Technical Report

Alt-FEMP Performance Report

Enhance Energy and Qube Technologies Single-Operator Pilot

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Prepared for

enhance

QUBE

Executive Summary

In this report, Highwood Emissions Management (Highwood) and Enhance Energy (Enhance) summarize Key Performance Indicators and key takeaways from a one-year deployment of an Alternative Fugitive Emissions Management Program (Alt-FEMP) based around the Qube Technologies. Specifically, this report focuses on the performance metric reporting requirements specified by the Alberta Energy Regulator (AER) Alt-FEMP[1] through the use of pertinent data analysis and discussion of more qualitative elements of the pilot program.

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.

Enhance Energy and Qube Technologies Single-Operator Pilot

On April 2021 Enhance Energy and Qube Technologies Single-Operator Pilot was approved to monitor seven Enhance facilities in the Red Deer region already regulated under Section 8 of AER Directive 060 using Qube's continuous monitoring solution. As two of these facilities had several distinct legal locations, the total number of sites monitored was sixteen.

[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."

On September 2021 Qube deployed Industrial Internet of Things (IIoT) devices at distances of 10-100 m from potential sources with the goal of continuously monitoring for CH_4, H_2S, NO_2, CO, and VOCs. Qube's initial method of tracking program data was done manually in an Excel sheet referred to as the "Alt-FEMP Reporting Tool", the reporting tool, populated with all detection events and associated metadata (wind data, etc.) was sent to Enhance from Qube monthly. After receiving the report Enhance would classify the detection events as "Potential Fugitive Emissions Events" or "Vented or Offsite Event" and perform follow-ups. For this pilot, close-range follow-up inspections were scheduled as soon as a defined detection event was classified as a Potential Fugitive Emission to confirmed to investigate leak sources.

The main goals of the pilot were: (i) validate work practice (ii) acquire a better understanding of Enhance emissions profiles (iii) acquired feedback on operator experience to automate reporting and follow-up recommendations (iv) acquire data to improve machine learning algorithms for detection, localization, quantification, and classification (v) understand important and unknown parameters such as environmental envelopes (e.g., whether Qube's system fails in extreme weather), time to detection, time to repair, quantification accuracy, the number of IIoT devices to use, and so on. The pilot was successful, and an extension was proposed. Enhance was able to quickly identify and resolve emission leaks, leading to improved emissions reductions. Data collected and feedback provided informed the development of multiple features within Qube's platform, essential for a comprehensive understanding of emissions on a site. Details of the pilot's success and the resulting developments are provided in the body of this report.

Summary of Key Performance Indicators

During deployment a total of 16 sites were monitored for 14 months. During this period a total 213 detection events were sent to Enhance, from which 36 were classified as potential fugitive emissions sources. Those detection events triggered 21 follow-up inspections (some detection events were triggered from the same source) that found 7 fugitive emissions sources. From the 21 follow-up inspections, 14 only found routine emissions sources and 7 found leaks. Most leaks tagged were caused by malfunctioning thief hatches, followed by valves.

Annual emissions assessment estimated that 13 tonnes of methane were emitted per year by the sites within scope of the Alt-FEMP and that up to 89% of emissions were mitigated due to Alt-FEMP deployment (depending on emissions estimated when no LDAR program was implemented). This assessment was performed based on assumptions around leak durations and using average site rates during periods where leaks were active. This last assumption means that leak rates could be overestimated because it includes venting contribution. Predictive modeling incorporating data collected in the program showed that annual emissions for sites in the scope could be estimated as 4 tonnes per year under Alt-FEMP program (The Alt-FEMP program in simulation achieves 93.9% mitigation), compared to 46.5 tonnes of methane by regulatory program (The AER Directive 060 based regulatory program in simulation achieves 29.6% mitigation). Updates in the modeling did significantly impact the estimated annual emissions submitted during the original Alt-FEMP application, indicating that the previous modeling was reasonable in predicting annual emissions for sites monitored by Qube. However, the updates in leak rates and detection performance had a significant impact on how the regulatory program performed, resulting in a wider gap between Alt-FEMP and the regulatory program, which highlights the advantages of the Alt-FEMP program over the regulatory program.

Key takeaways

- The program allowed Enhance to quickly identify and repair leaks in a timely manner, ultimately enabling an improvement in emissions reductions.
- Qube's switch to a new dashboard-based platform in May 2022 was beneficial for Enhance, enabling the visualization of where site leaks were occurring in real time. Qube's ability to group emission events right within the platform helps to categorize "events" that require follow up and helps Enhance understand where the priorities are at their sites. Ultimately, follow up OGI surveys were performed in a more efficient way due to Qube's ability to localize emissions to an equipment group.
- Improvements in the reporting piece are being built to satisfy operator and regulator needs (some of this is still in development. Currently the repair and OGI camera work is handled outside of Qube's platform, but Qube is looking for ways to incorporate this into the dashboard. Pilot tracking method was done in a manual Excel sheet (the Alt-FEMP Reporting Tool) and the learnings from that process was used to built functionalities into the dashboard allowing data to be exported directly from Qube's system.

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. Terminology based partly on the AER Alt-FEMP performance report guidelines[4].

[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
[4] https://www.aer.ca/regulating-development/rules-and-directives/directives/alt-femp-performance-report-requirements

- **"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. Terminology based partly on the AER Alt-FEMP performance report guidelines[5]
- **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.

[5] https://www.aer.ca/regulating-development/rules-and-directives/directives/alt-femp-performance-report-requirements

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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 2021-02-16, Enhance applied for an Alt-FEMP pilot for encompassing facilities in the Red Deer region. The application was approved, and the Alt-FEMP came into effect in April 2021. The approved Alt-FEMP was based around continuous monitoring with the Qube Technologies (Qube) IIoT devices and cloud-based data management and reporting software. Highwood Emissions Management, Enhance, and Qube have collaboratively prepared this performance report to summarize quantitative and qualitative learnings from the Enhance Qube Alt-FEMP. The guiding questions of this Alt-FEMP performance report are based on AER guidance.[6]

Highwood, using provided Qube data, led the quantitative investigation. Highwood compiled, cleaned, and analyzed the provided Qube continuous monitoring data to understand fugitive emissions trends and assess 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.[7] 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 Enhance Qube Alt-FEMP emissions mitigation performance.

Qube and Enhance, as co-authors of this performance report, led the qualitative data summary. Details of the qualitative analysis are primarily drawn from Enhance and Qube's expertise. Enhance and Qube worked extremely closely together, with Enhance ensuring Qube was provided with actionable feedback to effectively continue to improve their platform. 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 Qube Enhance 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.

[6] https://www.aer.ca/regulating-development/rules-and-directives/directives/alt-femp-performance-report-requirements
[7] 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. Performance Report Background

2.1. Work Practice Overview

The Alt-FEMP pilot program implemented covered 7 Enhance facilities situated in the Red Deer region, regulated under Section 8 of AER Directive 060. Given that two of these facilities had multiple legal locations, the program monitored a total of 16 sites. This terminology of facilities (overarching facilities) and sites (individual legal locations within a facility) will be used henceforth throughout the report. Table 1 in Section 3 lists all facilities / sites within scope of the Alt-FEMP.

Qube deployed IIoT devices at each of these sites to continuously measure levels of CH_4, NO_2, CO, and VOCs. Out of the 16 sites covered by the program, two that required tri-annual surveys under the base FEMP program received an additional comprehensive annual OGI survey.

At the onset of the program, the data collected by Qube was shared with Enhance exclusively via the “Alt-FEMP Reporting Tool” (an Excel based tool) monthly. In May 2022, Qube released a proprietary dashboard which provided Enhance greater interactivity and visualization options with regards to the continuous Qube monitoring data, however, Qube detection events were still manually provided to Enhance on a monthly basis.

Upon receiving the alerting data packages, responsibility shifted to Enhance operators. Enhance operators would evaluate the emissions source and categorize it as "potential fugitive emissions" or "vented or offsite event". If the emissions were classified as "potential fugitive emissions", Enhance operators would manually investigate potential sources. Both the classification and localization requirements were aided by the Qube dashboard which provided a visual estimation of emission source. If a follow-up survey was required, first, an Audio Visual Olfactory (AVO) inspection would be conducted, if the AVO inspection was not enough to effectively localize and classify the potential fugitive emission, the operator would perform a subsequent survey using either an OGI camera or a handheld Organic Vapour Analyzer device. If a leak was confirmed via this close-range inspection, the operator would record common data fields such as the leak source, cause, date, etc., in accordance with the AER Directive 060 in Internal Enhance data storage. All leaks found during these surveys were tagged and repaired. After leak repair was completed, emissions were continuously monitored by Qube to ensure they returned to baseline levels. If emissions persisted above baseline levels, close-range follow-up OGI inspections would be conducted immediately for further investigation.

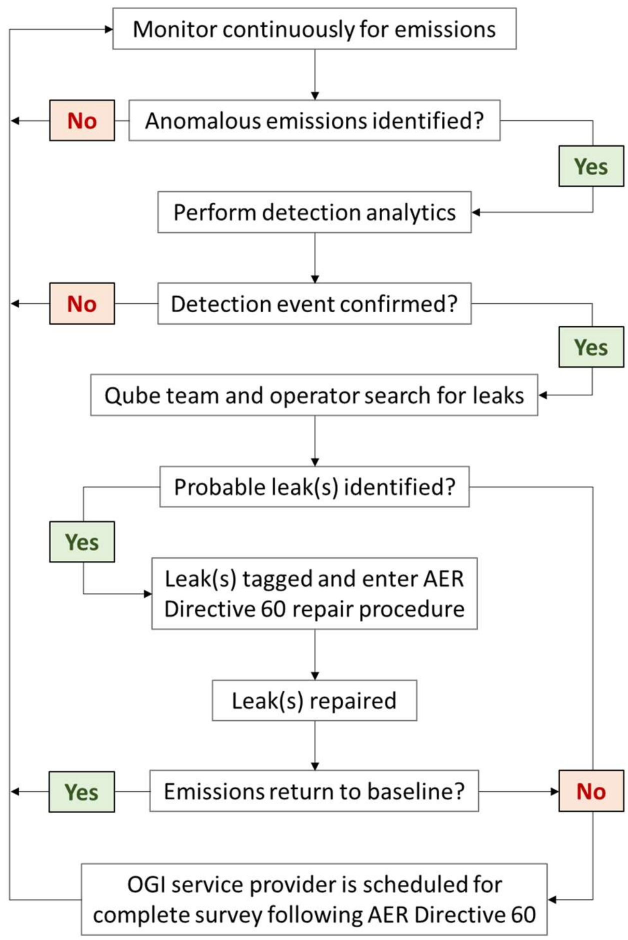

Figure 1. Proposed work practice decision tree.

