complementary and helped to maximize leaks discovery. As per Figure 10, the locations of identified emissions are captured by Bridger and PoMELO. During PoMELO screening follow-up, the same emissions flagged by Bridger were identified and an additional emission as described in Table 11 . Based on the PoMelo findings, Canadian Natural was able to confirm the fugitive emissions utilizing OGI.

Table 11. Alt-FEMP Survey- Lloydminster & Bonnyville

Inspection Method	Date	Emissions Count
Bridger	Jun 14th, 25th 2021	2
PoMelo	Jul 17th, 2021	3
OGI	Jul 17th, 2021	3

Based on the collected data, the FEMP team believes that each of the technologies are complimentary to one another. By evaluating the Bridger surveys, the findings enabled Canadian Natural to execute ground-based follow-ups more efficiently, working to reach the goal of “Surveying with Purpose”. Canadian Natural field operations personnel were instrumental in differentiating from desktop review if the Bridger Survey outcome was a routine vent or a potential for a fugitive emission. From the desktop review, if an emission point source from a Bridger Survey is suspected to be a fugitive emission, the PoMelo unit is utilized to narrow down the location of potential fugitive emission and give an approximate quantification of the emission. From there, OGI is used to identify the discreet location of the fugitive emission where it is then tagged for repair.

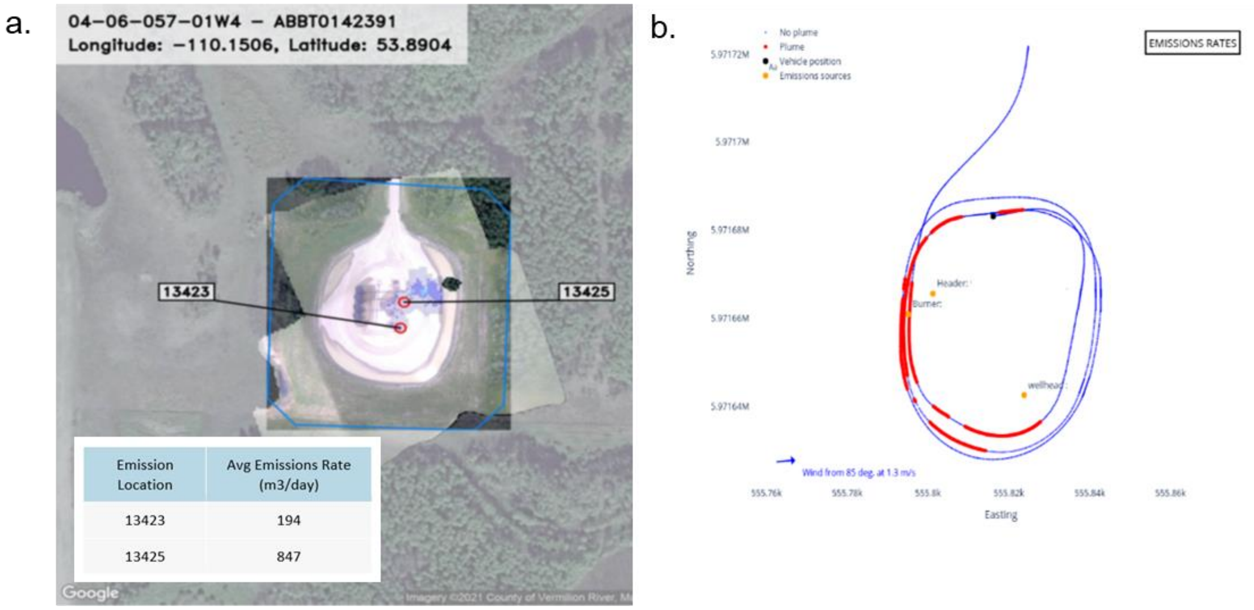

Figure 10. a. Bridger Aerial Photo and b. PoMelo Survey Map

4.3 Nonperforming program elements and additional control measures

4.3.1 Bridger Screening with Gas Mapping LiDAR (GML)

Canadian Natural and Bridger worked closely together to improve the reporting format and data delivery. Improvements were made in presentation of location level total emission roll-ups, integration of high-resolution imaging at the time of detection with public aerial imaging base maps, and individual location summary reports or presentation to field Operations personnel.

