Technical Report

Alternative Methane Detection Technologies Evaluation

Modelling Update

Focus
Report detailing technology tier and work practice updates.

Date
February 2025

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Prepared for
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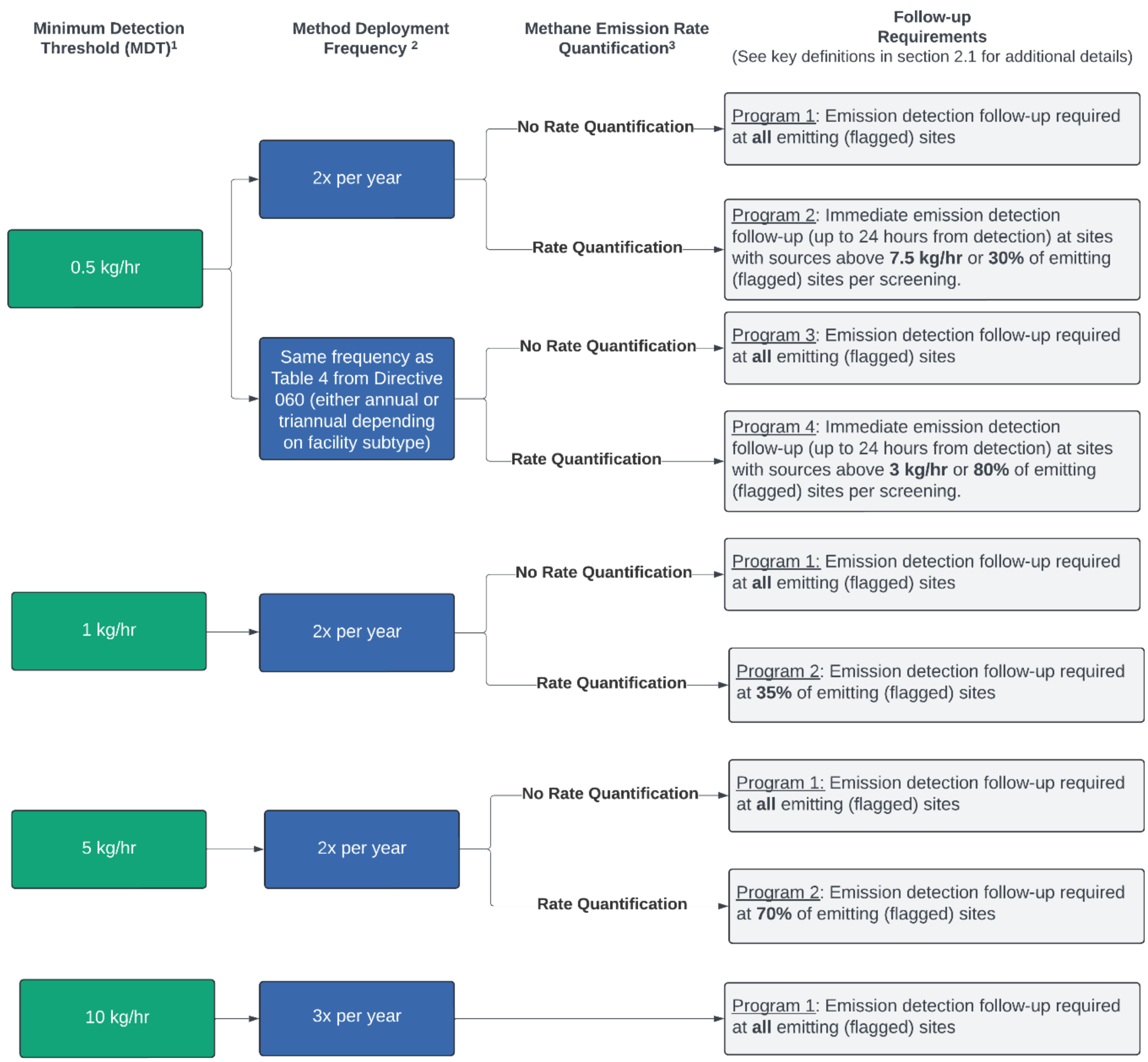
1. Background

The following sections provide an overview of modeling results when updating technology tiers and work practices. Namely, the detection thresholds were updated to be kg/hr as opposed to the previously used m^3/day. For more detailed information on how LDAR-Sim works and further explanation of parametrization assumptions, please refer to the original report and previous reports in the Appendix.

2. Modelling Results

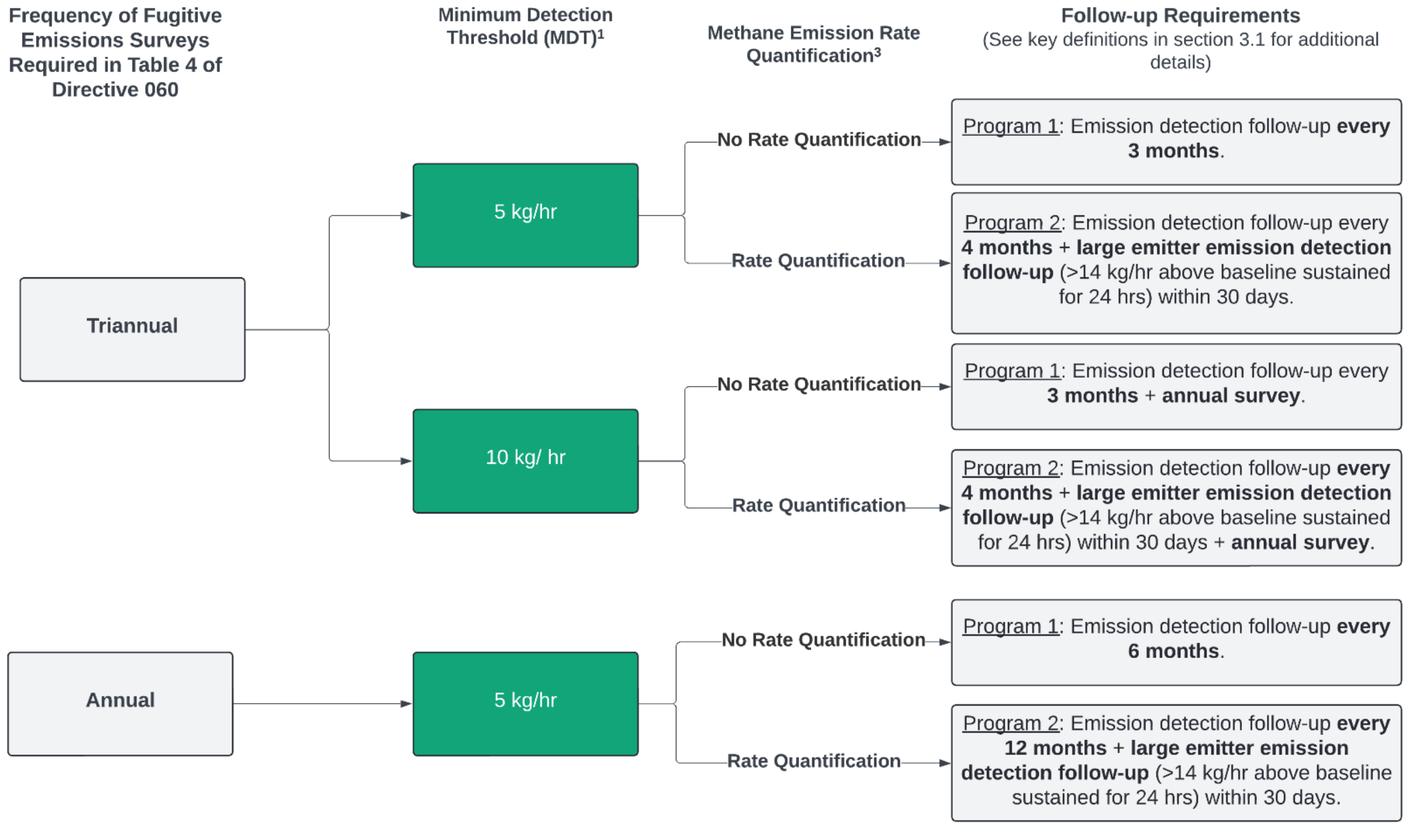
2.1. Mobile Matrix



[1] The CH_4 emission rate that will be detected 90% of the time by the method under standard operating conditions (90% Probability of Detection). This metric must be established via controlled release testing.
[2] Semiannual screenings (2x per year) must be performed at least 4 months apart, and triannual screenings (3x year) should be performed at least 3 months apart.
[3] A method can be classified as "capable of quantification" if it can demonstrate a mean relative quantification error ranging from -40% to 100% under typical operating conditions for methane emissions > 1 kg/hr.

Figure 1. Equivalency Matrices Flowchart for Mobile / periodic Work Practices. Readers should work left to right through the flowchart to be directed to the appropriate work practice. This table is only relevant to the standard fugitive emission management program Directive 60 Table 4 Release Date April 6, 2022.

2.2. Stationary Matrix



[1] The CH_4 emission rate that will be detected 90% of the time by the method under standard operating conditions (90% Probability of Detection). This metric must be established via controlled release testing.
[3] A method can be classified as "capable of quantification" if it can demonstrate a mean relative quantification error ranging from -40% to 100% under typical operating conditions for methane emissions > 1 kg/hr .

Figure 2 Equivalency Matrices Flowchart for stationary/continuous monitoring Work Practices. Readers should work left to right through the flowchart to be directed to the appropriate work practice. This table is only relevant to the standard fugitive emission management program Directive 60 Table 4 Release Date April 6, 2022.

2.3. Modelling Results

2.3.1. Mobile Matrix

Nomenclature used in the Mobile Equivalency Matrix Flowchart

Table 1. Programs Nomenclature

Technology Tier	Screening Frequency	Quantification Capacity	Program	Modelling Nomenclature
0.5 kg/hr	2	No Quantification	1	Mobile_0.5kgh_2x
0.5 kg/hr	2	Quantification	2	Mobile_0.5kgh_2x_Quantification_Proportion
0.5 kg/hr	2	Quantification	2	Mobile_0.5kgh_2x_Quantification_Threshold
0.5 kg/hr	D60	No Quantification	3	Mobile_0.5kgh_3x_1x
0.5 kg/hr	D60	Quantification	4	Mobile_0.5kgh_3x_1x_Quantification_Threshold
0.5 kg/hr	D60	Quantification	4	Mobile_0.5kgh_3x_1x_Quantification_Proportion
1kg/hr	2	Quantification	1	Mobile_1kgh_2x_Quantification
1kg/hr	2	No Quantification	2	Mobile_1kgh_2x
5kg/hr	2	Quantification	1	Mobile_5kgh_2x_Quantification
5kg/hr	2	No Quantification	2	Mobile_5kgh_2x
10kg/hr	3	Quantification	1	Mobile_10kgh_3x

Mitigation

Figure 3 is a bar graph where the bar length is the % of mitigation each Alt-FEMP program present in the mobile matrix achieves. The % mitigation is based on a comparison to a program devoid of any LDAR and only considers mitigable emissions (fugitive emissions). For example, if this program devoid of LDAR led to an annual total of 100 kg of CH_4 fugitive emissions, and an Alt-FEMP program achieved a mitigation of 60 kg of CH_4 emissions, that Alt-FEMP's bar distance would be 60%. The programs were modeled considering typical AB site distribution, where 34% received triannual surveys under Directive 60 (subtypes 601, 621, and 401), and 76% of sites received annual surveys under Directive 60.

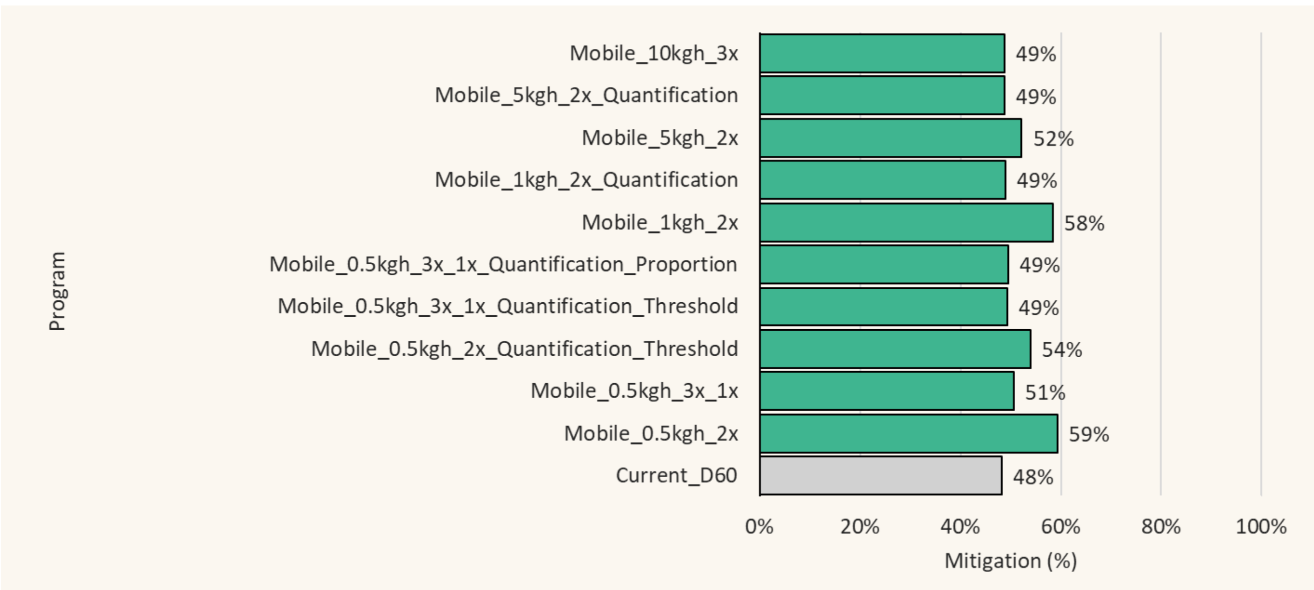


Figure 3. Emissions mitigation of mobile method-based programs and a comparison standard FEMP scenario based on current AER D060 FEMP requirements. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH_4 from fugitive emissions the program mitigates.