2.2. Deployment schedule

In October 2021 Qube started the continuous monitoring of sites included in the pilot. In this report, data collected until December 2022 was used to inform program performance. The program proved successful, prompting a proposal for an extension of the pilot program.

2.3. Data Background

2.3.1. Provided Data

This section will summarize the “raw” data recorded during Alt-FEMP pilot program and provided to Highwood for further cleaning and analysis.

Two sources of data informed this report:

- Alt-FEMP Reporting Tool: The method of tracking data at the onset of the Alt-FEMP pilot program until May 2022 was an Excel sheet, manually updated by Qube, used to track detection events and follow-up data.
- The Qube Continuous Monitoring Dashboard: Put into use in May 2022, the Qube continuous monitoring dashboard autonomously kept track of many program elements. Exports from this dashboard were used to inform site level rates and associated timestamps for the quantitative data analysis component of this report (Section 3). Note that while the dashboard was established in May 2022, Qube was still responsible for providing detection event packages to Enhance (the dashboard did however greatly assist in evaluating and classifying these detection reports).

2.3.2. Tools used for Data Analytics

All data cleaning and analysis was conducted with Excel. It should also be noted that analyzing the provided data was a highly collaborative process between Highwood, Qube and Enhance, with ample communication throughout the project.

2.3.3. Additional Files Attached to this Report

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

- Quantitative data analysis summary - An Excel file containing all quantitative analysis performance criteria required by the AER performance report guidelines. File name: *Quantitative data analysis summary*
- Alt-FEMP Enhance Data - Highwood transferred Enhance "raw" data to the official AER Alt-FEMP reporting template. It should be noted that due to the nature of Qube technology, some modifications were proposed to accommodate the type of data collected. File name: *AER_Screening and Follow-up Data_Enhance*

2.4. LDAR-Sim Modelling Background

One component of the emissions reduction summary requested by AER has mandated the incorporation of a duty holder-specific emissions profile into simulation modelling used to explore emission reduction equivalency. To meet these requirements Highwood used the Leak Detection and Repair Simulator (LDAR-Sim) as a modelling tool, which will be briefly described in the following sections with the goal of aiding in model output/results interpretation.

2.4.1. 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 consists of unique methods, are then applied to the virtual world to predict emissions reductions and compare performance amongst the programs. LDAR-Sim uses a geospatial approach to simulating LDAR, accounting for actual facility locations and local environmental conditions anywhere in the world. In this case, historical Alberta weather with Enhance's infrastructure locations were used. All relevant LDAR-Sim information can be found on the LDAR-Sim GitHub page[8].

LDAR-Sim contains more than 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 is outside this scope of this report. This section will describe the most relevant parameters to the Enhance Alt-FEMP simulations, a full breakdown of all model parameterization can be found in Appendix A.

Figure 2 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 functionalities have been added to LDAR-Sim since its creation. Figure 2 is based on a previous version of LDAR-Sim and does not include travel time considerations used in the modelling detailed in this report.

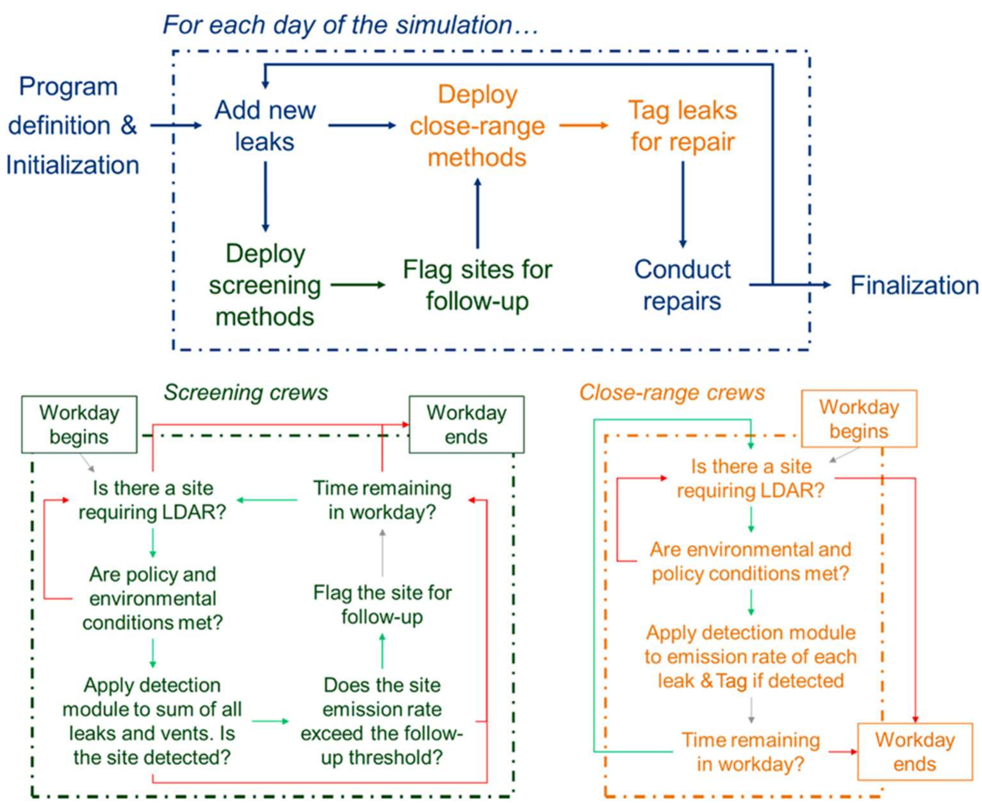

Figure 2. A detailed overview of the processes which occur in LDAR-Sim simulations each day of the simulated time, modified from Fox et al. 2020. In the Alt-FEMP described by this report, screening methods (green text and arrows) will be represented by Qube, while close-range methods (orange text and arrows) are OGI crews. Red arrows represent "no", green arrows are "yes", and grey arrows are mandatory.

[8] https://github.com/LDAR-Sim/LDAR_Sim

2.4.2. LDAR-Sim Parameterization Hierarchy

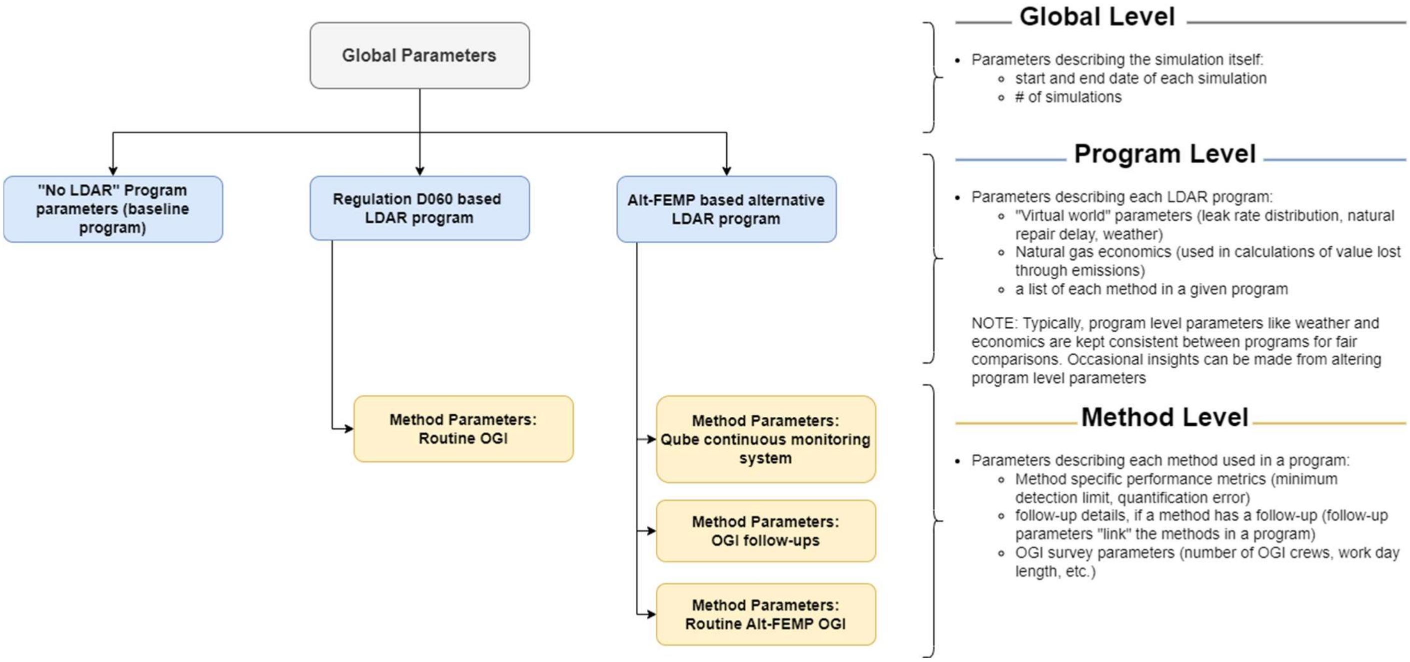

Figure 3: LDAR-Sim parameterization hierarchy

As shown in the hierarchy of Figure 3, in this simulation investigation, the regulatory program employs one routine OGI method, while the Alt-FEMP alternative employs three different methods: Qube continuous monitoring, routine/supplemental Alt-FEMP OGI and OGI follow-up.

The following sections provide more detailed descriptions of key parameterizations, organized by parameter hierarchy level (Figure 3). A detailed description of all parameters is available on the LDAR-Sim GitHub page. Note that nomenclature of some parameters described in the following sections is simplified to enhance readability.

2.4.3. LDAR-Sim – Relevant Parameters

A full breakdown of the LDAR-Sim parameterization used to model the Enhance Alt-FEMP pilot program and regulatory OGI program is provided in Appendix A of this report. In the following list, a summarized version of important parameterizations to interpret simulation modeling 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 leak counts and known survey frequency available in the provided Enhance data (detailed in Section 2.3.1) to calculate the LPR. This parameter will be covered in more detail in section 2.4.4.1.