4.3.2 PoMELO Screenings

Canadian Natural and PoMELO worked closely together to improve program results. The following actions were taken during the pilot program:

1. PoMELO emissions quantifications were improved in the project to aid the quantification-based work practice. This improved the accuracy of OGI follow-up and enhanced the efficiency of operations.
2. PoMELO emissions quantifications were modified to a probability-based format to better manage measurement-specific quantification error and improve the ability for crews to model site emissions profiles.
3. PoMELO software was modified and matured throughout to improve operational efficiency.
4. PoMELO hardware underwent minor improvements throughout to mature the design and improve operational efficiency.

4.4 Key Performance indicators

Key performance indicators detailed in original Alt-FEMP application, with references to sections in this performance report where they have been updated follow:

- Quantified emissions reduction over time, corporate-wide and by operating area: Covered in Section 3.3.1
- Cost of detection ($/t methane detected): Cost of mitigation evolved throughout the program as detection algorithms improved and sites within scope were adjusted. As this is an evolving metric, it was deemed proprietary and outside the scope of this performance report.
- Volume of gas conserved by managing fugitive emissions: Covered in the Emissions Summary Section 3.3.1
- Number of leaking components over time, corporate-wide and by operating area: Covered in Section 3.2
- Specific components within facilities that are more prone to leaks: Covered in Section 3.2.1.
- Time between leak detection and repair: Assumptions around this discussed in Section 3.2.

5 Conclusions

This report contests that the Canadian Natural Alt-FEMP pilot program should be evaluated as a success as it was able to realize results in the following key performance set by the FEMP management team to evaluate the performance of a FEMP or Alt-FEMP program over time.

Quantification of emissions reductions over time

Analysis performed using data collected during the duration of the Alt-FEMP pilot program was able to quantify the emissions reductions of the Alt-FEMP both at a corporate scale, and on the scale of individual operating areas. Specifically, emissions reductions were able to be quantified in tonnes CH_4 per site per year of the Alt-FEMP deployment despite setbacks due to learnings and unknown variables. Emissions reductions for the first year of the Alt-FEMP deployment period, 2021 were quantified as 146.25 tonnes CH_4 per site for the Lloydminster operating area and 39.04 tonnes CH_4 per site for the Bonnyville operating area. Conversely, for the second year of the Alt-FEMP deployment, emissions reductions were quantified as 22.46 tonnes CH_4 per site for the Lloydminster operating area and 110.08 tonnes CH_4 per site for the Bonnyville operating area. The overall decrease in emissions from 2021 to 2022 is partly due to improvements to the PoMELO quantification algorithm (which was used to inform the reported CH_4 emissions), anecdotally it had been reported to be overestimating emissions in 2021.

Another benefit of emissions quantification is that the thorough data collection process has allowed Canadian Natural to be better informed of their emissions profile and typical fugitive emissions rates.

Quantification of the number of leaking components over time

Analysis of collected data also allowed for the quantification of the number of leaking components over time both at the corporate and operating region scale. This metric provides valuable insight into emissions patterns for operating regions and could help inform decision making about equipment health, need for refurbishment and lifespan. During 2021, 780 leaking components were identified, as apposed to 2022 where 878 leaking components were identified. Possible rationale for this upwards trend in the number of leaking components identified include ageing of the equipment, the improvement of screening and surveillance technology, an improvement in the data collection process or even chance. Without more information over a longer period to analyse trends it is difficult to pinpoint the exact cause of this discrepancy.