Follow-up Estimative

The following table summarizes estimates of the minimum follow-up required considering all site's scope to achieve equivalency. Follow-up requirements above this threshold (more conservative follow-up thresholds) are expected to exceed emissions mitigation.

Table 2. After each screening cycle, the average proportion of sites under the scope will receive follow-up under the proposed work practice.

Program	Follow-up Requirements According to Modelling (Figure 1)	Estimated percentage of sites under the scope that will receive follow-up (per screening)	Estimated percentage of sites under the scope that will receive follow-up (per year)
Mobile_0.5kgh_2x	All emitting (flagged) sites	44%	88%
Mobile_0.5kgh_3x_1x	All emitting (flagged) sites	Note 1	74%
Mobile_0.5kgh_2x_Quantification_Proportion	30% of emitting (flagged) sites	16%	**32%**
Mobile_0.5kgh_2x_Quantification_Threshold	Immediate emission detection follow-up (up to 24 hrs from detection) at sites with sources emitting >7.5kg/hr	20%	40%
Mobile_0.5kgh_3x_1x_Quantification_Threshold	Immediate emission detection follow-up (up to 24 hrs from detection) at sites with sources emitting >3kg/hr	Note 1	46%
Mobile_0.5kgh_3x_1x_Quantification_Proportion	80% of emitting (flagged) sites	Note 1	62%
Mobile_1kgh_2x	All emitting (flagged) sites	41%	82%
Mobile_1kgh_2x_Quantification	35% of emitting (flagged) sites	17%	**34%**
Mobile_5kgh_2x	All emitting (flagged) sites	23%	45%
Mobile_5kgh_2x_Quantification	70% of emitting (flagged) sites	18%	**35%**
Mobile_10kgh_3x	All emitting (flagged) sites	10%	**31%**

Note [1] This program covers a different site scope depending on the screening cycle (all sites in the first screening and only triannual sites in the last two screenings), which impacts the follow-up percentage. The metric was not derived for those types of deployment.

2.3.2. Stationary Matrix

Figure 4 is a bar graph, where the bar length is the percentage of mitigation each program achieves. Since stationary systems were modeled by the site (the site scope included only one type of site subtype), each site subtype would have a specific mitigation. Due to the many subtypes included, we modeled the most representative subtypes (with a higher proportion of AB sites scope) that required annual and triannual surveys under D60. For triannual sites fitting the 601 subtypes, the Directive 060 program achieves 2% greater mitigation than Program 1 under the 5 kg/hr tier. Given the high variability in modeling and the fact that mitigation exceeds Directive 060 for other subtypes, the results were deemed satisfactory.

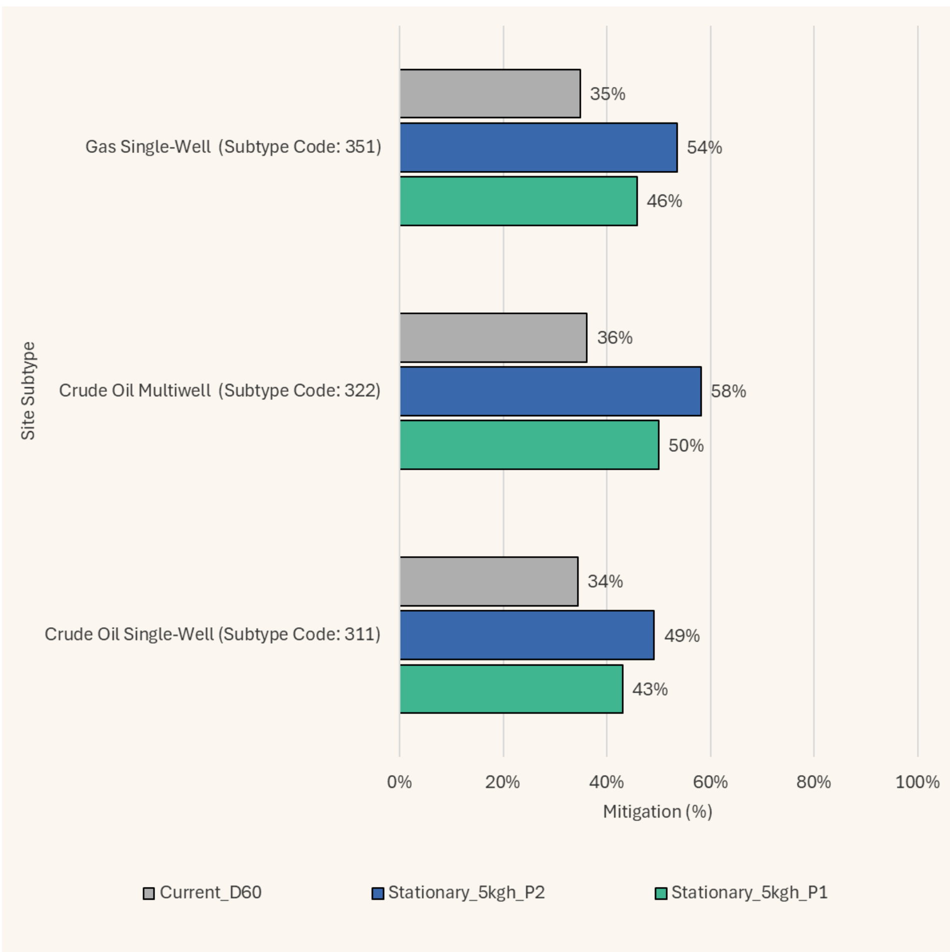


Figure 4. Emissions mitigation of stationary method-based programs and a comparison standard FEMP scenario based on current AER D060 FEMP requirements for subtypes, which currently require 1x survey per year. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH4 from fugitive emissions the program mitigates. Each bar color represents one of the programs modeled.

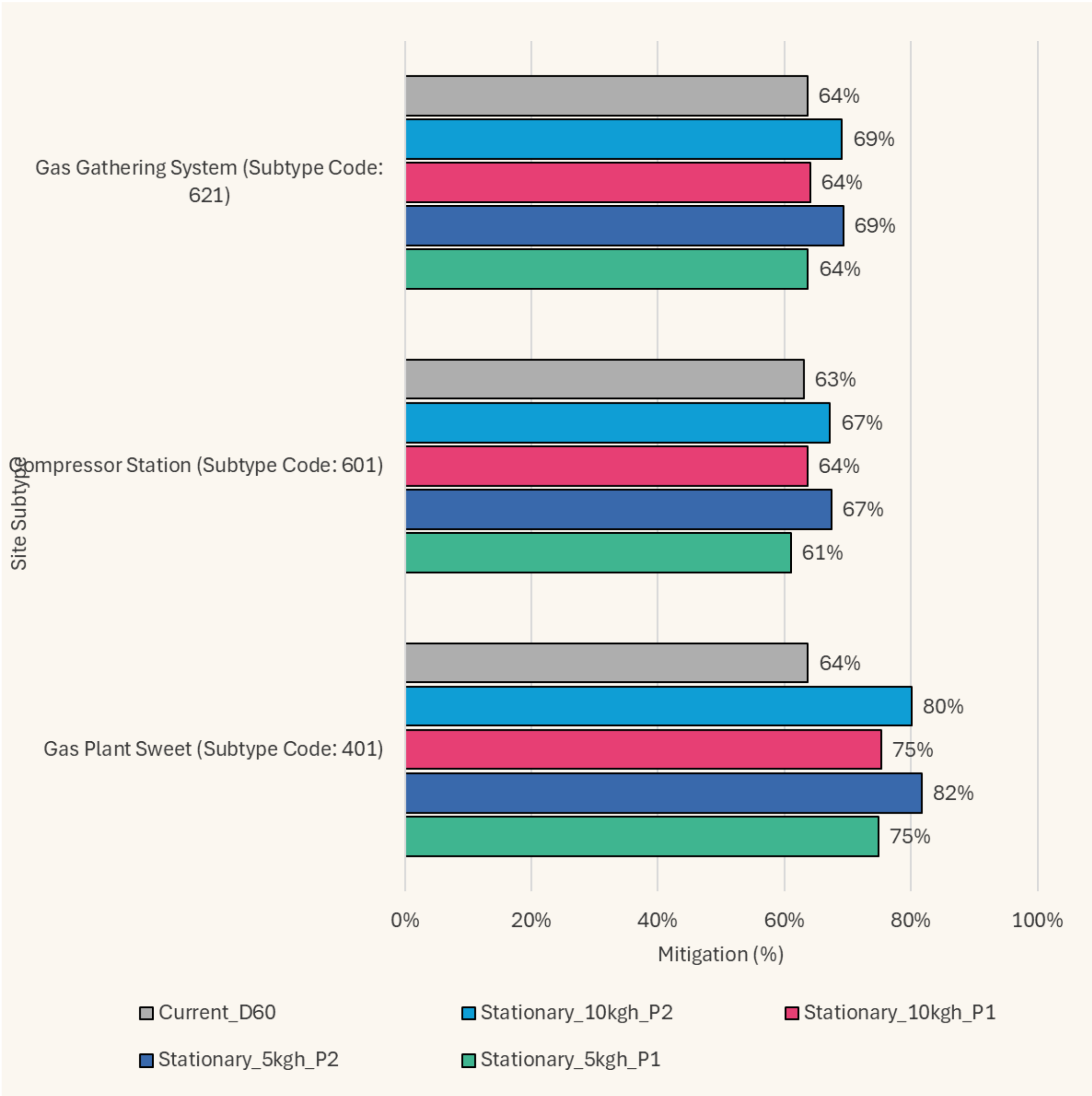


Figure 5. Emissions mitigation of stationary method-based programs and a comparison standard FEMP scenario based on current AER D060 FEMP requirements for subtypes, which currently require 3x surveys per year. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH4 from fugitive emissions the program mitigates. Each bar color represents one of the programs modeled.

Technical Report

Alternative Methane Detection Technologies Evaluation

Alternative Technology Equivalency Matrix Analysis Update

Focus
This report includes Alternative Technology Equivalency Matrix updates based on a second round of modelling.

Date
September 2024

Authors
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Appendix A: Alternative Methane Detection Technologies Evaluation - Modelling Update

Appendix B: (Original Report) Alternative Methane Detection Technologies Evaluation - Alternative Technology Equivalency Matrix Analysis

Executive Summary

In December 2023, Highwood Emissions Management ("Highwood") completed an analysis for the Alberta Energy Regulator ("AER"), evaluating the methane emissions mitigation of multiple standard Fugitive Emissions Management Program (FEMP) scenarios and alternative FEMPs (alt-FEMP). Standard FEMP scenarios are those based on currently regulatorily approved methane detection technology (optical gas imaging (OGI) cameras and portable gas analyzers), while alternative FEMP scenarios are those based around non-standard methane detection technology (aerial screening methods, continuous monitoring, truck-based screening, etc.). The analysis aimed to establish which alt-FEMPs (combinations of alternative methane detection technology and work practice) could achieve methane emissions reduction equivalency with standard FEMP scenarios. The study was conducted using the Leak Detection and Repair Simulator (LDAR-Sim) to carry out emissions simulation modelling and was presented in an equivalency matrix that summarized the details of the alt-FEMPs which achieved emissions reduction equivalency. The report was published on the AER website, and feedback was received from multiple stakeholders, who raised questions on simulation modelling assumptions and their impact on the equivalency matrix.

To address the feedback, Highwood and the AER collaboratively completed a second simulation modeling analysis, exploring the impact of several key model inputs. This analysis resulted in a parametrization update, including an updated and more granular parameterization of the modelled infrastructure and the associated leak behavior. Parametrization update impacted mobile screening methods the most, with most mobile work practices requiring one less annual screening than in the original equivalency matrix (Appendix B). In addition, the mobile screening follow-up requirements were updated to create simplified, more easily adoptable work practices. Highwood also modeled the stationary (continuous monitoring) alt-FEMPs on the new inputs, but the equivalency remained consistent with the original equivalency matrix (Appendix B).