- **Leak Rate Distribution (LRD) / Leak Rates File:** This parameter dictates the simulated fugitive emission "sizes" as a rates. 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 2.4.4.2.
- **Minimum Detection Limit (MDL):** 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 0.66 kg/hr.[9]
  - The Qube MDL is parameterized with a PoD curve based on detection performance at 75m distance from emission source to the Qube device assuming conservatively favourable wind speed and angle found during testing at CRTF.[10] Under these assumptions, the Qube PoD is 95% at emission rates of 1.9 kg/hr. In addition, a cut-off was applied to the Qube PoD curve which ensures a minimum detection limit of 0.1kg/hr (rates lower than 0.1 kg/hr could be detected based on the modeled PoD curve, albeit rarely. However, as 0.10 kg/hr was the smallest rate used in controlled release testing it was used as a cut-off).
- **Spatial 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 will also not be able to detect it on ensuing survey visits. We assumed the following spatial coverage values for the modelling carried out for this report:
  - 0.75: Used for "Routine" OGI methods (the regulatory OGI method used in the programs representing current D060 regulations and the supplemental OGI method used in the Alt-FEMP program at sites requiring triannual surveys)
  - 1.00: Used for the Qube continuous monitoring method.
  - 1.00: Used for the OGI follow-up method of the Alt-FEMP program.
- **Reporting delay:** The time from when the screening method (Qube) flags an emission to when the operator is notified. The parameter is based on days, so, a value of 0 s used to represent < 1 day (it could represent some number of hours less than 24). A value of 0 is used for the Qube continuous monitoring method to reflect the current capabilities of the Qube system (instant reporting through the reporting tool and the Qube dashboard).
- **Repair delay:** The average time needed to conduct repairs. 14 days is used for all programs based on the quantitative data analysis investigation described in Section 3.2.2 of this report.

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[9] 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).
[10] Moorhouse, B., Palma, B. & Fox, T. Qube Technologies Continuous Monitoring Probability of Detection. https://highwoodemissions.com/wp-content/uploads/2022/09/2022-08-25_Qube-Probability-of-Detection-White-Paper.pdf (2022).

- **Infrastructure:** The infrastructure file defines each unique Enhance facility represented in simulation. Each row represents an individual facility and columns describe the facilities' latitude, longitude and required survey frequencies for different methods. For this report, the infrastructure file consisted of 16 sites. Under Directive 060, 14 of these sites require annual FEMP surveys and 2 require triannual FEMP surveys (these 2 sites which require triannual surveys were also surveyed with a routine, supplemental OGI method under the Enhance Alt-FEMP program).

2.4.4. Emissions Profile

Highwood used Qube provided emissions data to determine two key emissions parameters, Leak Production Rate (LPR) and Leak rate Distribution (LRD).

2.4.4.1. Leak Production Rate (LPR)

The leak production rate informs the probability that a leak will arise at a given site at a given day. As the previous Alt-FEMP provides data on leaks identified at the given sites, we were able to assign a unique leak production rate to Enhance's sites based on the reported 2021-2022 data. Calculating this leak production rate for the sites was done with the following formula:

$$LPR = \frac{\#\ of\ leaks\ identified}{(\#\ of\ days\ collecting\ data)\ x\ (\#\ of\ sites\ monitored)}$$

Applying this formula to the sites within scope of the Alt-FEMP (Table 1) provides the overall leak production rate used in the simulation of 0.001 $leaks.site^{-1}.day^{-1}$, which represents around 0.4 leaks per site per year.

2.4.4.2. Leak Rate Distribution / Leak File

A leak rate distribution is an empirically defined, heavy tailed lognormal distribution of known leak emission rates which is randomly sampled from to assign a leak size to simulated leaks. In practice, LDAR-Sim defines a leak rate distribution from an input "shape" and "scale" parameter; for a log-normal distribution, this "shape" and "scale" are represented by the distribution's mean and standard deviation. Figure 4 is a graphical representation of the cumulative density function of known distributions.

Depending on available data, instead of a leak rate distribution, a leak file of known emission rates can be randomly sampled from to inform leak rates in simulation.

As discussed in Section 3: Quantitative Summary - Screening and Survey Details, only 7 leaks were tagged across the span of the Alt-FEMP pilot, and of these, only 4 have a known, associated site level emission rate. 4 known rates are too few to fit a distribution, and it is also too few to randomly sample from to inform emission rates in simulation. To remedy this lack of available data, the mean site level emission rate of 3.3 kg/hr was compared against the means of known, peer reviewed leak rate distributions. The lognormal leak rate distribution of production facilities used in Zavala-Araiza, 2015[11] has an average emission rate of 1.76 kg/hr, so this distribution was used in simulation as it allows conservative modelling (the smaller the

[11] Zavala-Araiza, D., Lyon, D.R., Alvarez, R.A., et al., (2015). Reconciling divergent estimates of oil and gas methane emissions. PNAS, 112(51), 15597-15602. https://doi.org/10.1073/pnas.1522126112

emission rates in simulation, the “better” the OGI-based regulatory program can do when compared the Qube based Alt-FEMP program due to the lower MDL of the OGI method, see Section 2.4.3, Minimum Detection Limit). An additional sensitivity analysis was conducted with a smaller distribution (Ravikumar at al 2020) for comparison purposes.[12]

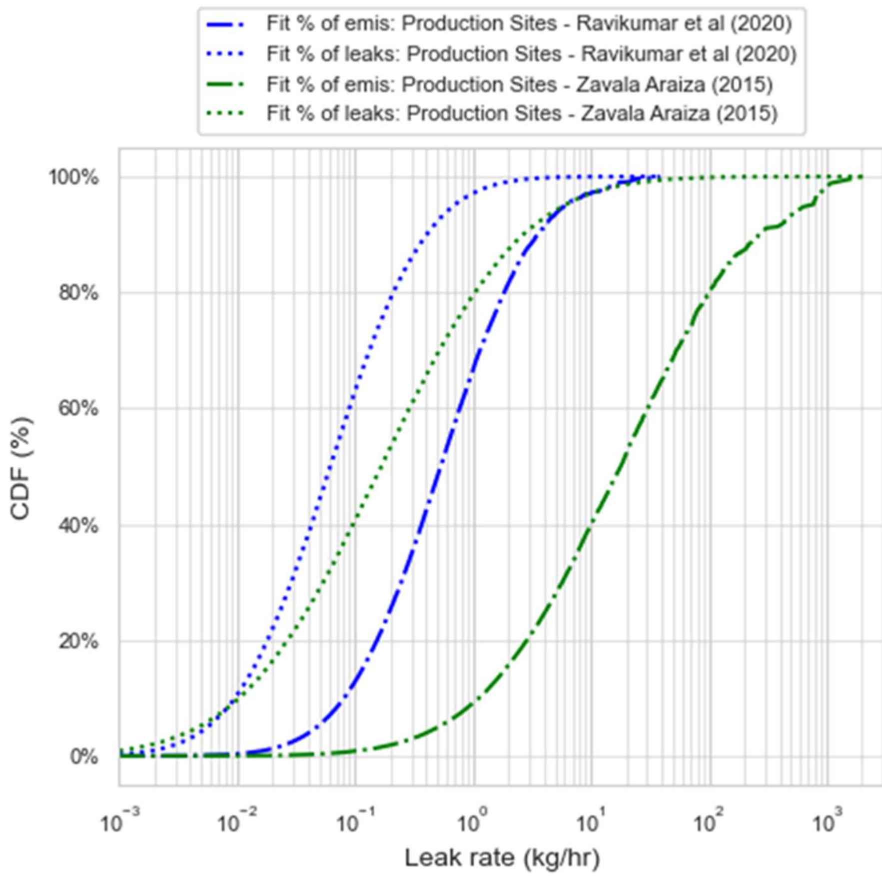

Figure 4: Visual representation of the leak rate distributions used in modeling. Solid lines (% of leaks) show the distribution of the leak sizes that were observed in the study. Dashed lines (% of emissions) show the relationship between individual leak size categories and the overall emissions that were observed in the study. The relationships between the dashed and solid curves illustrate how, across all studies shown, a smaller proportion of larger leaks is responsible for most emissions.

3. Quantitative Summary - Screening and Survey Details

The purpose of this section is to present the performance metrics specified in the AER website. The section begins with an overview of the screening and survey details, followed by an assessment of emissions

[12] Ravikumar, Arvind P., Daniel Roda-Stuart, Ryan Liu, Alexander Bradley, Joule Bergerson, Yuhao Nie, Siduo Zhang, Xiaotao Bi, and Adam R. Brandt. “Repeated Leak Detection and Repair Surveys Reduce Methane Emissions over Scale of Years.” Environmental Research Letters 15, no. 3 (February 2020): 034029. https://doi.org/10.1088/1748-9326/ab6ae1.

reduction. This assessment also compares the annual emission reductions with predictive modeling performed using LDAR-Sim.

3.1. Screening Details

3.1.1. Sites monitored

Table 1 provides a list of the Enhance facilities and sites monitored under the approved Alt-FEMP program, including the area, licence number, facility ID and subtype code.

Table 1. Sites monitored under the scope of the Qube Enhance Alt-FEMP

Location	Area	License Number	Facility ID	Subtype Code
04-15-40-24W4	Clive	F8154	ABBT2240034	322
01-10-37-20W4	Fenn Bigvalley	F5591	ABBT3710049	322
03-10-35-20W4	Fenn Bigvalley	F5591	ABBT3710049	322
04-35-36-20W4	Fenn Bigvalley	F5591	ABBT3710049	322
05-11-35-20W4	Fenn Bigvalley	F5591	ABBT3710049	322
05-14-36-20W4	Fenn Bigvalley	F5591	ABBT3710049	322
16-23-35-20W4	Fenn Bigvalley	F5591	ABBT3710049	322
16-27-36-20W4	Fenn Bigvalley	F5591	ABBT3710049	322
05-02-49-27W4	Glen Park	F11168	ABBT4180001	322
10-15-38-24W4	Haynes	F6625	ABBT4550001	322
01-03-35-01W5	Innisfail	F5118	ABBT4940020	322
07-03-35-01W5	Innisfail	F5118	ABBT4940020	322
11-10-35-01W5	Innisfail	F5118	ABBT4940020	322
15-33-34-01W5	Innisfail	F5118	ABBT4940020	322

16-28-42-23W4	Woodriver	F9009	ABBT9880004	322
08-02-49-27W4	Glen Park	F30809	ABCS0030809	601

3.1.2. Sites emitting

Once the Qube monitoring system device(s) had been installed at a given Enhance site to be monitored, continuous monitoring of emissions began. During the onset of the program, all detections events and associated meta data were sent from the Qube IIoT device(s) to Qube staff who updated the “Alt-FEMP Reporting Tool” (more details in Section 2.3.1), the contents of which was submitted monthly to Enhance. Upon the receiving the data, it was Enhance’s responsibility to classify each detection event into either “Potential Fugitive Emissions Events” or “Vented or offsite event”. This classification was executed by a qualified operator, who relied on operational knowledge and the provided Qube data. If an event was classified as a “Potential Fugitive Emission Event” a follow-up survey was scheduled. It is noteworthy that the Qube system recognizes a unique detection event as the period in which sensors indicate emissions above the baseline (Figure 1). Therefore, a single source could trigger multiple detection events due to intermittent emissions, or changes in environmental conditions such as wind direction.