Identification of specific components within facilities that are more prone to leaks

During data analysis, emissions contributions were able to be categorized by component type. This allowed for analysis of emissions contributions by component type on a yearly basis, where observed trends could provide valuable insight into informing component related decision making. It is possible that in the future information such as this could help inform work practices aimed at reducing emissions by targeting facilities with large densities of high emitting components for more frequent screening and/or surveys. In the case of facilities in scope of the Alt-FEMP pilot, component labelled as control valves and connectors were clearly identified as contributing 69% and 92% of total annual emissions for 2021 and 2022 respectively. Meanwhile open-ended lines, which contributed 23% of total annual emissions for 2021 did not follow a consistent trend in 2022, where they instead contributed only 3% of total annual emissions. This is due to a considerable reduction in open-ended valves between 2021 and 2022 in the facilities in scope of the Alt-FEMP pilot, resulting in a corresponding reduction in emissions caused by open-ended lines.

Measurement of time that has passed between leak detection and repair

Measurement was conducted during data analysis to determine the average time between leak detection screening and leak repair on a yearly basis. The time measured between leak detection and repair for leaks initially screened by PoMELO surveys was consistent between years of the Alt-FEMP pilot deployment at 19 days and 23 days on average for 2021 and 2022 respectively. Conversely, a large variation in time between leak detection and repair was observed between the 2 years of the Alt-FEMP pilot for leaks initially screened by Bridger surveys at 22 days and 60 days on average for 2021 and 2022 respectively. This discrepancy can be explained by a change in the measurement criteria for “leak detection”. For 2021, leak detection calculated as the time that leaks were tagged for repair, whereas for 2022 as there were gaps in the compiled data, the leak detection date had to be substituted for the initial screening date. This explains the increased delay for in 2022 for leaks initially screened by Bridger as repaired leaks that were initially screened by the Bridger aerial screening method by nature have a longer time between the initial detection and repair date due to the necessity of a second screening resulting from Bridger flagging of sites before leak can be tagged for repair, whereas if they are initially detected by PoMELO screening they are tagged the same day.

Appendix A – LDAR-Sim modelling virtual world

Table 12 - Modelling parameters used to simulate virtual world.

Global Parameters	Parameter and Description	Justification & Source
Number of simulations, temporal resolution, and duration, as applicable	Number of simulations to perform for each program: 5 simulations. Temporal resolution: 5 years	Multiple simulations were run to better-constrained results. Additional simulations could be requested, but past experience has shown that minor improvements are observed by further increasing this number. A temporal resolution of 5 years was chosen as 5 years is a sufficiently long duration to mitigate the impact of outliers generated from the inherent randomness of the virtual world while avoiding adding unnecessary duration to the simulations.
Empirical fugitive and vented data source(s)*	The empirical fugitive emissions data source is typically either chosen from a peer-reviewed empirical studies the most representative of the region to be modelled or actual empirical data obtained from the facilities to be modelled. This data is used to generate input emissions data. Currently, there are not sufficient studies of emissions data with corresponding data of vented emissions sources. Vented emissions are only considered when actual empirical emissions data contains sufficient information about vented emissions sources.	Empirical fugitive emissions data source: Actual Canadian Natural Alt-FEMP emissions data provided to Highwood. Empirical vented emissions data source: Actual Canadian Natural Alt-FEMP emissions data provided to Highwood.

Global Parameters	Parameter and Description	Justification & Source
Description of input emissions data (e.g., sampling distributions and parameters) *	There are two possible valid inputs for emissions data: 1. The μ and σ of a log-normal distribution are added as inputs to inform the leak sizes. These values informed the log-normal shape of the leak distribution sampled every time a leak is generated. 2. Actual empirical emissions data is added as inputs to inform leak sizes. This data is sampled from at random every time a leak is generated.	For the base case virtual world modelling, a lognormal distribution modelled by a μ of 1.565 and a σ of 1.929 was used. This was based on a lognormal curve fit to actual Canadian Natural emissions data provided.
Leak production behavior	Leak production behavior in the digital world is governed by the “Leak Production Rate” parameter. This parameter represents the chance for a leak to begin at a given site on a given day.	For this simulation a single Leak Production Rates was modelled based on observed leak rates in actual Canadian Natural emissions data: LPR: 0.003689437 See Section 2.3.3.2 for more details
Natural leak removal behavior*	365 days. This number represents leak removal from the leaks pool due to routine maintenance, refits, retrofits, and other unintentional leak repairs.	Most programs are performed annually, and it was assumed that most leaks would be repaired in this time frame. Past experience has shown that changes in this parameter impact overall emissions (baseline), but mitigation comparison should not be affected.