This report supplements the previous work and describes work practice updates for mobile and stationary methods. Please refer to **Appendix A** for updates on parametrization and modeling results and **Appendix B** for the original report.

1. Equivalency Matrix Flowcharts

The flowcharts in Figure 1 and Figure 2 serve as a visual representation of the updated equivalency matrix and are intended to be referenced to define the equivalent alt-FEMPs work practice. The equivalent alt-FEMPs in the flowcharts are defined by their deployment platform (mobile/stationary), minimum detection threshold, and quantification capabilities. The reader must answer the following questions when working through the flowcharts:

1. Is the alternative method mobile? See Figure 1.
2. Is the alternative method stationary? See Figure 2.
3. What is the minimum detection threshold for the alt-FEMPs primary methane detection method (CH_4 emission rate that will be detected 90% of the time under standard operating conditions)?
   a. The 90% probability of detection values in the flowchart can be considered "<=" until the next most sensitive option. For example, if a mobile method has a 90% probability of detecting 130 m^3 CH_4/ day, it must follow the 150 m^3 CH_4/ day flowchart option. It is not until a method can prove an equivalent or better probability of detection of the next more sensitive probability of detection option that the applicant can follow that flowchart lane.
   b. Once the minimum detection threshold is selected, the reader will be directed to the required deployment/follow-up frequency given the answer. For some options, multiple follow-up work practices are available.
4. Can the method quantify? A method can be classified as “capable of quantification” if it can demonstrate a mean relative quantification error ranging from -40% to 100% under typical operating conditions for methane emissions > 1 kg/hr (35 m^3/day).

2. Equivalency Matrix for Mobile Methods

The modeling conducted to construct the updated equivalency matrix (Figure 1) involved deploying mobile method-based alt-FEMPs and comparing their emissions reduction to the current regulatory standard FEMP scenario (AER Directive 60) across a representative infrastructure of Alberta site types (see Appendix A for more details). For each given probability of detection "tier" (10, 150, 300, and 500 m^3 ch_4/day), multiple equivalent alt-FEMPs are available to the applicant to choose a work practice that best suits their needs. Highwood recommends that the regulatory application process requests verification of the MDT (90% probability of detection) and the mean quantification error of applicant alternative mobile alt-FEMPs (likely requiring controlled release testing results).

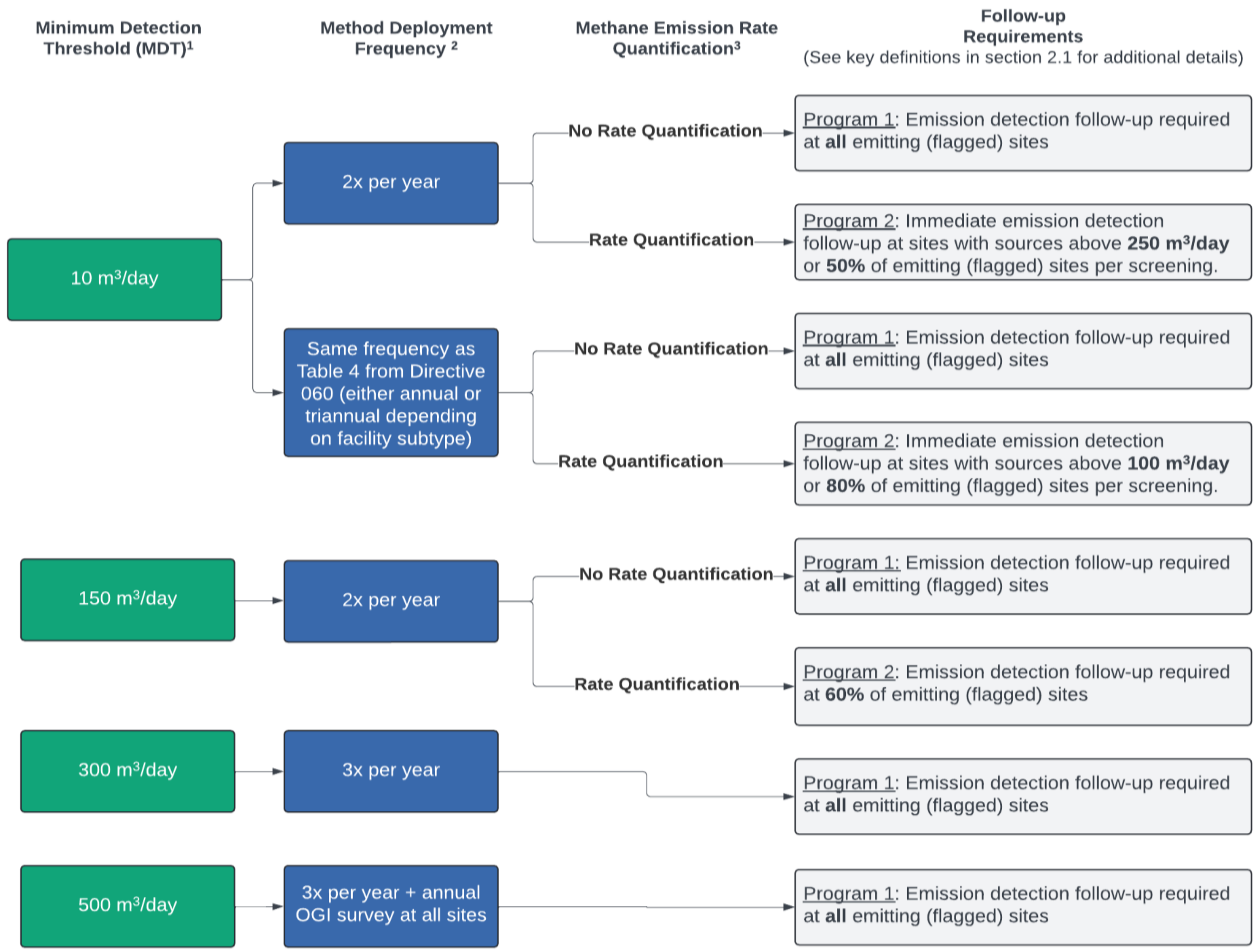
2.1. Key Definitions

- Minimum Detection Threshold (MDT): The CH_4 emission rate that will be detected 90% of the time by the method under standard operating conditions (the 90% probability of detection).
- The mobile equivalency matrix includes 3 potential follow-up work practices.
    - ***Follow-up at X% of emitting (flagged) sites***: After each screening round, all flagged sites should be ranked based on either their measured site-level emission rates or their deviation from previous screenings. The top X% of flagged sites with the highest emissions or the highest deviations must undergo follow-up within 21 days. This follow-up practice is specific to the alt-FEMP protocols that use mobile alternative methods capable of quantifying emission rates, as this quantification is necessary for ranking the flagged sites. The option to rank by deviation can be applied after the initial screening. In this case, operators can use data from previous screenings to justify follow-ups on lower-emitting sites by looking at sites with high deviations.
    - ***Follow-up at all emitting (flagged) sites:*** After each screening round, all flagged sites must receive follow-up within 21 days. This follow-up work practice is only present in alt-FEMPs based on mobile alternative methods that cannot quantify emission rates (flagged sites cannot be ranked by emission rate) and with higher relative MDTs (300/500 m^3 CH_4/day).
    - ***Immediate follow-up at sites with sources above Y m^3 of CH_4 /day***: Alternative methods with a 90% probability of detection <= 10m^3 of CH_4/day and the capability to quantify emission rates have the option to follow-up at the top X% of emitting (flagged) sites (see

above definition) or immediately follow-up all sites with a site-wide emission rate >Y m^3 of CH_4/day. If the immediate follow-up option is chosen, all sites with a source emitting > Y m^3 of CH_4 /day must receive a follow-up within 12 hours from the initial screening time.

- Modelling considered follow-up surveys investigating emissions from the entire site.
- For all proposed mobile programs, the operator can replace a mobile screening with an OGI survey.

2.2. Equivalency Matrix



[1] The CH_4 emission rate that will be detected 90% of the time by the method under standard operating conditions (90% Probability of Detection). This metric must be established via controlled release testing.
[2] Semiannual screenings (2x per year) must be performed at least 4 months apart, and triannual screenings (3x year) should be performed at least 3 months apart.
[3] A method can be classified as "capable of quantification" if it can demonstrate a mean relative quantification error ranging from -40% to 100% under typical operating conditions for methane emissions > 1 kg/hr (35 m³/day).

Figure 1. Flowchart for Mobile Work Practices. Readers should work left to right through the flowchart to be directed to the appropriate work practice. This table is only relevant to the standard fugitive emission management program Directive 60 Table 4 Release Date April 6, 2022.

3. Equivalent Matrix for Stationary Methods

While mobile methods typically rapidly screen many sites of differing types, stationary methods often see targeted deployment at a given facility type. Therefore, when modelling stationary methods, the LDAR-Sim virtual world was populated entirely with a single given Alberta subtype (as opposed to a representative infrastructure used in the mobile modelling). This is reflected in the stationary method equivalency matrix (Figure 2), where Alt-FEMP program options depend on the current FEMP survey frequency requirements of Table 4 of Directive 060.

Stationary method alerting work practices are complex and must consider the following:

- What are the alerting criteria?
- How are emissions baselines defined?
- When should the baseline be updated?

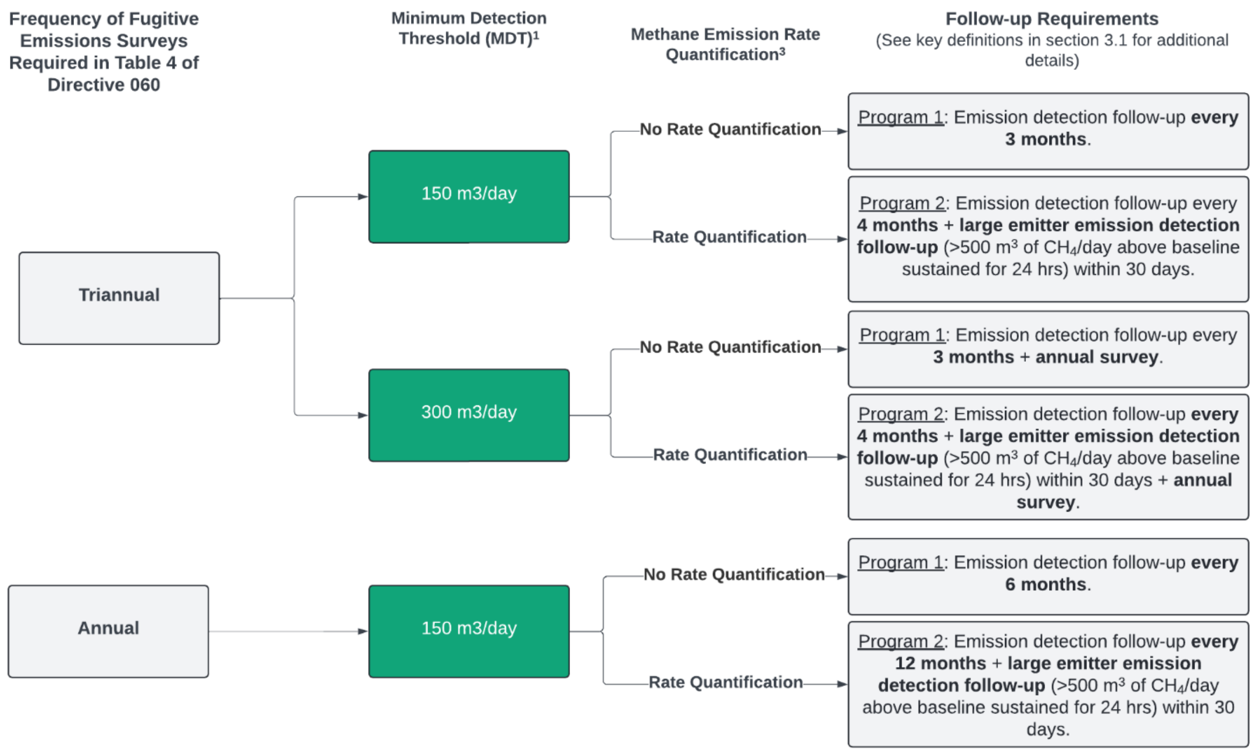
Highwood suggests including a well-documented alerting work practice from stationary-based alt-FEMP applications since point sensor methods are expected to handle alerting differently than continuous-OGI solutions. Therefore, work practices should be defined on a case-by-case basis.

Defining a stationary alerting work practice is outside the scope of this report. The version of LDAR-Sim assumes the stationary method "knows" the emission rate baseline, and an alert is generated when the site-level emission rate is above the baseline.