Table 2 describes the number of detection events triggered by the Qube system and the number of those detection events which were classified as a potential fugitive emission source by Enhance. 213 detection events were triggered by the Qube system, 36 of which were classified as potential fugitive emissions. Averaging these counts across the sites included gives us an average of 13 detection events and 2 potential fugitive emissions per site across the span of the available Alt-FEMP pilot program data.

Table 2. Detection events and detection events with potential fugitive emissions sources per site monitored. Metrics based on data collected from October 2021 to December 2022.

Site / LSD	Detection Events	Detection Events Classified as Potential Fugitive Emissions Sources
03-10-35-20W4	26	5
01-10-37-20W4	23	3
04-15-40-24W4	22	1
16-28-42-23W4	22	1
05-02-49-27W4	20	3
05-11-35-20W4	15	1
05-14-36-20W4	15	7
11-10-35-01W5	14	3
15-33-34-01W5	13	2

04-35-36-20W4	11	5
16-27-36-20W4	11	1
10-15-38-24W4	9	2
07-03-35-01W5	6	0
08-02-49-27W4	4	2
01-03-35-01W5	1	0
16-23-35-20W4	1	0
Total	**213**	**36**
Average per Site	**13**	**2**

3.1.3. Average time between detection and follow-up

For the duration of the Alt-FEMP pilot program, Qube manually tracked monitoring data in the "Alt-FEMP Reporting Tool" Excel sheet (Section 2.3.1). The "Alt-FEMP Reporting Tool" was an essential part of the program as the learnings it provided were all incorporated during the concurrent development of Qube's dashboard. Throughout the program, the "Alt-FEMP Reporting Tool" was manually updated by Qube, with detection events and associated metadata (wind speed, etc.) sent to Enhance monthly. After receiving the report, Enhance would classify the detection events as "Potential Fugitive Emissions Events" or "Vented or offsite event" and perform close range follow-ups with OGI cameras.

From the 36 detection events classified as potential fugitive emissions sources, 25 had the actual follow-up inspection date recorded and 11 had an estimated follow-up date recorded in the "Alt-FEMP Reporting Tool". **The following metrics focus on these 25 potential fugitive emission sources with records of actual follow-up inspection date**:

- **11** follow-up inspections occurred (of the 25 potential fugitive emission alerts, some stemmed from the same source, therefore 25 individual follow-up inspections were not required).
- The average time between the alert that led to the detection event and the close-range follow-up inspection was **27 days**.
- The minimum / shortest follow-up inspection time was **7 days**.
- The maximum / longest follow-up inspection time was **38 days**.

In May of 2022 Qube transitioned from the "Alt-FEMP Reporting Tool" to a proprietary interactive, live and autonomously updated dashboard with new functionalities tailored to individual operator needs. In December 2022, this dashboard was further updated with the "dashboard reporting tool" which allowed operators to be instantly notified of detection events (established based on their specific thresholds) with accompanying visualizations, considerably reducing the average time between detection and follow-up.

Qube anticipates a full transition away from the "Alt-FEMP Reporting Tool" into full reliance on the dashboard within 2023 and anticipates the dashboard will be used for all data processing for much of the upcoming Enhance Alt-FEMP extension.

3.1.4. Screening Summary

A summary of the performance metrics concerned with the screening elements of the Alt-FEMP program is presented in Table 3.

Table 3. Alt-FEMP screening summary. Metrics based on data collected from October 2021 to December 2022.

Number of Sites Monitored	Total Detection Events[1]	Detection Events classified as Potential Fugitive Emissions Sources[1]	Average Time Between Detection and Follow-up[2]
16	213	36	27 days

[1] The Qube system recognizes a unique detection event as the period in which sensors indicate emissions above the baseline. Therefore, a single source could trigger multiple detection events due to intermittent emissions or changes in environmental conditions such as wind direction.

[2] Only inspections with actual dates updated in the Alt-FEMP Reporting Tool were used to estimate this metric: time between detection and follow-up considers the reporting time (up to 30 days) and the additional days (2-8 days) for crews to go to site. In December of 2022 Qube updated its dashboard with the capability of sending detection event alerts and associated emissions visualizations in real time, considerably reducing the average time between detection and follow-up. The renewed Enhance Qube Alt-FEMP will see reporting handled with this method.

3.2. Survey Details

3.2.1. Follow-up Summary

During the Alt-FEMP pilot program, close-range follow-up inspections were performed to investigate Qube Detection Events classified as “Potential Fugitive Emissions Sources” by Enhance. These follow-up inspections are summarized in Table 4. Since multiple alerts/detection events can be generated stemming from the same source, the number of follow-up inspections performed was smaller than the number of Detection Events classified as Potential Fugitive Emissions Sources (all potential fugitive emission sources were investigated). Follow-ups were initially AVO survey informed by Qube data (Qube data provided localization estimates), if the AVO survey could not effectively localize and classify the potential fugitive emission, a subsequent OGI or organic vapour analyzer survey was performed.

The “Follow-up Inspections Performed” values reported in Table 4 were estimated based on the count of unique dates that a site was visited for follow-up. Based on the dates available, we see only 21 actual close-range follow-ups conducted. This discrepancy between the 36 potential fugitive emission sources and 21 close range follow-up surveys is due to multiple potential fugitive emission source alerts stemming from a single source (see Table 4, Site 03-10-35-20W4 where 1 follow-up inspection was performed for the 5 potential fugitive emission sources).

From the 21 follow-up inspections performed, 14 (67%) found vents and 7 (33%) found one source of fugitive emissions. There was no case where a follow-up inspection was completed, and no source was identified (vent or leak). However, there were cases where operators went to site for a first assessment and did not find the source using AVO. For those cases a second visit with OGI was scheduled. The number of

OGI surveys performed was not tracked in the "Alt-FEMP Reporting tool" but can be provided upon request. Follow-up information shows that throughout the pilot, an average of 1 follow-up per site was required and less than 1 (1-2 leaks every 3 sites) source per site was tagged for repair throughout the program.

Table 4. Follow-up summary. Metrics based on data collected from October 2021 to December 2022.

Site	Detection Events classified as Potential Fugitive Emissions Sources[1]	Follow-up Inspections Performed[2]	Follow-up Inspections where a vent was found	Follow-up Inspections where a leak was found	Sources tagged for repair
03-10-35-20W4	5	1	0	1	1
01-10-37-20W4	3	1	1	0	0
04-15-40-24W4	1	1	0	1	1
16-28-42-23W4	1	1	1	0	0
05-02-49-27W4	3	1	1	0	0
05-11-35-20W4	1	1	1	0	0
05-14-36-20W4	7	6	4	2	2
11-10-35-01W5	3	2	1	1	1
15-33-34-01W5	2	1	1	0	0
04-35-36-20W4	5	2	2	0	0
16-27-36-20W4	1	1	1	0	0
10-15-38-24W4	2	2	0	2	2
07-03-35-01W5	0	0	0	0	0
08-02-49-27W4	2	1	1	0	0
01-03-35-01W5	0	0	0	0	0
16-23-35-20W4	0	0	0	0	0
Total	36	21	14	7	7
Average per Site	2	1	1	(0.4) Less than 1	(0.4) Less than 1

[1] Qube system recognizes a unique detection event as the period in which sensors indicate emissions above the baseline. Therefore, a single source could trigger multiple detection events due to intermittent emissions or changes in environmental conditions such as wind direction.

[2] Number of follow-up inspections were estimated based on the count of unique dates that a site was visited for a first assessment follow-up (usually an AVO, that could be followed by a second assessment with OGI, if required). It noteworthy to mention that from the 36 detection events with potential fugitive emissions sources, 25 had the actual dates of inspection included in the data and 11 were based on estimates. The 25 detection events that had dates lead to 11 follow-up inspections (some were from the same source) and the 11 detection events without dates lead to 10 follow-up inspections. Some of the 11 detection events without actual dates were form the same site and days apart, which means that the count of 10 follow-up inspections could be potentially smaller number when considering actual dates. **All potential emissions were followed up during the pilot.**

3.2.2. Leak Repair

For all leaks tagged (see glossary), the Enhance operator followed data recording and repair guidelines in accordance with the AER Directive 060. All seven repairs were successfully completed within the stipulated time frame without any delays. Qube monitored emissions to ensure they returned to baseline levels, and no additional OGI inspections were required after repairs. Although the average time between follow-up inspections and repairs was recorded by Enhance for reporting purposes, it was not included in the Alt-FEMP reporting tool. Ideally, Qube sees the workflow being able to be captured within Qube's dashboard, right from leak identification to follow up, repair data, and ultimately a resolution and return down to baseline, but this is still a work in progress. Despite this inconsistency in available data, it is a fair assumption that most repairs were conducted within 14 days.

Currently, operators can add notes in the dashboard about follow-up inspections, but the functionality to directly export this data for reporting purposes is under development. These requirements were identified during the pilot, and in future iterations of the dashboard, the operator will be able to enter follow-up inspection dates, the first attempt to repair, actual repair date, and the dates when emissions returned to baseline levels. Qube expects to complete the full implementation of these features by 2023.

3.2.3. Recurring Fugitive Emissions

In this pilot program, partially due to the small number of facilities in the scope, only seven leaks were identified, with none of them being recurring. The leaks were attributed to malfunctioning thief hatches, valves, connectors, and cleaning tanks turnaround. The program also allowed tracking of venting sources such as high bleed pneumatics, details on venting sources were logged for future, additional mitigation efforts such as replacing these pneumatic devices with low bleed devices.

While less of a concern for this Alt-FEMP program with its small scope of facilities, as general feedback, effectively tracking recurring fugitive emissions is difficult. A consistent definition of what constitutes a "recurring" leak needs to be communicated across all operators to guide data collection (very detailed data on each fugitive emission would be necessary) and would require considerable operator effort.

Nonetheless, recognizing the importance of this information for evaluating emissions trends and mitigation efforts, Qube is developing a feature for the dashboard that will provide measured fugitive emission volumes measured for each equipment group on site. This timeseries metric will allow a clear view of how much each equipment group at each site is contributing to total emissions over time and will help with identify recurring leaks in specific equipment groups.