Global Parameters	Parameter and Description	Justification & Source
Site list and characteristics (count, source, types, etc.)	Sites can be represented in the virtual world by a variety of information. Site locations are represented though latitude and longitude, which allow for the use of weather data from the region surrounding the site to model weather envelopes. Sites are assigned a subtype, which allows for the use of subtype specific leak production and leak generation data. Sites can also be assigned survey frequencies for specific methods, allowing site specific modelling of LDAR work practices (regulatory or otherwise).	See Section 2.3.2
Describe assumptions made to model the fraction of repairable vs. non-repairable emissions	All leaks tagged were considered repairable.	There is an absence of sufficient empirical/historical data to support more complex modelling of repairable versus non-repairable emissions.
Weather data basis	Historical weather data from 2019/2020 containing total precipitation, wind data, temperature, and cloud coverage was downloaded as an ERA5 NetCDF4 file for the facilities region.	Variables were chosen to reproduce environment constraints faced by the different methods evaluated. Data source:

Appendix B – Program and Methods Parametrization

Table 13. Program descriptions and methods included in each program.

LDAR Programs	Description	Methods
P_Regulatory OGI	Modelling representing the currently required regulatory OGI program for all sites. The work practice of this program models the required regulatory OGI survey frequency for each site. This program consists of one method: M_Regulatory_OGI, which models a regulatory OGI survey.	M_Regulatory_OGI
P_CNRL_AltFEMP	Modelling representing the Canadian Natural ALT-FEMP pilot program. The work practice of the program involves 4 methods, Aerial surveys, routine PoMELO surveys, PoMELO follow-up surveys and follow-up OGI surveys. See Section 2.1.1 Figure 1 for a detailed breakdown of the modelled work practice of the program.	M_Aerial M_PoMELO M_PoMELO_FU M_OGI_FU

Table 14. Methods descriptions

LDAR Program Methods	Description
M_Regulatory_OGI	Method modelling a regulatory OGI survey that would be performed as part of the regulatory OGI program.
M_Aerial	Method modelling the Bridger Aerial LiDAR surveys that are routinely performed as part of the Canadian Natural ALT-FEMP pilot program.
M_PoMELO	Method modelling the PoMELO ground, truck-based screening surveys that are routinely conducted as part of the Canadian Natural ALT-FEMP pilot program.
M_PoMELO_FU	Method modelling the PoMELO ground, truck-based screening surveys that are conducted as a follow-up to Aerial surveys where the detected site-level emissions surpass the threshold, and the site requires a follow-up.
M_OGI_FU	Method modelling the close range OGI surveys that are conducted as a follow-up to any PoMELO screening survey where the measured emissions indicate a close-range follow-up is required to identify emissions sources.

Table 15. Methods parametrization

Methods Parameters	M_Regulatory_OGI	M_Aerial	M_PoMELO	M_PoMELO_FU	M_OGI_FU
Consider daylight	True	True	True	True	True