3.1. Key Definitions

- **Follow-up every X months:** Operators must review detection events generated through the Stationary method every X months, depending on the site type and MDT of the stationary method (Figure 2). In practice, the operator must review the emissions data collected by the stationary method every X months and follow up on any new deviations/shifts from the baseline, addressing potential fugitives.
- The modelling investigation was based on follow-ups investigating emissions from the entire site.

3.2. Equivalency Matrix



[1] The CH_4 emission rate that will be detected 90% of the time by the method under standard operating conditions (90% Probability of Detection). This metric must be established via controlled release testing.
[3] A method can be classified as "capable of quantification" if it can demonstrate a mean relative quantification error ranging from -40% to 100% under typical operating conditions for methane emissions > 1 kg/hr (35 m^3/day).

Figure 2. Flowchart for Stationary Work Practices. Readers should work left to right through the flowchart to be directed to the appropriate work practice. This table is only relevant to the standard fugitive emission management program Directive 60 Table 4 Release Date April 6, 2022.

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Alternative Methane Detection Technologies Evaluation

Modelling Update

Focus
Report detailing parametrization and results updates for the second round of modelling.

Date
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1. Parametrization Update

The following sections provide an overview of parametrization updates in the second modeling round. For more detailed information on how LDAR-Sim works and further explanation of parametrization assumptions, please refer to the previous report (Appendix B).

The previous modeling was conducted using LDAR-Sim Version 3,[1] The results presented here were produced with Version 4. Despite the version change, no significant differences in results due to parameter migration between the versions are anticipated.

LDAR-Sim V4 allows for emissions parametrization down to the source level if data is available. For modeling completed in this report, all parametrizations (such as infrastructure, leak frequency, and size) were defined at the site level.

1.1. Data Overview

- The original dataset (AER ST102: Facility List) used to inform sites within the modeling scope was not updated (total sites remained the same). However, with more granular data on leak frequency available to Highwood, this site list saw more granular parameterization.
- For this update, the AER provided a more comprehensive dataset, including data that reached 2020, which is further than the data range used in the original modeling and report (Appendix B).

1.2. Modeled Infrastructure

The modeling conducted for updated matrices had site subtypes following facility subtype codes from AER Manual 011. To be conservative, sites containing multiple facilities within the site boundary were classified as the facility subtype with a higher leak frequency. Simulations were conducted considering a 500-site scope for the mobile matrix and a 100-site scope for the continuous monitoring matrix. Similar mitigation outcomes are anticipated for a different site scope if the same proportions are applied.

[1] LDAR-Sim Version 3. https://github.com/LDAR-Sim/LDAR_Sim/tree/Legacy_Branch_V3

In Figure 1, we illustrated site-type proportions of the modeled infrastructure, highlighting the seven most representative sites in the infrastructure scope (corresponding to more than 80% of sites under scope). A detailed description of the proportion of each site subtype is included in Table 1. Subtypes that represent less than 0.2% of infrastructure scope were not included.

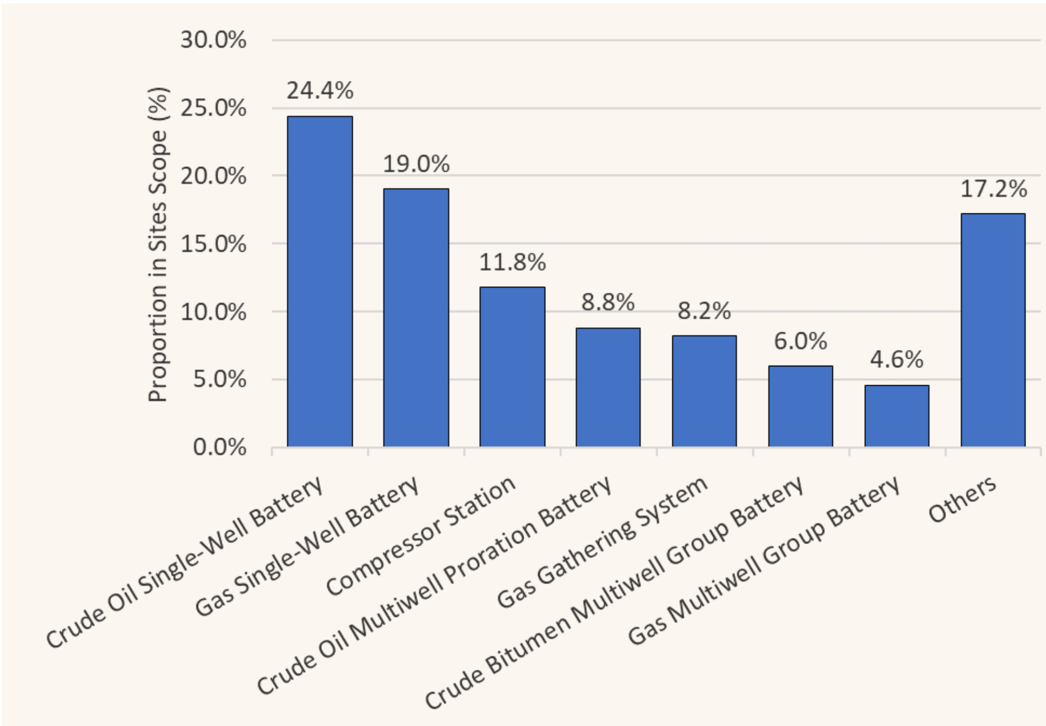


Figure 1. Proportion of sites in scope. The chart highlights the seven most representative sites by proportion, with all remaining sites grouped under "Others. See Table 1 for details for each subtype.

1.3. Emissions Size

The emissions size parametrization was kept consistent with the original modelling. For additional details, see Appendix B (original report) (Appendix B—Section 4.2.3).

1.4. Emissions Frequency

Fugitive Emissions (Repairable Emissions)

The fugitive emissions frequency was the key updated infrastructure parameter in this modelling update. Operational FEMP data from Alberta (routine OGI surveys) were used to calculate leak frequency (repairable emissions production rate) for each modeled subtype. Table 1 summarizes the calculated rates for the modeled subtypes and includes site subtype proportions in infrastructure scope. See Appendix B (original report) for additional details (Appendix B - Section 4.2.2) to compare the updated results with the original modelling.

Table 1. The proportion of sites under each subtype and the average number of leaks per facility per year.

Subtype Code	Subtype	Infrastructure Proportion	Average number of leaks per year per facility	Repairable Emissions Production Rate[1]
311	Crude Oil Single-Well Battery	24.4%	0.6	0.0016
351	Gas Single-Well Battery	19.0%	0.8	0.0023
601	Compressor Station	11.8%	2.3	0.0064
322	Crude Oil Multiwell Proration Battery	8.8%	2.3	0.0062
621	Gas Gathering System	8.2%	3.3	0.0091
341	Crude Bitumen Multiwell Group Battery	6.0%	2.3	0.0063
361	Gas Multiwell Group Battery	4.6%	2.0	0.0054
331	Crude Bitumen Single-Well Battery	3.6%	3.1	0.0084
321	Crude Oil Multiwell Group Battery	2.0%	1.5	0.0042
401	Gas Plant Sweet	1.8%	19.4	0.0531
503	Disposal	1.8%	0.3	0.0008
362	Gas Multiwell Effluent Measurement Battery	1.6%	7.0	0.0192
501	Enhanced Recovery Scheme	1.6%	0.3	0.0007
342	Crude Bitumen Multiwell Proration Battery	1.0%	0.6	0.0018
364	Gas Multiwell Proration Outside SE Alberta Battery	0.8%	1.1	0.0029
671	Tank Farm/Oil Loading and Unloading Terminal	0.6%	2.1	0.0058
363	Gas Multiwell Proration SE Alberta Battery	0.4%	0.5	0.0014
507	Disposal (Approved as part of a Waste Plant)	0.4%	0.1	0.0003

Subtype Code	Subtype	Infrastructure Proportion	Average number of leaks per year per facility	Repairable Emissions Production Rate[1]
405	Gas Plant Sulphur Recovery	0.2%	35.6	0.0976
344	In-Situ Oil Sands Battery	0.2%	33.5	0.0918
403	Gas Plant Acid Gas Flaring > 1 T/D Sulphur	0.2%	29.6	0.0811
506	In-Situ Oil Sands Injection	0.2%	29.1	0.0798
404	Gas Plant Acid Gas Injection	0.2%	25.7	0.0703
402	Gas Plant Acid Gas Flaring < 1 T/D Sulphur	0.2%	10.2	0.0280
611	Custom Treating Facility	0.2%	5.0	0.0136
505	Underground Gas Storage	0.2%	2.9	0.0079
406	Gas Plant Mainline Straddle	not included	128.7	0.3525
345	Sulphur Reporting at Oil Sands	not included	76.4	0.2092
407	Gas Plant Fractionation	not included	39.2	0.1075
502	Concurrent Production/Cycling Scheme	not included	2.3	0.0064
504	Acid Gas Disposal	not included	0.6	0.0017
673	Third-Party Tank Farm/Oil loading and Unloading Terminal	not included	0.4	0.0010
612	Custom Treating Facility (Approved as part of a Waste Plant)	not included	0.1	0.0002

[1] The repairable emission production rate represents the probability that a new fugitive emission will arise each day for each site.

Routine Emissions (Non-repairable emissions)

The parameterization of routine emissions was not updated. It was considered that during a screening or survey of a given site, there is a 25.8% chance that the site will be venting. This 25.8% chance is informed by a preprint by Conrad et al., which collected top-down measurements of 3,454 unique Alberta facilities using Bridger Photonics. Non-routine emissions parameterization is set up differently in LDAR-Sim version 4, but tests were completed to ensure that the version change was not interfering with the results.

1.5. Other Key Inputs

All other key inputs were kept consistent with the original modelling. See Appendix B (original report) for additional details (Appendix B - Section 4.2.5).

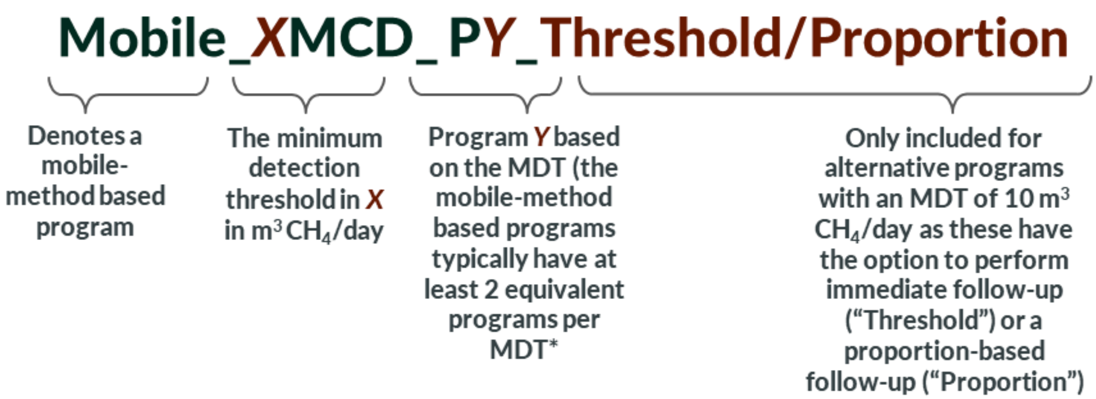
2. Modelling Results

The following section presents the simulation modeling results, which informed the updated alt-FEMPs matrices.