3.3. Emissions Reduction Summary

Section 3.3 will present investigations into the calculated and modeled emissions and emissions mitigation of the Qube Enhance pilot program. Section 3.3.1 presents high-level look at emissions reductions from an assumed baseline emissions scenario (no formal mitigation efforts were used). Section 3.3.2 presents modelling with LDAR-Sim which heavily draws from available Enhance Alt-FEMP data and can be viewed as a “future looking” investigation into ongoing Qube Enhance 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 Based on Leaks Tagged

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 close-range OGI inspection) during the Alt-FEMP pilot in 2022 (only 2022 leaks are considered so we can assume a 12-month duration) and their rate were used for these calculations. Total emissions and emissions mitigation per year were calculated by the following formulas:

$$\text{Annual Emissions [kg CH}_4\text{]} = \sum_i (\text{Leak Rate [kg CH}_4\,.\,hr^{-1}] * \text{Leak Duration [hr]})_i \tag{1}$$

$$\text{Annual Mitigation [kg CH}_4\text{]} = Baseline\ \ Emissions\ [\text{kg CH}_4\,.\,year^{-1}] - AltFEMP\ Emissions\ [\text{kg CH}_4\,.\,year^{-1}] \tag{2}$$

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 Qube Enhance Alt-FEMP work practices (continuous monitoring and OGI follow-up).

To calculate emissions using Equation (1), we considered two parameters: leak rate and duration, both of which were estimated based on available data. Leak duration is often unknown and was based on assumptions. For the Qube Enhance Alt-FEMP, we assumed an average time between detection and follow-up of 27 days (section 3.1.3), plus an estimated time between survey and repair of 14 days, resulting in a leak duration of 41 days. For the baseline emissions scenario, we assumed two different leak duration scenarios, one more conservative (360 days) and one less conservative (180 days). Leak rates were estimated by averaging known site rates (provided by Qube) between the leak start date and the estimated end date (41 days after the start date). Note that comprehensive emission rate data was only available for 4 of the 7 leaks found under the Alt-FEMP program, to minimize assumptions only these emission rates are used (this gap in data for 3 of the 7 leaks was due to Qube transitioning away from the Excel “Alt-FEMP Reporting Tool” to the proprietary dashboard, while a temporary loss in data, the gap is worthwhile for the innovation the dashboard will provide). Furthermore, the emission rates reported by Qube are site rates and thus account for both fugitive and routine emissions, potentially causing an overestimation of annual fugitive emissions as we are assuming no routine emissions are present for the 4 leaks considered. Finally, we assumed that leak rates were sustained throughout the entire 41-day period (intermittency is not considered).

Equation (2) was used to estimate annual emissions mitigation by calculating the difference between baseline emissions and Qube Enhance Alt-FEMP emissions. Results from this analysis are described in Table 5, which lists annual emissions per leak, while Table 6 provides the emissions mitigation. Our approach was purely calculation-based and did not rely on simulation modeling.

Table 5. Annual emissions assessment considering leaks tagged in 2022.

Leak	Site	Estimated Site Rate (kg/hr)	Annual Emissions (tonnes of CH_4)		
			Baseline Leaks (emitting for 360 days)	Baseline Leaks (emitting for 180 days)	Alt-FEMP Leaks (emitting for 41 days)
004	05-14-36-20W4	1.10	9.53	4.76	1.09
005	10-15-38-24W4	3.44	29.73	14.87	3.39
006	11-10-35-01W5	2.20	19.03	9.52	2.17
007	04-15-40-24W4	6.46	55.80	27.90	6.35
Total			**114.09**	**57.05**	**12.99**

Table 6. Alt-FEMP annual mitigation assessment considering leaks tagged in 2022.

Scenario	Leak Duration	Baseline Emissions (tonnes of CH_4 per year)	Alt-FEMP Mitigation (tonnes of CH_4 per year)	Alt-FEMP Mitigation (%)
Baseline 1	360	114.09	101.10	88.6%
Baseline 2	180	57.05	44.05	77.2%

3.3.2. Annual Emissions Reductions Based on Modeling

3.3.2.1. Simulation Modeling Results

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 Qube Enhance Alt-FEMP against FEMP OGI inspections at the sites within scope of the Qube Enhance Alt-FEMP should the trends observed thus far in the pilot program continue. The simulation modelling replicated FEMP survey requirements (sites requiring annual and triannual surveys received the correct amount in simulation). Refer to Section 2.3.2 for further discussion of LDAR-Sim parameterization and assumptions.

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 baseline “program”, in which no LDAR is performed (Referred to as “P_none” in LDAR-Sim result visualizations)

- **P_Regulatory_OGI**: A regulatory OGI-based program in which all facilities receive the same number of simulated OGI surveys they are required to undergo as per Section 8 of AER Directive 060
- **P_Enhance_AltFEMP:** An Alternative LDAR program that replicates the work practice described in this report which sees continuous monitoring of all sites with Qube devices, follow-up OGI inspections, and supplemental OGI inspections at sites which require triannual FEMP OGI inspections.

Figure 5 is a series of donut plots showing the total emissions and mitigation across all the 16 modeled sites (7 monitored facilities). The baseline scenario (P_none), where no leak detection and repair are conducted, provides insight into the expected emissions under modeling assumptions (LPR based on Alt-FEMP data, leak rates informed by Zavala Araiza, 2015[13]) in the absence of any LDAR program. The D060 regulatory OGI (P_Regulatory_OGI) and Qube-based Enhance Alt-FEMP (P_Enhance_AltFEMP) programs illustrate the methane emitted and mitigated under those LDAR programs (which is computed as the difference between methane emissions from P_none and a given LDAR program). Predictive modeling shows that the Enhance Alt-FEMP program mitigated 3 times more emissions than regulatory OGI-based program achieved, by emitting and mitigating 4 and 62 tonnes of methane per year respectively.

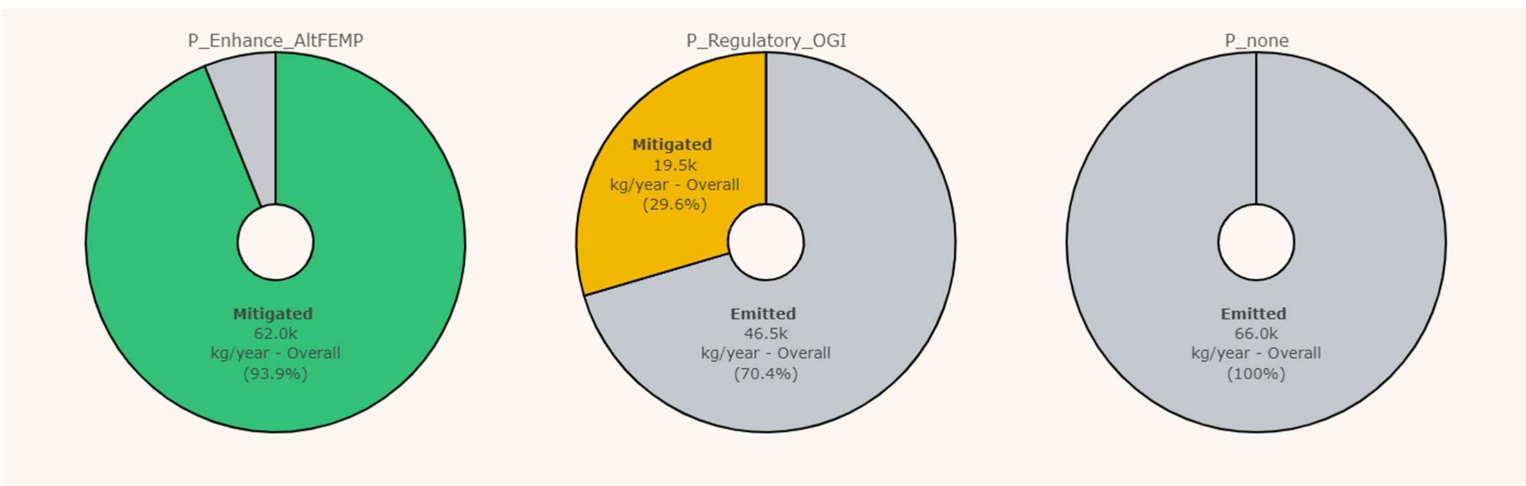

Figure 5. Methane emitted and mitigated per year for the different program simulated considering the 16 sites in scope (averaged across rounds of simulation). Comparison of programs based on the Enhance Qube-based Alt-FEMP (P_Enhance_AltFEMP), FEMP routine OGI inspections defined by Directive 060 (P_Regulatory_OGI) and annual emissions in the absence of an LDAR program (P_none).

Figure 6 is a series of box plots showing daily emissions in simulation for each modeled program for the 16 modeled sites (7 monitored facilities). The box plot “thickness”, or the interquartile range is a means of understanding daily emissions variance outside the realm of outliers, or very large emitters. The smaller

[13] Zavala-Araiza, D., Lyon, D.R., Alvarez, R.A., et al., (2015). Reconciling divergent estimates of oil and gas methane emissions. PNAS, 112(51), 15597-15602. https://doi.org/10.1073/pnas.1522126112

interquartile range of the Qube based program (P_Qube) indicates that overall daily emissions have less variance, likely due to continuous monitoring nature of the Qube system.