Methods Parameters	M_Regulatory_OGI	M_Aerial	M_PoMELO	M_PoMELO_FU	M_OGI_FU
Spatial coverage	0.8	0.9	0.9	0.9	0.9
Temporal coverage	1	Variable	Variable	Variable	1
Is follow-up	No	No	No	Yes	Yes
Consider venting	True	True	True	True	True
Measurement scale	Site-Level	Site-Level	Site-Level	Site-Level	Component-Level
Reporting delay (days)	2	0	0	0	2
Follow-up Delay (days)	Not Applicable. Close range OGI surveys do not require a follow-up survey.	30	0	0	Not Applicable. Close range OGI surveys do not require a follow-up survey.
MDL (g/s)	95% PoD at an emission rate of 0.182 g/s	3.93 g/s	0.785 g/s	0.785 g/s	95% PoD at an emission rate of 0.182 g/s
Required annual surveys (Surveys / Year)	Dependent on-site subtype. Wells require 1 survey/year while compressors require 3 surveys/year	1 survey/year	1 survey/year	Not applicable. This method is a follow-up to another method requiring routine surveys.	Not applicable. This method is a follow-up to another method requiring routine surveys.
Precipitation (mm) [min,max]	[0.0, 0.5]	[0.0, 0.5]	[0.0, 0.5]	[0.0, 0.5]	[0.0, 0.5]
Temperature (°C) [min,max]	[-40.0, 40.0]	[-40.0, 40.0]	[-40.0, 40.0]	[-40.0, 40.0]	[-40.0, 40.0]

Methods Parameters	M_Regulatory_OGI	M_Aerial	M_PoMELO	M_PoMELO_FU	M_OGI_FU
Wind (m/s) [min,max]	[0.0, 10.0]	[0.0, 10.0]	[0.0, 10.0]	[0.0, 10.0]	[0.0, 10.0]

Table 16. Methods parameter descriptions, justification and source.

Methods Parameters	Description	Justification / Source
Consider daylight	Parameter modelling whether surveys should consider the limitations of daylight when scheduling surveys. A value of True limits surveys to only be performing during daylight hours, while False will allows for surveys to be performed anytime during the workday, regardless of daylight/	Following technology provider guidelines
Consider venting	A value of True enables modelling of venting at facilities based on a provided site record of site-level emissions. Vents are assigned a rate based on the difference between a randomly sampled site-level emission and the sum of fugitive emissions at the site. A value of False results in venting behavior not being modelled.	All methods were set to be modelled taking venting into considering for an equal comparison. Venting was able to be considered due to the collection of both site-level emission and estimated site fugitive emissions.
Spatial coverage	The probability (0-1) that a method can locate a leak. Internally, each leak will be randomly assigned a True or False value based on this probability indicating whether the leak can be detected by the work practice. This value is rolled once for each leak and work practice pair and remains consistent for subsequent surveys. This parameter models the real-world inability of certain methods to survey all components and/or sites to the same degree of accuracy.	M_Regulatory_OGI: Set to 0.8 to model the inability of OGI surveys to adequately survey elevated emissions sources. M_Aerial: Set to 0.9 to model the inability of Aerial surveys to adequately survey covered emissions sources. M_PoMELO: Set to 0.9 to model the inability to adequately survey covered emissions sources. M_PoMELO_FU: Set to 0.9 to model the inability to adequately survey covered emissions sources. M_OGI_FU: Set to 0.9 to model the increased ability of close-range OGI surveys to adequately survey elevated emissions sources as compared to standard OGI surveys when provided screening information to help locate fugitive emissions sources.