2.1. Mobile Matrix

2.1.1. Nomenclature

All modeled mobile method-based programs correspond to a row in the equivalency tables. The modeled program names employ the following nomenclature (orange text varies program-to-program):

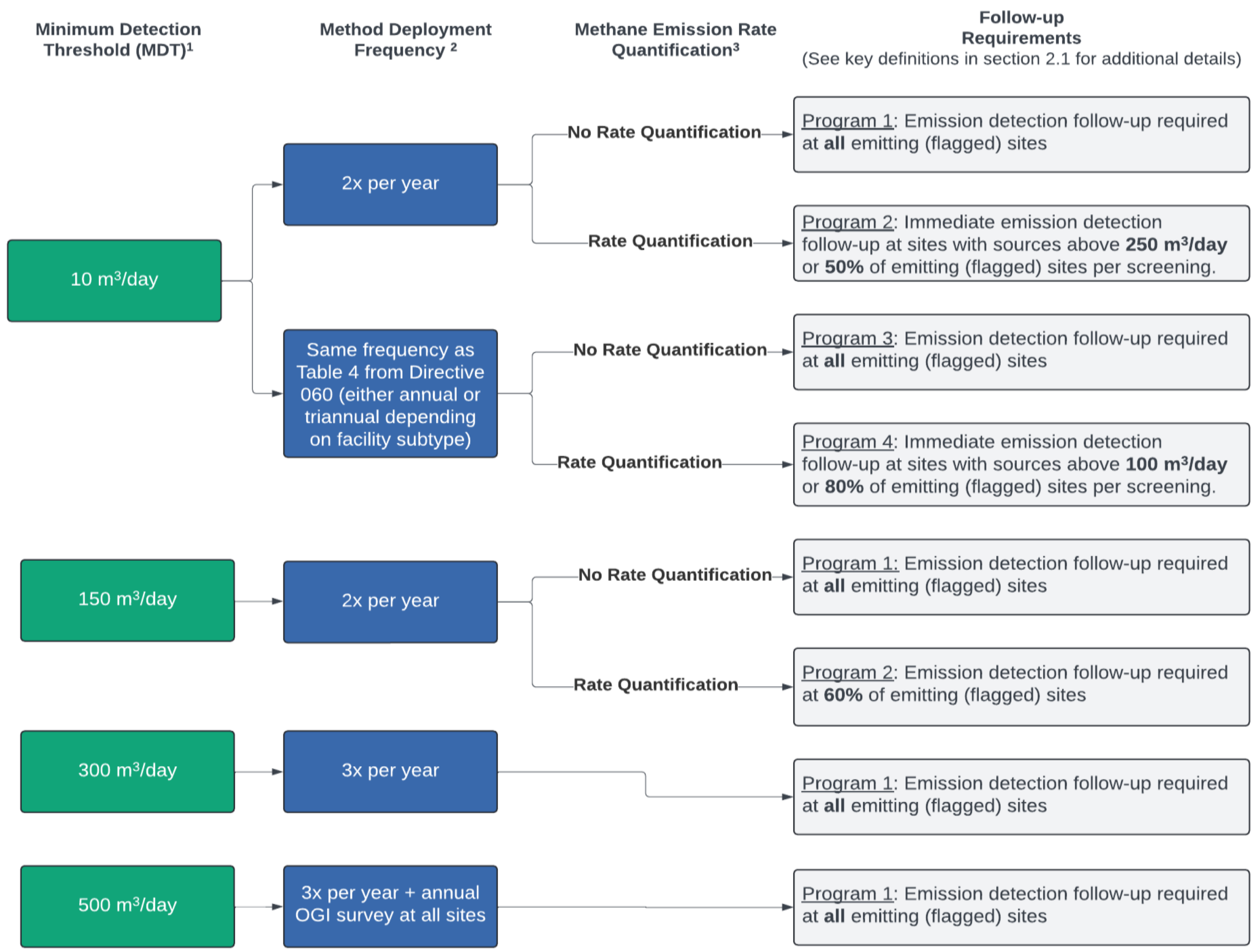


The comparison standard FEMP scenario (Current_D60) is the only program not following this nomenclature.

1.1.1. Current Standard FEMP Scenario (AER D060)

2.1.2. Emissions Mitigation

The plot (below the mobile matrix) is a bar graph where the bar length is the % of mitigation each program achieves. The % mitigation is based on a comparison to a program devoid of any LDAR and only considers mitigable emissions (fugitive emissions). For example, if this program devoid of LDAR led to 100 kg of CH_4 fugitive emissions, and a given program mitigated 60 kg of CH_4 emissions, that program's bar would be 60%.



[1] The CH_4 emission rate that will be detected 90% of the time by the method under standard operating conditions (90% Probability of Detection). This metric must be established via controlled release testing.
[2] Semiannual screenings (2x per year) must be performed at least 4 months apart, and triannual screenings (3x year) should be performed at least 3 months apart.
[3] A method can be classified as “capable of quantification” if it can demonstrate a mean relative quantification error ranging from -40% to 100% under typical operating conditions for methane emissions > 1 kg/hr (35 m³/day).

Figure 2. Equivalency Matrices Flowchart for Mobile Work Practices. Readers should work left to right through the flowchart to be directed to the appropriate work practice. This table is only relevant to the standard fugitive emission management program Directive 60 Table 4 Release Date April 6, 2022.

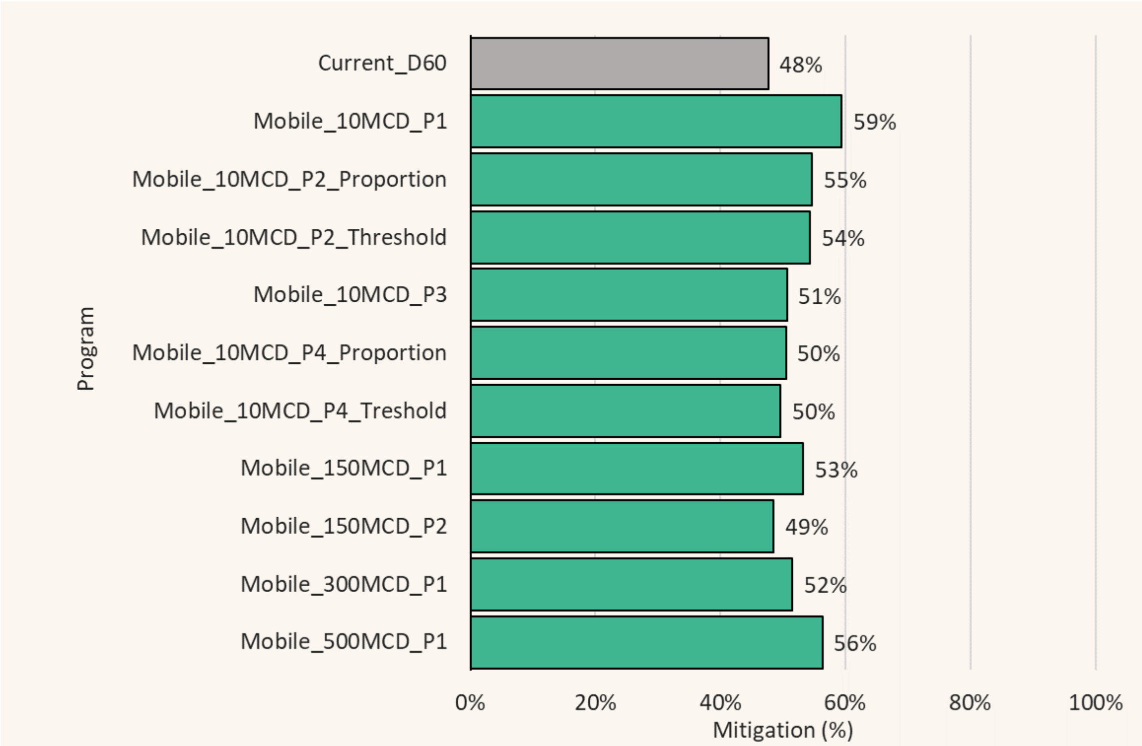


Figure 3. Emissions mitigation of mobile method-based programs and a comparison standard FEMP scenario based on current AER D060 FEMP requirements. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH_4 from fugitive emissions the program mitigates.

2.1.3. Follow-up Estimative

Table 2After each screening cycle, the average proportion of sites under the scope will receive follow-up under the proposed work practice.

Program	Estimated percentage of sites under the scope that will receive follow-up (per screening)
Mobile_10MCD_P1	48%
Mobile_10MCD_P2_Threshold	21%
Mobile_10MCD_P2_Proportion	27%
Mobile_10MCD_P3	(note 1)
Mobile_10MCD_P4_Proportion	(note 1)
Mobile_10MCD_P4_Treshold	(note 1)
Mobile_150MCD_P1	25%
Mobile_150MCD_P2	17%

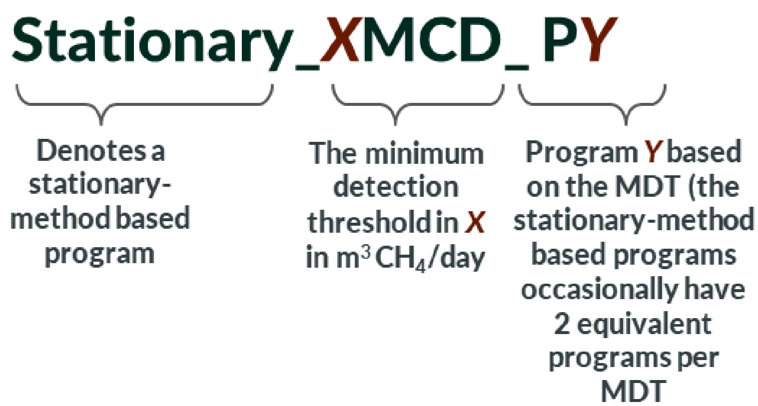
Program	Estimated percentage of sites under the scope that will receive follow-up (per screening)
Mobile_300MCD_P1	12%
Mobile_300MCD_P2	8%
Mobile_500MCD_P1 (note 2)	6%

Note 1 This program covers a different site scope depending on the screening cycle (all sites in the first screening and only triannual sites in the last two screenings), which impacts the follow-up percentage. The metric was not derived for those types of deployment.
Note 2 This program also includes a comprehensive OGI survey at all sites. This estimate only considers close-range surveys conducted as follow-ups.

2.2. Stationary Matrix

2.2.1. Nomenclature

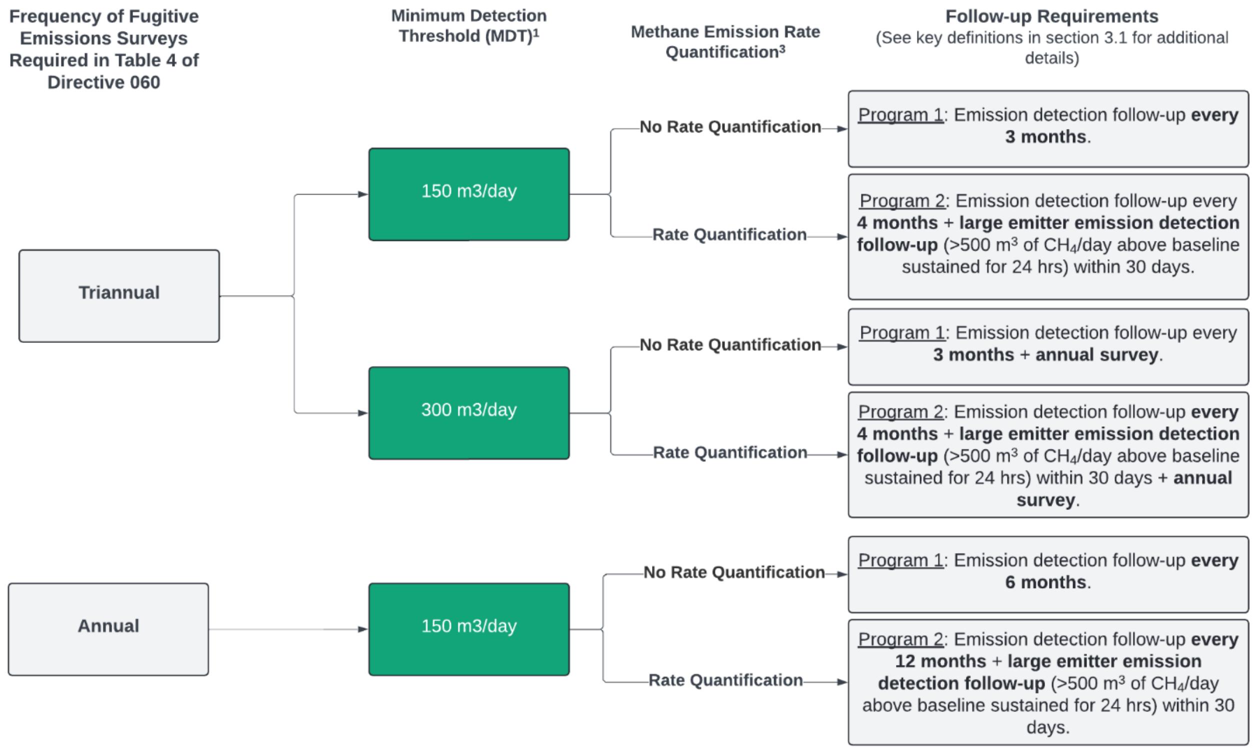
All modeled stationary method-based programs correspond to a row in the equivalency matrices. The modeled program names employ the following nomenclature (orange text varies from program to program)



2.2.2. Emissions Mitigation

The plot below the stationary matrix is a bar graph, where the bar length is the percentage of mitigation each program achieves. Since stationary systems were modeled by the site (the site scope included only one type of site subtype), each site subtype would have a specific mitigation.

Due to the many subtypes included, we modeled the most representative subtypes (with a higher proportion of AB sites scope) that required annual and triannual surveys under D60.



[1] The CH_4 emission rate that will be detected 90% of the time by the method under standard operating conditions (90% Probability of Detection). This metric must be established via controlled release testing.
[3] A method can be classified as "capable of quantification" if it can demonstrate a mean relative quantification error ranging from -40% to 100% under typical operating conditions for methane emissions > 1 kg/hr (35 m^3/day).

Figure 4. Equivalency Matrices Flowchart for Stationary Work Practices. Readers should work left to right through the flowchart to be directed to the appropriate work practice. This table is only relevant to the standard fugitive emission management program Directive 60 Table 4 Release Date April 6, 2022.