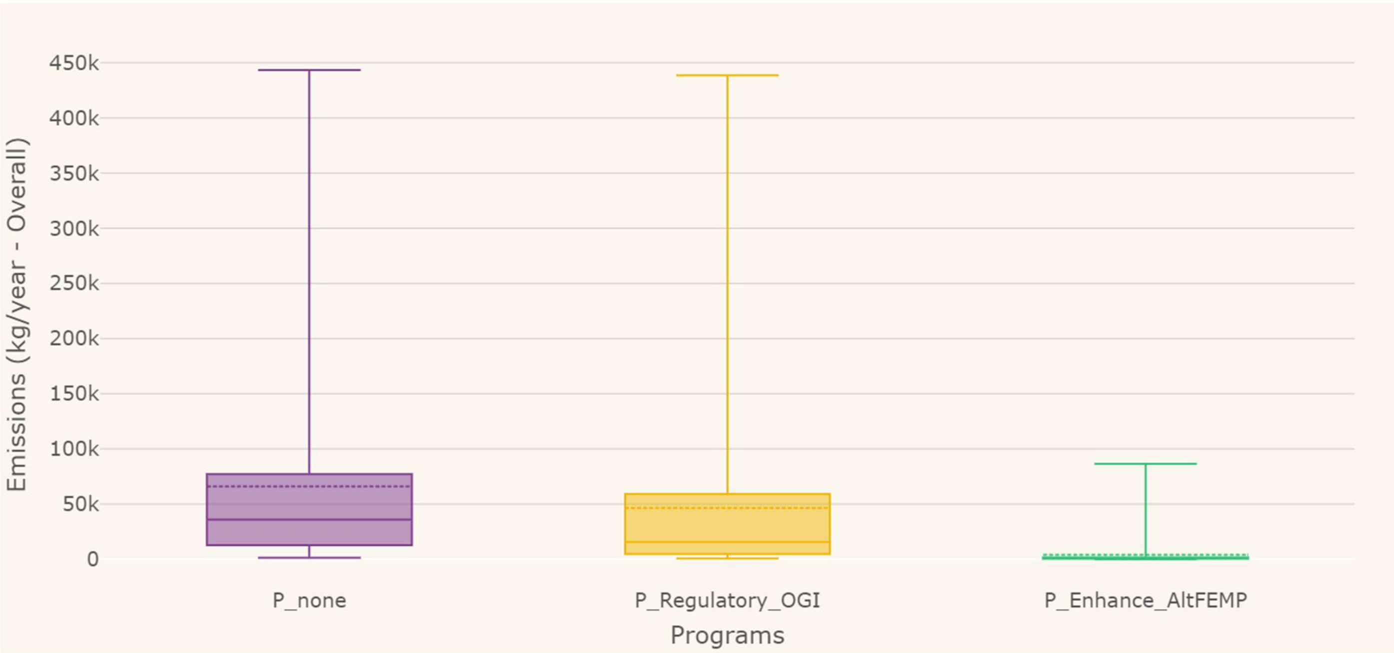

Figure 6. Box plots of daily emissions for the different program simulated considering the 16 sites in scope. Comparison of programs based on the Enhance Qube-based Alt-FEMP (P_Enhance_AltFEMP), FEMP routine OGI inspections defined by Directive 060 (P_Regulatory_OGI) and annual emissions in the absence 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 timeseries of daily emissions (averaged across the different rounds of simulation) across all sites within the Alt-FEMP scope for each modeled program. The emissions timeseries will “build up” as emissions are introduced to the virtual world and left to emit prior to mitigation. This is most readily apparent in the “P_Regulatory_OGI” timeseries where a faint annual cyclicity can be seen caused by most sites in the simulation (and real world) requiring annual OGI surveys. This represents emissions building up for a year, the annual OGI survey taking place (recall, most facilities in simulation require annual OGI surveys) which then leads to the emissions being localized and mitigated. Conversely, there is no real observable cyclicity under the “P_Enhance_AltFEMP” program as the Qube method will continuously monitor for emissions. A good example of the benefits of continuous monitoring can be seen around day 790. We see a large “spike” in emissions in both the “P_Regulatory_OGI” and “P_Enhance_AltEMP” timeseries, however, the “P_Enhance_AltFEMP” timeseries rapidly drops again, implying this emission was immediately identified by the Qube continuous monitoring system, while it goes on to emit for almost a whole annual survey period in the "P_Regulatory_OGI program".

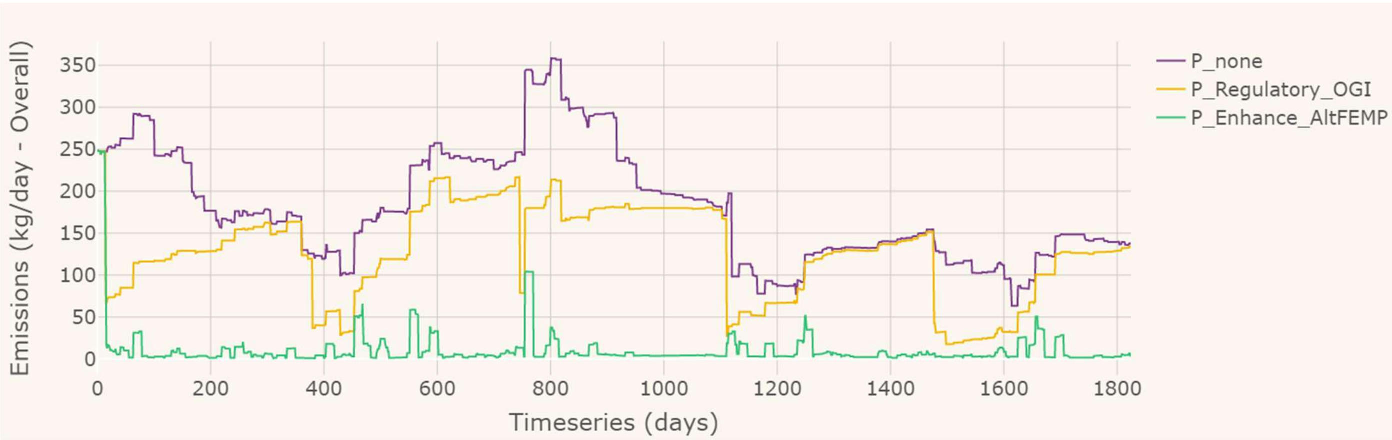

Figure 7. Timeseries of average emissions per day considering the 16 sites in scope. Comparison of programs based on the Enhance Qube-based Alt-FEMP (P_Enhance_AltFEMP), FEMP routine OGI inspections defined by Directive 060 (P_Regulatory_OGI) and annual emissions in the absence of an LDAR program (P_none). The cyclicity of the P_Regulatory_OGI time series is indicative of the dominant annual survey requirements of the modeled programs with the Alt-FEMP (P_Enhance_AltFEMP) showing a lack of cyclicity due to the continuous monitoring nature of the program.

3.3.2.2. Sensitivity Analysis

Simulated leak rates will have a marked impact on modeled program mitigation performance. As discussed in 2.4.4.2, the Zavala-Araiza, 2015[14] leak rate distribution was chosen for primary simulation results due the proximity of that study's average leak rate with the average leak rate of the available Alt-FEMP pilot data. However, with such little Alt-FEMP pilot leak data available, a sensitivity analysis exploring a smaller leak rate distribution was undertaken. This sensitivity analysis presents LDAR-Sim results in leak rates are generated from the Ravikumar, 2020[15] leak rate distribution (Figure 4). By comparison, the average leak size of the Ravikumar, 2020 distribution is 0.18 kg CH4 /hr whereas the Enhance Alt-FEMP pilot average leak rate was 3.3 kg CH_4 /hr and the Zavala-Araiza, 2015 average leak rate is 1.75 kg CH_4 /hr. All other parameters outside of leak rate distribution were kept consistent. The results of the LDAR-Sim modelling done assuming a leak rate distribution informed by Ravikumar, 2020 are shown in Figure 8, Figure 9, and Figure 10.

[14] Zavala-Araiza, D., Lyon, D.R., Alvarez, R.A., et al., (2015). Reconciling divergent estimates of oil and gas methane emissions. PNAS, 112(51), 15597-15602. https://doi.org/10.1073/pnas.1522126112
[15] Ravikumar, A.P., Roda-Stuart, D., Liu, R., et al., (2020). Repeated leak detection and repair surveys reduce methane emissions over scale of years. Environ. Res. Lett. 15, 034029. https://doi.org/10.1088/1748-9326/ab6ae1

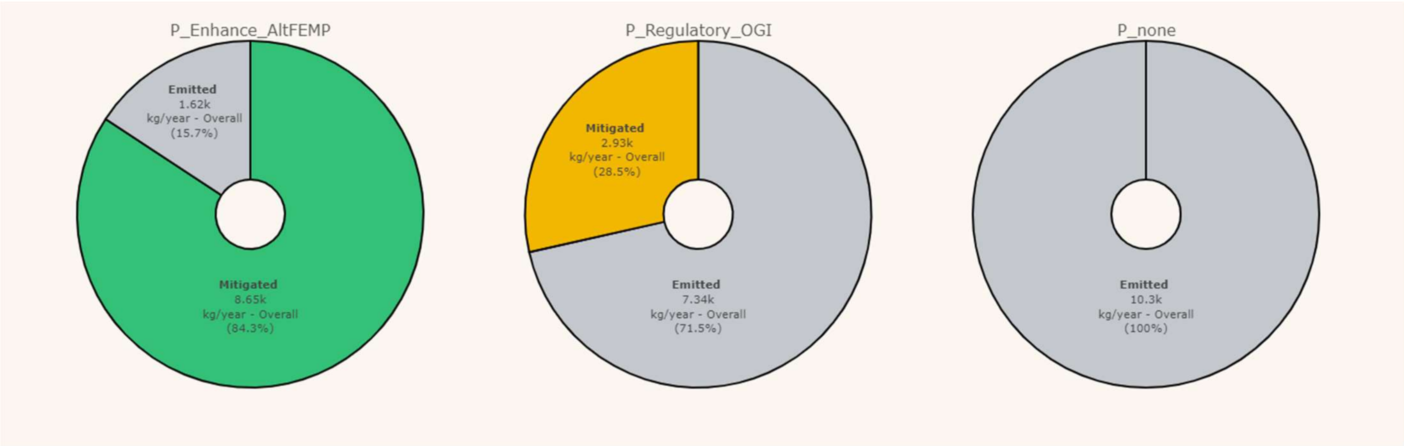

Figure 8. Emissions distribution sensitivity analysis - Methane emitted and mitigated per year for the different program simulated considering the 16 sites in scope (averaged across rounds of simulation) and a leak rate distribution based on data from Ravikumar et al. 2020. Comparison of programs based on the Enhance Qube-based Alt-FEMP (P_Enhance_AltFEMP), FEMP routine OGI inspections defined by Directive 060 (P_Regulatory_OGI) and annual emissions in the absence of an LDAR program (P_none).