Methods Parameters	Description	Justification / Source
Temporal coverage	A representation of the average proportion of a facility the method can effectively survey. For example, a value of 0.7 indicates that the method will find a leak 100% of the time in 70% of the site. In practice, every time a method goes to survey a new leak, a weighted coin is flipped representing spatial coverage. If the method "loses" the weighted coin flip, it will not detect the emission and it will also not be able to detect it on ensuing survey visits.	M_Regulatory_OGI: Set 1 for conservative modelling of Alt-FEMP performance versus regulatory requirements as there is not enough data to accurately chose a representative value. M_Aerial: Variable. Sensitivity analysis was performed on this parameter to explore the impact of different temporal coverage parametrizations. M_PoMELO: Variable. Sensitivity analysis was performed on this parameter to explore the impact of different temporal coverage parametrizations. M_PoMELO_FU: Variable. Sensitivity analysis was performed on this parameter to explore the impact of different temporal coverage parametrizations. M_OGI_FU: Set 1 to match the parametrization of the regulatory OGI since this method is the same technology.
Is follow-up	A Boolean value to inform internal simulation logic of when to treat a method as a follow up. The naming convention for methods is that follow-up methods are terminated by _FU to clearly identify as such to users.	-
Measurement scale	The level at which the method measures emissions. Can be either site-level or component level. Methods with a site-level measurement scaler measure total emissions at a site, while methods with a component level measurement scale measure individual emission.	M_Regulatory_OGI: OGI survey methods are only capable of measuring component-level emissions. M_Aerial: Aerial surveilance methods are only capable of measuring site-level emissions. M_PoMELO: PoMELO screening surveys are capable of measuring site-level emissions. M_PoMELO_FU: PoMELO screening surveys are capable of measuring site-level emissions. M_OGI_FU: OGI survey methods are only capable of measuring component-level emissions.
Reporting delay (days)	This parameter models the number of days that pass from the completion of a survey to when the duty holder is informed of the need for a follow-up or the need to repair a leak. With the advent of automated reporting systems this parameter is often 0, but it can be longer internal analytics.	M_Regulatory_OGI: Set to 2 based on technology provider guidelines. M_Aerial: Set to 0 based on technology provider guidelines. M_PoMELO: Set to 0 based on technology provider guidelines. This reflects the reality that the crew to perfom close-range OGI follow-ups is the same crew that is performing the PoMELO screening survey. M_PoMELO_FU: Set to 0 based on technology provider guidelines. This reflects the reality that the crew to perfom close-range OGI follow-ups is the same crew that is performing the PoMELO screening survey. M_OGI_FU: Set to 2 based on technology provider guidelines.

Methods Parameters	Description	Justification / Source
Follow-up Delay (days)	The number of days to have passed after a site has been surveyed by a method before it can be flagged as requiring a follow-up survey. This parameter is often used to represent delays (intentional or otherwise) that result from proposed work practices.	M_Aerial: Set to 30 days based on Canadian Natural Alt-FEMP pilot program work practice. M_PoMELO: Set to 0 days based on Canadian Natural Alt-FEMP pilot program work practice. M_PoMELO_FU: Set to 0 days based on Canadian Natural Alt-FEMP pilot program work practice. See Section 2.1.1 for details on the Canadian Natural pilot program work practice.
MDL (g/s)	The minimum detection limit of the survey method in g/s. This can be parametrized as a single minimum detection limit or as a probability of detection curve.	OGI was parameterized with a probability of detection (PoD) curve informed by Zimmerle et al. which accounts for operator experience and has a 95% PoD at an emission rate of 0.182 g/s. [13] Other methods of methane detection were parametrized in accordance with the proposed work practice.
Required annual surveys (Surveys / Year)	The number of required annual surveys each method must perform per site. This value can be set at the site-level as needed.	Regulatory OGI: Set to 1 or 3 surveys per year depending on the regulatory requirements of the site subtype. PoMELO: Set 1 survey/year as proposed for the Canadian Natural Alt-FEMP pilot program. Briger: Set 1 survey/year as proposed for the Canadian Natural Alt-FEMP pilot program. Follow-up methods: This parameter is not applicable to follow-up methods as they are scheduled as required.
Precipitation (mm) [min,max]	The range of precipitation accumulation (mm) allowed over one hour. If the precipitation is outside this range for a given day at a site, surveys will not be sent to the site that day.	Following technology provider guidelines
Temperature (°C) [min,max]	The bounding range of allowable average hourly temperature (°C). If the temperature is outside this range for a given day at a site, surveys will not be sent to the site that day.	Following technology provider guidelines

[13] Zimmerle, D., Vaughn, T., Bell, C., Bennett, K., Deshmukh, P. and Thoma, E. (2020). Detection Limits of Optical Gas Imaging for Natural Gas Leak Detection in Realistic Controlled Conditions. Environmental Science & Technology, 54(18), pp.11506-11514

Methods Parameters	Description	Justification / Source
Wind (m/s) [min,max]	The bounding range of allowable hourly average wind speed (m/s at 10m). If the wind speed is outside this range for a given day at a site, surveys will not be sent to the site that day.	Following technology provider guidelines