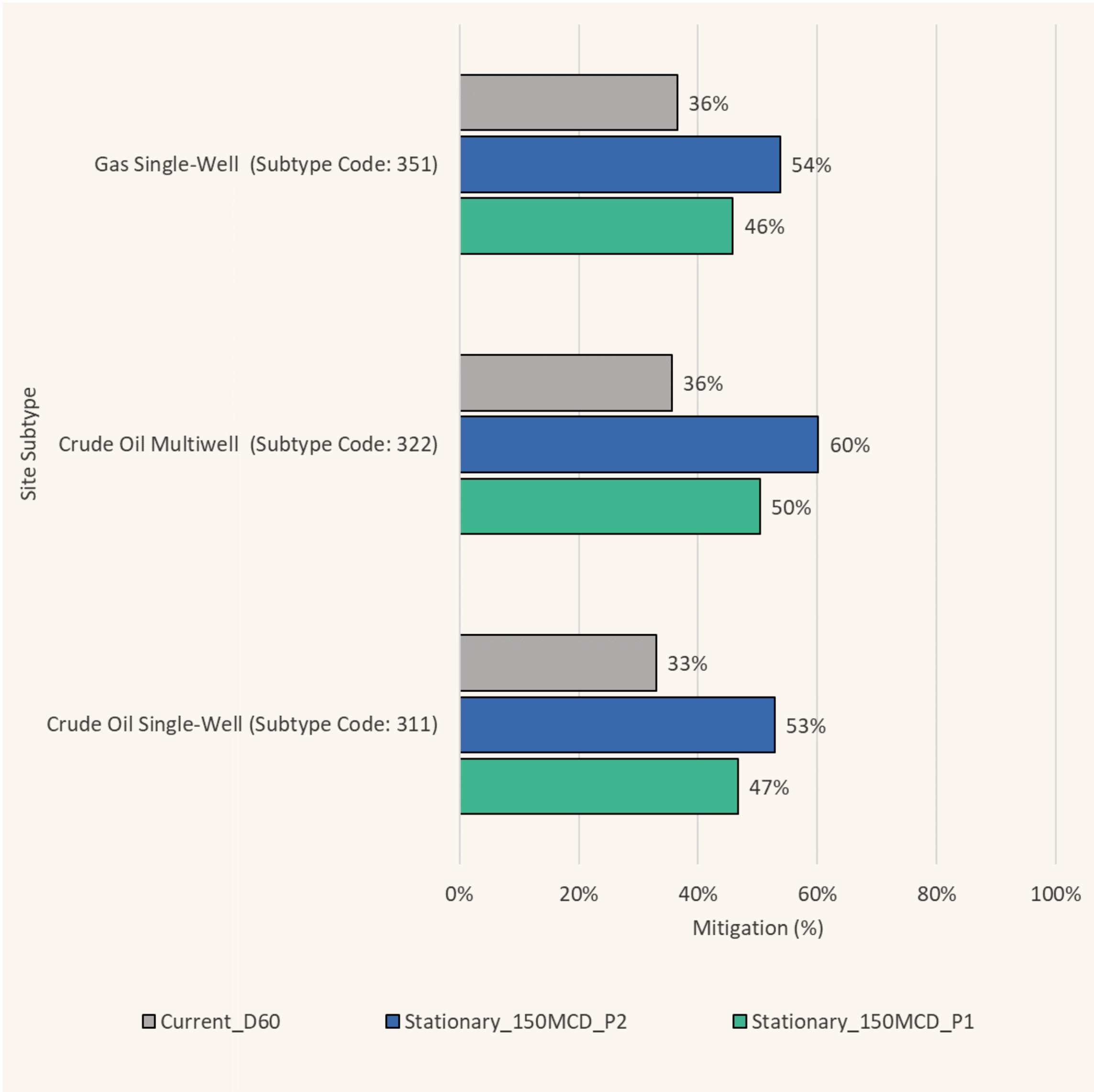


Figure 5. Emissions mitigation of stationary method-based programs and a comparison standard FEMP scenario based on current AER D060 FEMP requirements for subtypes, which currently require 1x survey per year. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH4 from fugitive emissions the program mitigates. Each bar color represents one of the programs modeled.

Figure 6. Emissions mitigation of stationary method-based programs and a comparison standard FEMP scenario based on current AER D060 FEMP requirements for subtypes, which currently require 3x surveys per year. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH4 from fugitive emissions the program mitigates. Each bar color represents one of the programs modeled.

Highwood Emissions Management

Innovate. Collaborate. Educate.

Technical Report

Alternative Methane Detection Technologies Evaluation

Alternative Technology Equivalency Matrix Analysis

Focus
Modelling standard FEMP scenarios to determine equivalent alt-FEMP practices.

Date
December 2023

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Executive Summary

Methane emissions, and their significant contribution to climate change, have become a global concern. Methane emissions at O&G facilities can occur by design (i.e., vented emissions and incomplete combustion) or through unintentional loss of containment (i.e., fugitive emissions or "leaks"). Fugitive methane emissions are difficult to mitigate because methane is invisible, and the precise timing and location of leak events is difficult (or impossible) to predict, however, mitigating fugitive emissions is an increasingly important strategy for oil and gas companies and regulators seeking to meet greenhouse gas emissions reduction targets.

There has been a recent wave of innovation in technologies that can detect and measure (quantify) methane emissions. Over 200 methane detection solutions have appeared ranging from handheld systems to satellites, stationary lasers to drones, sensors mounted on trucks and piloted aircraft. These technologies vary greatly in their deployment work practices, their spatial and temporal resolution, detection and quantification capabilities, and the data products they provide. While so many technologies are available, there is no "silver bullet" to fugitive methane emissions using these technologies.

The Alberta Energy Regulator (AER) currently has Fugitive Emissions Monitoring Plan (FEMP) requirements which call for the use of "standard" methods like optical gas imaging (OGI) and portable analyzers. The AER also allows for the approval of "alternative" methane detection technologies through the alternative FEMP (alt-FEMP) program. This program has been successful; however, approval of alternative technologies is based on individual operator applications which typically center around a single technology and work practice. This report seeks to analyze various standard FEMP scenarios, and models what a generic alt-FEMP program would need to be to achieve equivalent outcomes.

A key concept when considering an equivalent alt-FEMP is emissions reduction equivalency; a proposed alt-FEMP must mitigate at least as much methane emissions as the comparable standard FEMP program. Equivalency is typically established through simulation modelling. In this report, the open-source simulation model Leak Detection and Repair Simulator (LDAR-Sim) is used to model the equivalency of a range of typical alt-FEMP programs. These alt-FEMP programs are divided into those based on mobile methods (aircraft, drones, ground-based vehicles, etc.) and stationary methods (point sensors and continuous OGI solutions) and a range of key alt-FEMP performance criteria were investigated including: the minimum detection threshold of the method, the screening frequency, and the ability of the method to quantify emission rates.

In addition to model inputs which define alt-FEMP performance, inputs which informed the behavior of the modeled "virtual world" were carefully considered. Modeled emissions were derived from empirical measurements of Alberta facilities and considered both site-level and source-level measurements. In addition, the differing emissions characteristics of Alberta specific subtypes was considered, with different subtypes behaving differently in the simulation from an emissions perspective.

The results of modelling are a series of equivalency matrices. These matrices present a range of alt-FEMPs which have been shown, via modelling, to achieve emissions reduction equivalency with the current Alberta regulatory requirements and a range of other standard FEMP scenarios. The alt-FEMPs presented in the matrix cover a range of deployment types (mobile or stationary), detection threshold, and the presence or absence of supplemental OGI surveys.

Peer reviewed studies and the simulation modelling conducted for this report highlight the importance of quickly mitigating large emission events. The alt-FEMP programs provided in the equivalency matrices seek to provide a wide range of options from which operators can choose from based on their specific needs, which all emphasize the importance of quickly detecting and repairing large emission events.

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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:[1]

- **Standard FEMP:** A base case fugitive emissions management program targeting various sites at a given frequency using the methods and scope as outlined in AER D060 Sections 8.10.2.2-8.10.2.3.
- **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. The term “alternative method” is occasionally used to describe any method “alternative” to the standard FEMP leak detection methods of handheld, “boots on the ground”, close-range surveys.
- **Fugitive Emissions Management Program (FEMP)**: A FEMP 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 at each site, along with survey frequency, repair response, and reporting standards. Ultimately, it is the FEMP that results in emissions mitigation, not the technologies or methods in isolation. Leak Detection and Repair program (LDAR program) is a synonymous term used in some figures describing the leak detection and repair simulator. Throughout this report, a FEMP is sometimes referred to simply as a “program”.
- **Alternative Fugitive Emissions Management Program (Alt-FEMP):** An LDAR program / FEMP which is based on an “alternative” gas detection and technology. For the purposes of this presentation, “alternative” technologies” are those which are not currently approved for use under AER D060 (optical gas imaging (OGI) cameras and handheld analyzers). Obtaining an alt-FEMP is based on an established process, but for this report, alt-FEMP will refer to any LDAR program/FEMP which primarily relies on an alternative technology (not necessarily one which has undergone traditional approval). Throughout this report, an alt-FEMP is sometimes referred to simply as an “alternative program”.
- **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.
- **Screen:** The process of rapidly identifying site or equipment level emissions at a group of sites. Screening methods flag sites for follow-up with surveys.

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[1] Fox, T. A., Ravikumar, A. P., Hugenholtz, C. H., Zimmerle, D., Barchyn, T. E., Johnson, M. R., ... & Taylor, T. (2019). A methane emissions reduction equivalence framework for alternative leak detection and repair programs. *Elem Sci Anth*, *7*, 30.

- **Flagging:** The process of a method identifying that a site, or equipment group, is the source of an emission which must be followed up on (*used for screening methods*).
- **Survey:** Conducting close range, component-level emissions investigations to identify the source of an emission, sometimes conducted with an OGI. Survey methods may be as a follow-up to screening methods (to localize and diagnose screening flags) or done in isolation.
    - **Note:** In this report, Audio Visual Olfactory (AVO) inspections are considered surveys *only* if they are supported by screening method data that can verify the finding quickly i.e.. continuous monitoring, onsite mobile.
- **Tagging:** Documenting the emission source component for repair. Typically done by close-range (survey) inspection personnel (*used for close-range survey methods*).
- **Minimum Detection Threshold (MDT)**: The smallest release rate of CH_4 a technology can detect, typically described as kg CH_4 / day.
- **Probability of Detection (PoD)**: The likelihood that a technology can detect a methane release given variables which could include release rate, windspeed, distance from measurement to source, etc. PoD is typically visualized as a logistic regression curve ("S" shaped curve) and constructed via controlled release testing.
- **Facility**: The overarching primary surface location. May include satellite locations referred to as sites. The facility requires FEMP monitoring under AER Directive 060.
- **Site**: The unique surface locations which fall under the scope of alt-FEMPs. Includes main facility locations and any satellite locations. Individual satellite sites do not require FEMP monitoring under AER Directive 060. "Site" will be used to describe the most granular location in LDAR-Sim modelling.

Introduction

The ever-increasing global concern over methane emissions and their significant contribution to climate change has prompted a wave of innovation to create technologies that can detect and measure (quantify) methane emissions, which are invisible to the human eye. Advances in sensing technology, deployment platforms, work practices, and analytics have paved the way for a better understanding of emission sources and their impact. Currently, over 200 methane detection solutions have appeared ranging from handheld systems to satellites, stationary lasers to drones, sensors mounted on trucks and piloted aircraft. These technologies offer a diversity of services and data products that span many orders of magnitude in spatial and temporal resolution, making it challenging to evaluate their effectiveness compared to “standard” methods like optical gas imaging (OGI) and portable analyzers.

In this report, Highwood Emissions Management (Highwood) analyzed various standard FEMP scenarios and modeled what a generic alt-FEMP program would need to be to produce equivalent outcomes. The primary tool used to carry out this evaluation was the open-sourced model, the Leak Detection and Repair Simulator (LDAR-Sim) and how these equivalencies are communicated is through a series of equivalency matrices.

The first step of this modeling exercise was to parametrize emissions behavior, encompassing aspects like emission rate, frequency, and type (fugitive or “routine” emissions) within the LDAR-Sim “virtual world”. The objective of the virtual world parameterization was to construct emissions profiles that faithfully mirror typical emissions characteristics encountered in Alberta. Parameterizing the virtual world was completed using peer-reviewed studies and emissions data collected in Alberta, provided by the AER. The second step involved defining the deployment criteria of alternative methane detection programs which would allow them to achieve emissions reduction equivalency with standard method-based programs. This evaluation was completed for two sensor platform types (stationary and mobile) and considered technology sensitivity, deployment frequency, and the ability for a method to quantify emission rates. This investigation considered various standard FEMP scenarios.