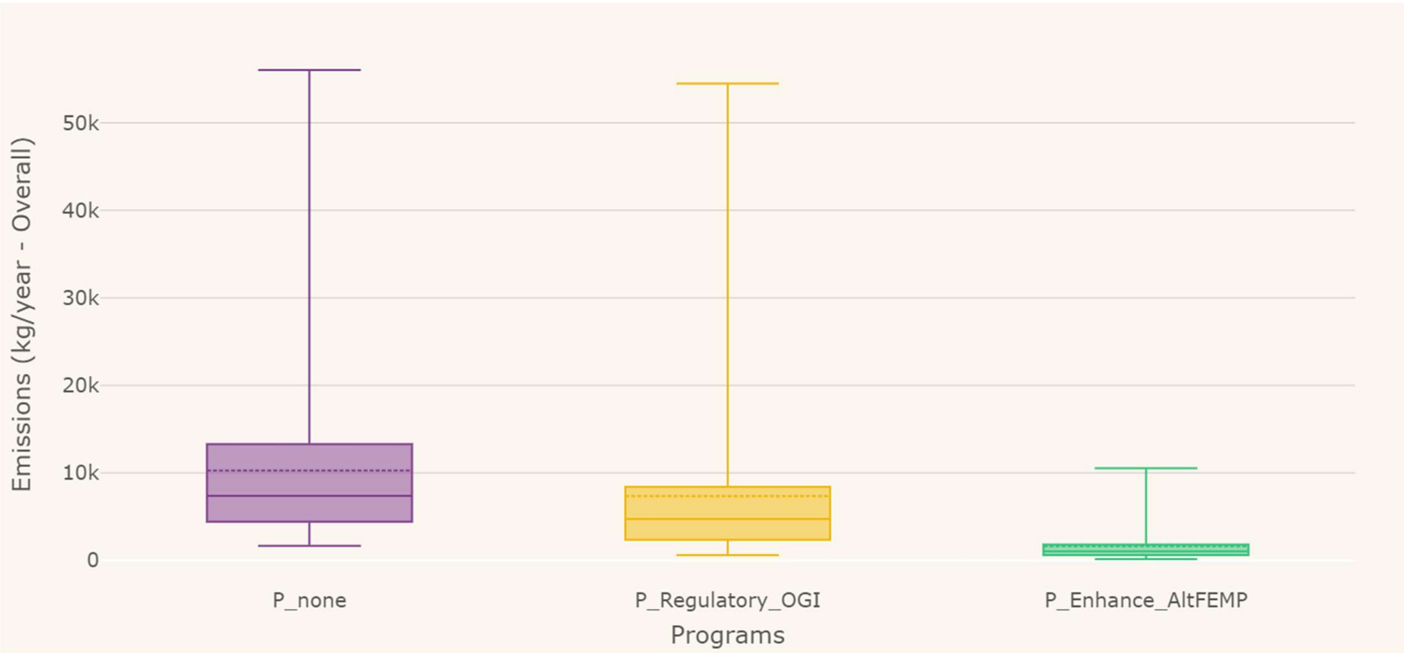

Figure 9. Emissions distribution sensitivity analysis - Box plots of daily emissions for the different program simulated considering the 16 sites in scope and leak rate distribution based on data from Ravikumar et al. 2020. Comparison of programs based on the Enhance Qube-based Alt-FEMP (P_Enhance_AltFEMP), 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.

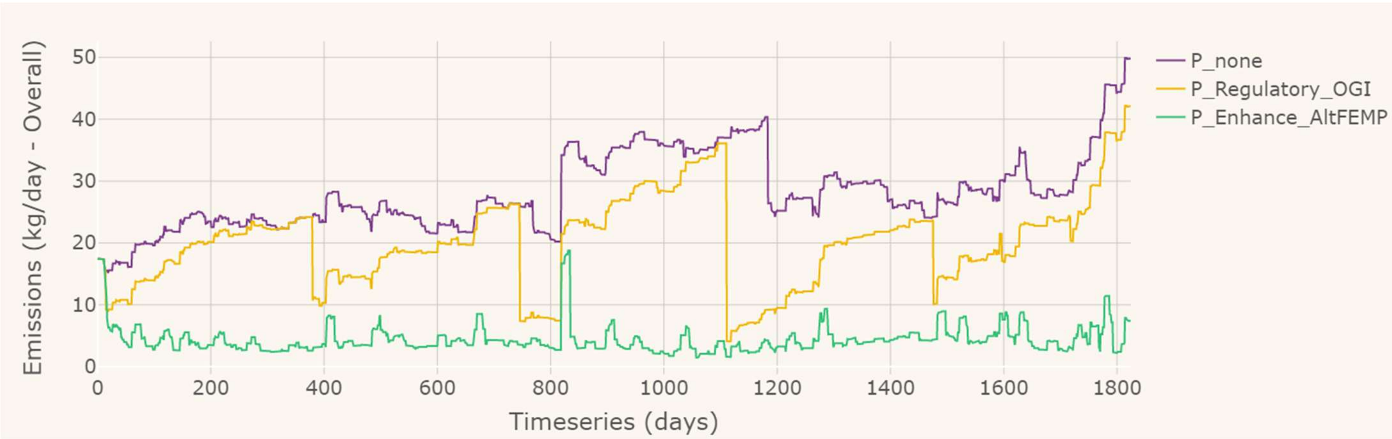

Figure 10. Emissions distribution sensitivity analysis - Timeseries of average emissions per day for the different program simulated considering the 16 sites in scope and leak rate distribution based on data from Ravikumar et al. 2020. Comparison of programs based on the Enhance Qube-based Alt-FEMP (P_Enhance_AltFEMP), 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 P_Regulatory_OGI time series is indicative of the dominant annual survey requirements of the modeled programs with the Alt-FEMP (P_Enhance_AltFEMP) showing a lack of cyclicity due to the continuous monitoring nature of the program.

When comparing simulation results assuming Ravikumar, 2020, we see overall emissions and mitigation are markedly lower than the emissions and mitigation when Zavala-Araiza, 2015 is assumed. This is due to, on average, leaks introduced to the system being much smaller. However, we see that the Qube-based Enhance Alt-FEMP program still meets and exceeds reduction equivalency with the OGI-based D060 program.

3.3.3. Analysis of Discrepancies Between Modelled Emission and Alt-FEMP Submission Results

During the application stage, LDAR-Sim simulation modeling showed that the expected annual emissions for the 16 sites under Alt-FEMP would be approximately 4.2 tonnes of methane per year. This was 4.6 times lower than the estimated 19.4 tonnes if the sites remained under base FEMP (routine OGI surveys).

Updated modeling results (section 3.3.2) based on emissions profiles informed by pilot data and updated technology performance metrics predicted average annual emissions for the 16 sites under Alt-FEMP to be 4.0 tonnes per year of methane compared to 46.5 tonnes estimated if the sites remained under the base FEMP program (Alt-FEMP was 11.6 times lower). Discrepancies observed are due to updates in leak profiles and detection capabilities of both Qube and OGI. LDAR-Sim has evolved since this initial modelling application and now additional parameters have been incorporated to better understand the limitations of detection methods such as OGI such as a more accurate MDL, and spatial coverage, further discussed in Section 2.3.2.

The results demonstrate that the updates did not have a significant impact on the annual emissions under the Alt-FEMP program, indicating that the previous modeling was reasonable in predicting annual emissions for sites monitored by Qube. However, the updates in leak rates and detection performance had a significant impact on how the regulatory program performed, resulting in a wider gap between Alt-FEMP and the regulatory program. This highlights the advantages of the Alt-FEMP program over the regulatory program.

4. Qualitative Summary

4.1. Technology limitations

Device functionality has been high for the duration of the Alt-FEMP with no major hardware limitations to speak of, the Qube devices proving robust against the environmental challenges of an Alberta based deployment.

Qube has developed a number of device health and site health dashboards that have allowed them to be more proactive on determining any hardware or communication issues from the devices and ultimately minimize downtime. Qube can quarantine devices that have faulty data, whereby the models still run with the remaining devices on site until we are able to resolve the issues with the quarantined device on site.

A discussion of the limitations of the associated software, and the steps made through the pilot program to remedy these limitations, is found in Section 4.3.

4.2. Successes of the Alt-FEMP

Overall, the program ran well, with Enhance being able to quickly identify emission leaks, provide follow ups, where required, and resolve leaks in a timely manner, ultimately enabling Enhance to improve their emissions reductions.

Some more specific examples of program success follow:

1. From the onset of the Alt-FEMP program, the Qube continuous monitoring devices acted as an effective “safety net” against large emissions. Although detection event updates were provided every 30 days, this cadence is still much faster than the typical annual to triannual survey frequency Enhance sites would typically be required to follow, allowing Enhance to find and mitigate emissions much quicker.
2. The program gave Qube an opportunity to enhance their solution through the development of the Qube proprietary dashboard. The incoming data allowed Qube to form a better understanding of how to handle incoming emissions data and how to provide it to an operator client in an efficient and actionable manner.
3. Enhance has been an avid user of Qube’s recent dashboard features to allow for annotations of emission events and is using the alarm feature regularly (daily, in some cases), to understand their facilities and dive into any emission event that Qube identifies.
4. The development of some features within Qube’s platform has been helpful in site-level understanding. The switch to the Qube dashboard in May 2022 was beneficial for Enhance to be able to visualize where site leaks were occurring. Qube’s ability to group emissions events right within the platform helps to categorize “events” that require follow up in real-time and helps Enhance understand where the priorities are at their sites. The autonomous reporting functionality is being built out to satisfy operator and regulator needs (some of this is still in development), and Qube is in the process of building out the full workflow to be tracked within the Qube system based on feedback from Enhance. Ideally, the workflow will be able to be captured within Qube’s dashboard, right from leak identification to follow up, repair data, and ultimately a resolution and return down to baseline.

Currently the repair and OGI camera work is handled outside of Qube's platform, but Qube is looking for ways to incorporate this into their dashboard.

5. Enhance has noted that their follow up OGI surveys when leaks are occurring have been much more efficient based on Qube's ability to localize to an equipment grouping. Enhance has noted this as a large win for the program, where they have the OGI crew start in a specific area to find a leak instead of blindly doing a survey of the full facility.

4.3. Nonperforming program elements

While not explicitly "nonperforming", software elements, specifically those involving the sharing of detection even data between Qube and Enhance underwent drastic overhauls through the pilot program to provide Enhance with a more actionable tool. These developments were based on feedback from Enhance throughout the duration of the program.

At the onset of the program, data tracking was handled manually by Qube through an Excel database ("The Alt-FEMP Reporting Tool"). Updated versions of this reporting tool were provided to Enhance every 30 days. While these 30-day updates were still a much higher cadence than Enhance's previous survey frequency of annual or triannual surveys depending on the site, there were still limitations to the reporting method:

1. The 30-day delay is not necessary as this data flow can be automated. Qube developed this functionality over the course of the Alt-FEMP, rolling out its implementation in December 2022.
2. The "Alt-FEMP Reporting tool" doesn't allow the storage of operator data including key insights into the classification of detection events ("potential fugitive" or "vented / offsite event").
3. The "Alt-FEMP Reporting tool" lacked a visual component. The roll-out of the Qube dashboard in May 2022 provided this visual component, providing Enhance with a much better localization starting point.
4. The manual nature of the "Alt-FEMP Reporting tool" could lead to human error and gaps in data.