Equivalency Matrices

The following section presents the methane emission reductions equivalency matrices built using the results of LDAR-Sim modelling. Central to the creation of these matrices is the concept of emissions reduction equivalency; it must be established that an alternative program can mitigate at least as much as the comparable standard FEMP scenario for the alternative program to be considered equivalent. LDAR-sim was used to test if the modeled alternative programs achieved this emissions reduction equivalency. LDAR-Sim modelling sees potential alternative programs and standard FEMP scenarios applied to sites in the LDAR-Sim "virtual world" where they mitigate fugitive methane emissions. LDAR-Sim model outputs include emissions mitigation values, which are then used to establish which alternative programs are equivalent with which standard FEMP scenario (the current AER D060 program is modeled as well as potential standard FEMP scenario). The behavior of the scenarios and the emissions in the virtual world are all based on empirical, Alberta specific data and discussed further in this report.

Alternative programs can take on many forms, and comparing the potential emissions reductions of the wide range of possible alternative program work practices to standard FEMP programs is difficult. To tackle this problem, alternative programs are broken down into 5 key components:

- **Method type**: Is the primary alternative method in the program "mobile" (methane detection and potentially quantification technology mounted on a vehicle like a truck, aircraft, drone, or satellite) or "stationary" (methane detection and potentially quantification permanently installed at the site requiring methane monitoring)?
- **Probability of detection**: What is the CH_4 emission rate that will be detected 90% of the time by the alternative method under standard operating conditions? (what is the 90% probability of detection). Must be established via controlled release testing.
- **Quantification**: Is the alternative method capable of emission rate quantification? Methods capable of quantification must have a mean relative quantification error ranging from -40% to +100% under typical operating conditions. This range of acceptable quantification error is based on controlled release testing of stationary methods at the Methane Emissions Technology Evaluation Center (METEC) under the Advanced Development of Emissions Detection (ADED) protocol where it was found that the mean quantification error

of the tested solutions was -40% to +93% for rates 1 kg CH_4/hr or above.[2] Mean quantification error must be established via controlled release testing.

- **Screening frequency**: How often does the alternative method screen sites within scope of the alternative program? (mainly relevant for mobile solutions).
- **Follow-up**: What is the follow-up work practice for sites which are flagged during alternative method screenings?

Highwood, via simulation modelling, explored practical combinations of these 5 key components to create a range of alternative programs which are emissions reduction equivalent to standard FEMP scenarios, standard method based programs and has presented these equivalent alternative programs in a series of equivalency matrices. If an alt-FEMP applicant follows one of the allowable alternative programs based on the detection and quantification performance of the alternative method (which is recommended to be verified by the AER), the LDAR-Sim modelling results show the alternative program will achieve equivalent emissions reductions to the standard FEMP program. Other considerations for ultimate alt-FEMP approval are outside the scope of this report, but Highwood will provide recommendations where applicable.

All LDAR-Sim model inputs and assumptions are detailed in later sections of this report. The equivalency matrices are preceded by a flowchart intended to guide the reader / alt-FEMP applicant to the appropriate equivalency matrix. It is recommended the flowchart is referenced prior to the equivalency matrices. Further guidance on interpreting the flowchart and equivalency matrices will precede each item.

1.1. Equivalency Matrix Flowchart

The flowchart shown in Figure 1 is intended to be referenced prior to viewing the associated equivalency matrix for the alternative method in question and is intended to be read left to right. The reader / alt-FEMP applicant must answer the following questions when working through the flowchart:

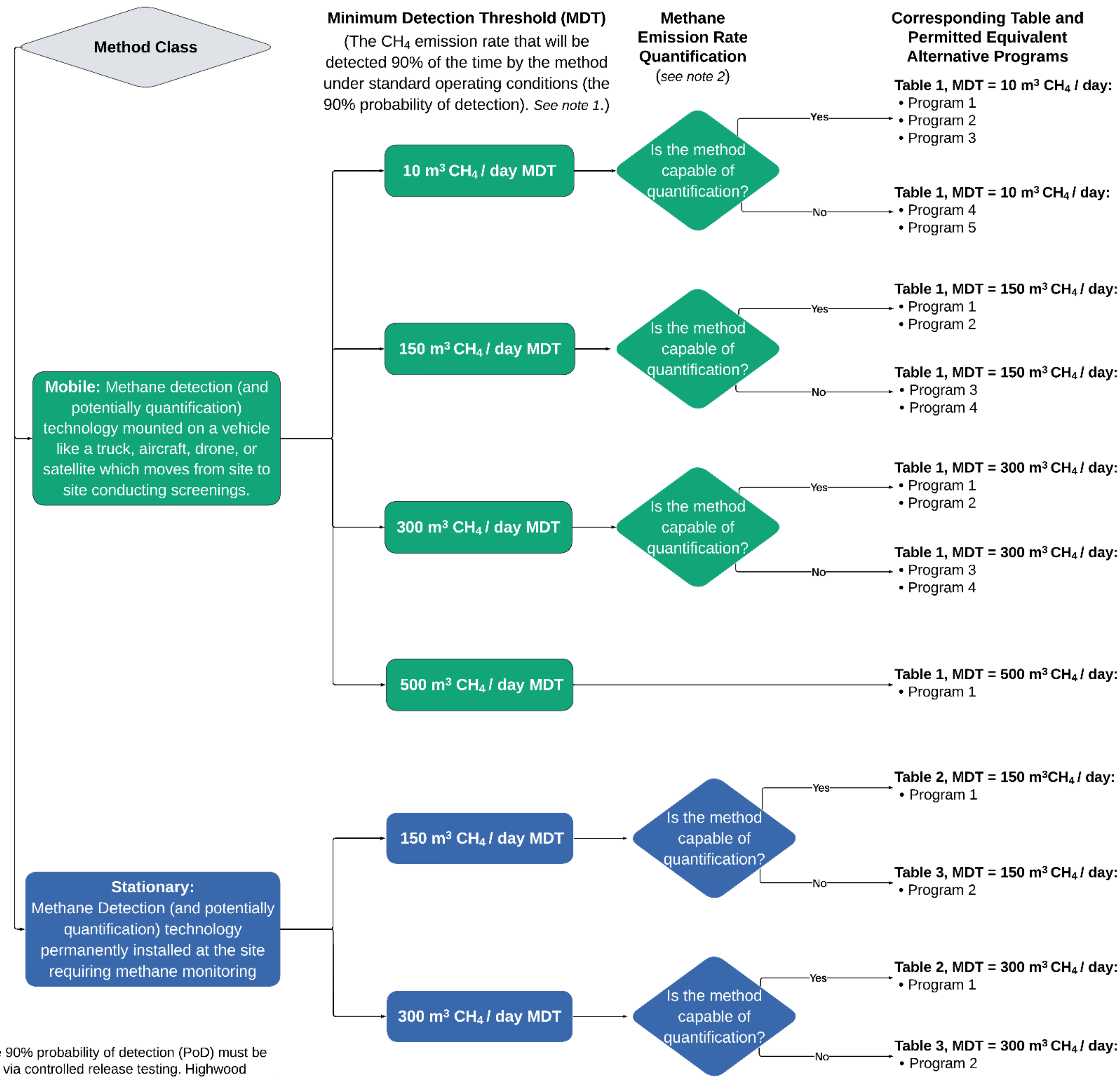
1. Is the alternative method mobile or stationary?

[2] Bell, C., Ilonze, C., Duggan, A., & Zimmerle, D. (2023). Performance of Continuous Emission Monitoring Solutions under a Single-Blind Controlled Testing Protocol. *Environmental Science & Technology*, *57*(14), 5794-5805.

2. What is the CH_4 emission rate that will be detected 90% of the time by the alternative method under standard operating conditions? **The 90% probability of detection values in the flowchart can be thought of as "<=" until the next most sensitive option**. For example, if a mobile method has a 90% probability of detection of 130 m^3 CH_4/ day, it must follow the 150 m^3 CH_4/ day flowchart option. It is not until a method can prove equivalent or better probability of detection of the next more-sensitive probability of detection option before the applicant can follow that flowchart option.
3. Is the alternative method capable of emission rate quantification?

Given the answers to these questions, the reader / alt-FEMP applicant will be directed to a Table (equivalency matrix) from this report and an associated range of alternative programs that must be followed to achieve emissions reduction equivalency with the given standard FEMP conditions.

This process of using the Figure 1 flowchart can be explained through an example scenario. Let us assume an alt-FEMP applicant is interested in building an alternative program around a mobile method with a 90% probability of detection at 90 m^3 CH_4/ day which *is* capable of quantifying emission rates. Based on these criteria, the applicant would be directed to Table 1, where they can choose from "program 1" and "program 2" for methods with a 90% probability of detection of <= 150 m^3 CH_4/ day. Further details on why multiple choices of alternative program are occasionally available will be provided before each equivalency matrix.



Note 1: The 90% probability of detection (PoD) must be established via controlled release testing. Highwood recommends AER verify provided controlled release testing results

Note 2: A Method can be classified as "capable of quantification" if it can demonstrate a mean relative quantification error ranging from −40% to +100% under typical operating conditions for methane emissions rates > 1 kg/hr.

Figure 1. Equivalency Matrices Flowchart. Readers / alt-FEMP applicants work left to right through the flowchart to be directed to the appropriate equivalency matrix based on the alternative method they wish to build their alt-FEMP around.

1.2. Equivalency Matrix Background

The following concepts are helpful when interpreting the equivalency matrixes presented in Sections 1.3 and 1.4.

- Each row in Tables 1-3 represents the minimum requirements of an alternative program which can be followed based on the 90% probability of detection (MDT) of the applicant method to achieve emissions reduction equivalency with the comparison standard FEMP program.
- Multiple standard FMEP scenarios are presented as columns in the matrices. The alternative program work practice will vary to achieve equivalence with the different standard FEMP scenarios:
    - **Current AER D060 requirements**: The current FEMP regulations as laid out in AER D060 Section 8.10.
    - **Scenario 2**: A standard FEMP scenario in which all facilities which currently require a single annual survey will increase to requiring 2 annual surveys, and all facilities which currently require 3 annual surveys will increase to 4 annual surveys.
    - **Scenario 3**: A standard FEMP scenario in which all facilities will require 4 annual surveys.

1.3. Table 1: Equivalency Matrix for Mobile Methods

Table 1: Equivalency Matrix for Mobile Methods Background:

Modelling conducted to construct this equivalency matrix saw the deployment of mobile method-based programs and comparison standard FEMP scenarios across a representative infrastructure of Alberta site types. More detail is provided in Section 1.6.2, but at a high level this means that as 27.8% of active Alberta facilities are single oil well batteries (calculated via data wrangling of public Alberta facility data), 27.8% of modeled sites are single oil well batteries, and these single oil well batteries will behave differently from an emissions perspective than other site types (compressor stations, gas plants, etc.).

For each given alternative method's probability of detection, multiple equivalent alternative programs are made available to the applicant so they can choose a work practice which best suits their needs. These equivalent alternative program work practices see trade-offs between screenings frequency, follow-up work practice, and the presence or absence of additional OGI surveys.

Highwood recommends that the regulatory application process sees verification of the MDT (90% probability of detection) and the mean quantification error of applicant alternative mobile methods.

Table 1: Equivalency Matrix for Mobile Methods Key Definitions:

- Minimum Detection Threshold (MDT): The CH_4 emission rate that will be detected 90% of the time by the method under standard operating conditions (the 90% probability of detection).
- The mobile equivalency matrix includes 4 potential follow-up work practices.
    - ***Follow-up at top X% of emitting (flagged) sites***: After each screening round, all flagged sites must be ranked by the measured site-level emission rate (highest to lowest) and the top X% of emitting (flagged) sites must receive follow-up within 21 days. This follow-up work practice is only present in alternative program work practices based around mobile alternative methods which can quantify emission rates (quantification is necessary to rank the flagged sites).
    - ***Follow-up at all emitting flagged sites:*** After each screening round, all flagged sites must receive follow-up within 21 days. This follow-up work practice is only present in alternative programs based on mobile alternative methods which cannot quantify emission rates (flagged sites cannot be ranked by emission rate).
    - ***Immediate follow-up at sites with sources above Y m^3 of CH_4 /day***: Alternative methods with a 90% probability of detection <= 10m^3 of CH_4/day and the capability to quantify emission rates have the option to follow-up at the top X% of emitting (flagged) sites (see above definition) or immediately follow-up all sites with a site-wide emission rate >Y m^3 of CH_4/day. This choice of work practice is only available to the most sensitive mobile alternative methods (90% probability of detection <= 10m^3 of CH_4/day) as they can detect such a larger relative proportion of emissions that selectively ranking them will still allow for substantial emissions mitigation. If the immediate follow-up option is chosen, all sites with a site-level emission rate > Y m^3 of CH_4 /day must receive a follow-up the same day as the screening (in practice, this requires the screening method crews to have an OGI camera or portable analyzer with them to perform immediate follow-up).
    - ***Follow-up at 20% of total sites***: After each screening round, 20% of all sites must receive a follow-up (not just 20% of emitting/flagged sites). If the screening flagged >20% of sites, the top 20% of emitters must receive a follow-up (note that this work practice is only available to alternative method's capable of quantifying emission rates). If the screening flagged < 20% of sites, the minimum follow-up requirement must be followed, see next definition.