While the Qube dashboard and autonomous reporting functionality provide a much more informative tool for Enhance, a key remaining gap is that the various data streams (Qube data, Enhance classification and comment data, repair data, OGI survey data, etc.) of the LDAR program all remain disparate. This leads to increased reporting demands for the operator to aggregate all data streams into a cohesive package. Qube is aware of this and is actively enhancing the dashboard so that it pulls in and visualize these disparate data streams, providing Enhance with a single location from which to monitor all aspects of their LDAR program.

4.4. Additional control measures

Throughout the Alt-FEMP pilot program, Qube monitored allowable vented emissions to identify future opportunities for further abatement (i.e., retrofits) especially if these vented emissions exceed desired levels. Qube and Enhance have collaboratively analyzed this vented emissions data.

4.5. Key performance indicators

All performance indicators from the application have been discussed throughout this performance report.

5. Conclusion

This report contests that the Enhance Energy and Qube Technologies Single-Operator Alt-FEMP Pilot should be evaluated as a success as it was able to achieve the following goals set in the Alt-FEMP application to evaluate of Alt-FEMP program performance over time.

Verification of the Qube continuous monitoring work practice

The work practice followed during the pilot program achieved an average of 27 days between flagging of emissions by the Qube system and close-range follow-up inspection. These 27 days will decrease as the reporting functionality of the Qube dashboard platform is rolled out over the course of 2023. Furthermore, using the dashboard platform implemented in May 2022, the follow-up work practice was streamlined. Often, the operator was able to localize and classify emissions with only an AVO inspection due to the guidance of the Qube dashboard platform visualizations. Being able to perform targeted AVO inspections saves time and cost associated with OGI surveys.

Achieve a better understanding of Enhance emissions profiles and reduce emissions

Continuous monitoring throughout the pilot allowed Enhance to be better informed on their emissions profile and typical site rates. In the long run, collecting fugitive emissions patterns will help to inform decision making about equipment health, need for refurbishment and lifespan. Additionally localizing venting sources emitting above expected rates (such as high bleeding pneumatic devices) also highlighted opportunities to further reduce emissions.

Annual emissions assessment estimated that 13 tonnes of methane were emitted per year by the sites within scope of the Alt-FEMP and that up to 89% of emissions were mitigated due to Alt-FEMP deployment (depending on emissions estimated when no LDAR program was implemented). This assessment was performed based on assumptions around leak durations and using average site rates during periods where leaks were active. This last assumption means that leak rates could be overestimated because it includes venting contribution. Ultimately, Enhance being able to quickly identify emission leaks, provide follow ups, where required, and resolve leaks in a timely manner, enabled Enhance to improve their emissions reductions, which was a significant win for the project

Feedback acquisition on operator experience to automate reporting and follow-up recommendations

Improvement of the Qube platform was a central theme of the Alt-FEMP pilot program. Throughout the duration of the program, Qube data tracking and reporting transitioned from an Excel based system populated manually to a dashboard platform complete with 3D visualizations updated autonomously. Next steps will see live reporting based on operator specific feedback through the dashboard and ultimately, the dashboard will be used as a single point of reference for all LDAR elements (continuous monitoring, OGI surveys, leak repair, etc.). Enhance provided key feedback to help facilitate the development of these Qube platform enhancements throughout the duration of the Alt-FEMP. This Alt-FEMP pilot program is an excellent example of the benefits of an operator partner who is invested in the success of the program.

Data acquisition to inform technology improvements

The continuous monitoring data and Enhance comments and feedback collected were used to improve Qube machine learning algorithms for detection, localization, quantification, and classification. While these algorithms are always being improved upon, this pilot program provided excellent, real-world data.

Ultimately, the program allowed Enhance to minimize fugitive emissions through rapid response from the Qube continuous monitoring system and Qube was able to further develop their platform through invaluable feedback from a collaborative operator partner. These mutual benefits are emblematic of the goals of the Alt-FEMP program and signify a successful pilot.

Appendix A: LDAR-Sim Parametrization

Table 7. Global Parameters

Global Level Parameter Name	Parameter Description	Parameter Value Justification
# Simulations	Informs the number of simulations rounds.	10: Default number Additional simulations could be requested, but past experience has shown that minor improvements are observed by further increasing this number.
Start Date	The start date of the simulation	[2023, 01, 01] Start date based on simulating for a duration of 5 years
End Date	The end date of the simulation	[2027, 12, 31] End date based on simulating for a duration of 5 years

Table 8. Virtual world level parameters (Program level parameters that applies to all programs).

Virtual World Level Parameter Name	Parameter Description	Parameter Value Justification
NRd	Natural kill date of each leak in number of days. Represents leak removal from the leak pool due to routine maintenance, refits, retrofits, and other unintentional leak repairs	365 days: Default 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.
Leak Production Rate	LPR is the probability that a new leak will arise, each day, for each site. It is an empirical representation of all conditions that lead to the occurrence of leaks, including facility age, management practices, predictive maintenance, and random chance.	0.001 $leaks.site^{-1}.day^{-1}$ Calculated based on data collected during Alt-FEMP pilot. See details in section 2.4.4.1.

Virtual World Level Parameter Name	Parameter Description	Parameter Value Justification
Leak Rate Distribution	Empirical leak function (lognormal) from which leak emission rates are drawn. The first term is the distribution scale and the second the distribution shape.	[-1.79, 2.17] Known distribution from peer reviewed study (Zavala Araiza 2015). This choice of distribution is informed by calculations of average leak rate sizes for sites requiring annual OGI surveys under current regulations. See details in section 2.4.4.2.
# Sites	The total number of sites simulated	16 sites Based on Enhance infrastructure included in the Alt-FEMP scope.
Weather data basis	Historical weather data containing total precipitation, wind data, temperature and cloud coverage	Historical Alberta weather data from 2019-2020 from https://cds.climate.copernicus.eu/
Repair delay	Time between leak being tagged and repaired.	14 days Average time for leak repair

Table 9. Methods associated with a given program.

Program	Methods	Description
P_none	N/A	There are no methods associated with P_none as it a baseline comparison to the action of doing nothing and letting the natural repair time take effect.
P_Enhance_AltFEMP	M_Qube	Continuous monitoring method deployed at all sites in scope.
	M_OGI_FU	Follow-up method trigged every time
	M_OGI_AltFEMP	Follow-up work practice that the Qube technology triggers
P_Regulatory_OGI	M_OGI_Regulatory	OGI survey(s) performed at the required yearly frequency as stipulated by current regulations at all sites.

Table 10. Method level parameters

Parameter Name	Parameter Description	Method	Parameter Value Justification
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.	M_Qube	**False**
		M_OGI_FU	**True**
		M_OGI_AltFEMP	**False**
		M_OGI_Regulatory	**False**
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_Qube	0 Based on new capabilities of Qube to send real-time alerts.
		M_OGI_FU	0 Default
		M_OGI_AltFEMP	0 Default
		M_OGI_Regulatory	0 Default
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.	M_Qube	365 Under continuous monitoring sites are continuously surveyed.
		M_OGI_FU	N/A Follow-up methods survey on a as needed basis.
		M_OGI_AltFEMP	1 or 0 Annual *only* for sites that require triannual surveys under Base FEMP
		M_OGI_Regulatory	1 or 3 Follows requirements under D060
Scheduling	The potential months that a technology is allowed to survey or will be scheduled.	All methods	All months

Parameter Name	Parameter Description	Method	Parameter Value Justification
Consider daylight	Informs if methods 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/	M_Qube	**False** Qube does not require daylight to operate
		M_OGI_FU	**True** OGI inspections are only performed during daylight
		M_OGI_AltFEMP	**True** OGI inspections are only performed during daylight
		M_OGI_Regulatory	**True** OGI inspections are only performed during daylight
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_Qube	1 Qube can cover all potential sources in the site
		M_OGI_FU	1 Same coverage as M_Qube for being a target follow-up informed by M_Qube
		M_OGI_AltFEMP	**0.75** Used to estimate sources that would be missed by method (such as elevated sources)
		M_OGI_Regulatory	**0.75** Used to estimate sources that would be missed by method (such as elevated sources
Temporal coverage	A representation of the average proportion of leaks that a method will detect a leak in a single survey. For example, the value of 0.7 indicates that the method will find a leak 70% of the time. In practice, every time a method goes to survey a leak, a weighted coin is flipped, representing temporal coverage. If the method “loses” the weighted coin flip, it will not detect the emission, but will have a chance to detect it the next time it surveys	M_Qube	1 For being a continuous and automatic system
		M_OGI_FU	**0.75** Parameter to account for human errors. It also was used to represent events that could be missed due to intermittency
		M_OGI_AltFEMP	**0.75** Parameter to account for human errors. It also was used to represent events that could be missed due to intermittency

Parameter Name	Parameter Description	Method	Parameter Value Justification
		M_OGI_Regulatory	**0.75** Parameter to account for human errors. It also was used to represent events that could be missed due to intermittency
Consider venting	A value of False results in venting rates not being considerer in site level rates. (for detection purposes)	All methods	**False**
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_Qube	**Site** Qube can group leaks by equipment group, but it flag emissions based on site level rates
		M_OGI_FU	**Component** Method tag leaks based on component level rates
		M_OGI_AltFEMP	**Component** Method tag leaks based on component level rates
		M_OGI_Regulatory	**Component** Method tag leaks based on component level rates
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.	M_Qube	**95% PoD = 1.9 kg/hr** Parameterized with a probability of detection (PoD) curve informed by testing at CRTF[16]
		M_OGI_FU	**95% POD = 0.66 kg/hr** Parameterized with a probability of detection (PoD) curve informed by Zimmerle et al.[17]
		M_OGI_AltFEMP	**95% POD = 0.66 kg/hr** Parameterized with a probability of detection (PoD) curve informed by Zimmerle et al.[16]
		M_OGI_Regulatory	**95% POD = 0.66 kg/hr** Parameterized with a probability of detection (PoD) curve informed by Zimmerle et al.[16]

[16] Moorhouse, Brendan, Bruna Palma, and Thomas Fox. “Qube Technologies Continuous Monitoring Probability of Detection.” White Paper, August 2022. https://highwoodemissions.com/wp-content/uploads/2022/09/2022-08-25_Qube-Probability-of-Detection-White-Paper.pdf.
[17] 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).

Parameter Name	Parameter Description	Method	Parameter Value Justification
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.	All methods	[0.0, 0.5] Default window for deployment
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.	All methods	[-40.0, 40.0] Default window for deployment
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.	All methods	[0.0, 10.0] Default window for deployment