- ***Minimum Follow-up Requirement (20% of sites)*:** In alternative programs which note "minimum follow-up requirement must be met", after each screening performed, at least 20% of total sites must receive a follow-up regardless of the results of the screening. The minimum follow-up requirement comes into play if screening flags <20% of sites. In this case, all sites which were flagged must receive a follow-up and additional sites must be surveyed with an OGI camera to meet the minimum follow-up requirement. These additional ("make-up") OGI surveys must prioritize site types known to be prone to larger and more frequent emissions. This prioritization order is gas plants → compressor stations → multi well pads → single well pads. This prioritization was established via data analysis necessary for LDAR-Sim model parameterization. For example, let us assume a scope of 100 sites under an alt-FEMP based on a mobile alternative method with a 90% probability of detection <= 150m^3 of CH_4/day and the ability to quantify emissions. If during a given screening, 10 sites (10%) are flagged, those 10 sites must receive a follow-up. In addition, 10 more sites must receive an OGI survey. While these 10 additional sites are chosen by the operator, the operator must prioritize surveying, in order, gas plants → compressor stations → multi well pads → single well pads.

- **Regarding all follow-up work practices**: Follow-ups are to be carried out as per AER Directive 060 Section 8.10.2.2 (follow-ups can be thought of as having the same requirements as the currently existing AER D060 FEMP surveys, an OGI camera or portable analyzer is required), except for the "***Immediate follow-up at sites with sources above Y m^3 of CH_4 /day***" work practice. In this case, as the follow-up is required to occur on the same day as the screening, a first attempt at localizing and diagnosing the flagged emission can be made with an Audio Visual Olfactory (AVO) survey in combination with any other supporting data (screening data, SCADA data, etc.). If the emission cannot be localized and diagnosed by the supported AVO survey, the requirements of AER Directive 060 Section 8.10.2.2 must be followed.

Table 1. Equivalent alternative programs based on mobile alternative methods when compared to various scenarios.

Alternative Mobile Method	Alternative Program Equivalent with Current AER D060 Regulations	Alternative Program Equivalent with Scenario 1 *3x per year → 4x per year* *1x per year → 2x per year*	Alternative Program Equivalent with Scenario 2 *3x per year → 4x per year* *1x per year → 4x per year*
10 m^3 of CH_4/day MDT Program 1 (Quantification)	**Screenings at the same frequency as current AER D060 program** (either annual or triannual depending on facility type). Follow-up required at *top 50% of emitting (flagged) sites* per screening or *immediate follow-up* at sites with sources above 100 m^3 of CH_4 /day.	**Screenings at the same frequency as scenario 1** (either 2x or 4x annual screenings depending on facility type). Follow-up required at *top 50% of emitting (flagged) sites* per screening or *immediate follow-up* at sites with sources above 100 m^3 of CH_4 /day.	**Screening 4x per year**. Follow-up required at *top 75% of emitting (flagged) sites* per screening or *immediate follow-up* at sites with sources above 100 m^3 of CH_4 /day.
10 m^3 of CH_4/day MDT Program 2 (Quantification)	**Screening 2x per year**. Follow-up required at *top 75% of emitting (flagged) sites* per screening or *immediate follow-up* at sites with sources above 100 m^3 of CH_4 /day.	**Screening 3x per year.** Follow-up required at *top 75% of emitting (flagged) sites* per screening or *immediate follow-up* at sites with sources above 100 m^3 of CH_4 /day.	**Screening 4x per year**. Follow-up required at *top 75% of emitting (flagged) sites* per screening or *immediate follow-up* at sites with sources above 100 m^3 of CH_4 /day.
10 m^3 of CH_4/day MDT Program 3 (Quantification)	**Screening 3x per year.** Follow-up required at *top 50% of emitting (flagged) sites* per screening or *immediate follow-up* at sites with sources above 150 m^3 of CH_4 /day.	**Screening 4x per year.** Follow-up required at *top 50% of emitting (flagged) sites* per screening or *immediate follow-up* at sites with sources above 150 m^3 of CH_4 /day.	**Screening 5x per year.** Follow-up required at *top 50% of emitting (flagged) sites* per screening or *immediate follow-up* at sites with sources above 150 m^3 of CH_4 /day.
10 m^3 of CH_4/day MDT Program 4 (Non-Quantification)	**Screenings at the same frequency as current AER D060 program** (which varies with facility type). Follow-up required at *all emitting (flagged) sites*.	**Screenings at the same frequency as scenario 1** (which varies with facility type). Follow-up required at *all emitting (flagged) sites*.	**Screening 4x per year.** Follow-up required at *all emitting (flagged) sites*.

Alternative Mobile Method	Alternative Program Equivalent with Current AER D060 Regulations	Alternative Program Equivalent with Scenario 1 *3x per year → 4x per year* *1x per year → 2x per year*	Alternative Program Equivalent with Scenario 2 *3x per year → 4x per year* *1x per year → 4x per year*
10 m³ of CH_4/day MDT Program 5 (Non-Quantification)	**Screening 2x per year.** Follow-up required at *all emitting (flagged) sites*.	**Screening 3x per year**. Follow-up required at *all emitting (flagged) sites*.	**Screening 4x per year**. Follow-up required at *all emitting (flagged) sites*.
150 m³ of CH_4/day MDT Program 1 (Quantification)	**Screening 3x per year.** Follow-up required at *20% of total sites* per screening, prioritizing top emitting (flagged) sites. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 4x per year**. Follow-up required at *20% of total sites* per screening, prioritizing top emitting (flagged)sites. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 6x per year.** Follow-up required at *20% of total sites per screening*, prioritizing top emitting sites. *Minimum follow-up requirement (20% of sites)* must be met.
150 m³ of CH_4/day MDT Program 2 (Quantification)	**Screening 2x per year + Annual OGI**. Follow-up required at *20% of total sites* per screening, prioritizing top emitting (flagged) sites. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 3x per year + Annual OGI**. Follow-up required at *20% of total sites* per screening, prioritizing top emitting (flagged) sites. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 4x per year + Annual OGI**. Follow-up required at *20% of total sites* per screening, prioritizing top emitting (flagged) sites. *Minimum follow-up requirement (20% of sites)* must be met.
150 m³ of CH_4/day MDT Program 3 (Non-Quantification)	**Screening 3x per year.** Follow-up required at *all emitting (flagged) sites*. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 4x per year**. Follow-up required at *all emitting (flagged) sites*. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 6x per year.** Follow-up required at *all emitting (flagged)sites*. *Minimum follow-up requirement (20% of sites)* must be met.

Alternative Mobile Method	Alternative Program Equivalent with Current AER D060 Regulations	Alternative Program Equivalent with Scenario 1 *3x per year → 4x per year* *1x per year → 2x per year*	Alternative Program Equivalent with Scenario 2 *3x per year → 4x per year* *1x per year → 4x per year*
150 m³ of CH_4/day MDT Program 4 (Non-Quantification)	**Screening 2x per year + Annual OGI**. Follow-up required at *all emitting (flagged) sites*. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 3x per year + Annual OGI**. Follow-up required at *all emitting (flagged) sites. Minimum follow-up requirement (20% of sites)* must be met.	**Screening 4x per year + Annual OGI**. Follow-up required at *all emitting (flagged) sites. Minimum follow-up requirement (20% of sites)* must be met.
300 m³ of CH_4/day MDT Program 1 (Quantification)	**Screening 4x per year.** Follow-up required at *20% of total sites* per screening, prioritizing top emitting (flagged) sites. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 6x per year**. Follow-up required at *20% of total sites* per screening, prioritizing top emitting (flagged)sites. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 8x per year.** Follow-up required at *20% of total sites* per screening, prioritizing top emitting sites. *Minimum follow-up requirement (20% of sites)* must be met.
300 m³ of CH_4/day MDT Program 2 (Quantification)	**Screening 3x per year + Annual OGI**. Follow-up required at *20% of total sites* per screening, prioritizing top emitting (flagged) sites. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 4x per year + Annual OGI**. Follow-up required at *20% of total sites* per screening, prioritizing top emitting (flagged) sites. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 6x per year + Annual OGI**. Follow-up required at *20% of total sites* per screening, prioritizing top emitting (flagged) sites. *Minimum follow-up requirement (20% of sites)* must be met.
300 m³ of CH_4/day MDT Program 3 (Non-Quantification)	**Screening 4x per year.** Follow-up required at *all emitting (flagged) sites. Minimum follow-up requirement (20% of sites)* must be met.	**Screening 6x per year**. Follow-up required at *all emitting (flagged) sites. Minimum follow-up requirement (20% of sites)* must be met.	**Screening 8x per year.** Follow-up required at *all emitting (flagged) sites. Minimum follow-up requirement (20% of sites)* must be met.

Alternative Mobile Method	Alternative Program Equivalent with Current AER D060 Regulations	Alternative Program Equivalent with Scenario 1 *3x per year → 4x per year* *1x per year → 2x per year*	Alternative Program Equivalent with Scenario 2 *3x per year → 4x per year* *1x per year → 4x per year*
300 m^3 of CH_4/day MDT Program 4 (Non-Quantification)	**Screening 3x per year + Annual OGI**. Follow-up required at *all emitting (flagged) sites*. *Minimum follow-up requirement (20% of sites)* must be met.	**Screening 4x per year + Annual OGI**. Follow-up required at *all emitting (flagged) sites. Minimum follow-up requirement (20% of sites)* must be met.	**Screening 6x per year + Annual OGI**. Follow-up required at *all emitting (flagged) sites. Minimum follow-up requirement (20% of sites)* must be met.
500 m^3 of CH_4/day MDT Program 1 (Non-Quantification)	**Screening 8x per year + Annual OGI** with follow-up required at *all emitting (flagged) sites*	*Not equivalent*	*Not equivalent*

1.4. Tables 2 and 3: Equivalency Matrices for Stationary Methods

Tables 2 and 3: Equivalency Matrices for Stationary Methods background:

For a given alternative method (MDT and capability to quantify emissions) the equivalent alternative program will differ depending on if the site to be monitored requires annual or triannual surveys under the current AER D060 regulations. It is difficult to design an alternative program for stationary methods which can be unilaterally applied to all Alberta facility types (Alberta facility types refers to Table 4 of AER Directive 060) due to the nature of a typical stationary method deployment. While mobile methods typically rapidly screen many sites of differing type, stationary methods often see targeted deployment at a given facility type.

During the data analysis necessary for LDAR-Sim model parameterization, the Alberta facility types were grouped into somewhat broader categories than those presented in AER Directive 060 Table 4. These “LDAR-Sim Subtypes” (further details in Section 1.6) are: Oil Multiwell Battery, Oil Multiwell Battery (with controlled tanks), Oil Single-Well Battery, Gas Multiwell Battery, Gas Single-Well Battery, Compressor Station, Gas Plant, and Other. Each of these subtypes were parameterized with unique emission behavior. In modelling, the stationary method-based program was compared to the standard FEMP scenario where each modeled site was one of these LDAR-Sim subtypes. For example, a simulation was run in which all sites were Oil Single-Well Batteries, another was run in which each modeled site was a gas plant, etc. While equivalency was investigated for each subtype, Highwood elected to streamline the equivalency matrices by presenting the site type as either “triannual” or “annual”, for example, the equivalent stationary based programs for triannual sites are those which were found to be equivalent to each of the individual LDAR-Sim subtypes which currently require triannual surveys.

Highwood recommends that the regulatory application process sees verification of the MDT (90% probability of detection) and the mean quantification error of applicant alternative mobile methods. In addition, Highwood recommends the AER require a well-documented alerting work practice from stationary-based alternative program alt-FEMP applicants. Stationary method alerting work practices are complex and must consider: at what emission rate does an alert occur? How long does this given rate need to occur? What background is this anomalous rate applied to? Is this background continuously updated? Furthermore, point sensor methods (Qube, Project Canary) will handle alerting differently than continuous-OGI solutions (Kuva, Clean Connect). Highwood recommends the provided alerting work practice refer to known emissions (rates, frequency) at the facility to be monitored or similar facility. Defining a stationary alerting work practice is outside the scope of this report and LDAR-sim modelling capabilities. LDAR-Sim assumes the stationary method "knows" the background emission rate and an alert is generated each day the site level emission rate is larger than the stationary method's MDT.

Tables 2 and 3: Equivalency Matrices for Stationary Methods key definitions:

Periodic Follow-up: Operators must check detection events generated through the Stationary method every X days to list flagged sites that require follow-up. In practice, this means that every X days, operators will check all detection events (typically sent directly to the operator or logged in continuous monitoring data/dashboards) since the last follow-up round and investigate new emissions sources. Periodic follow-ups must be carried out as per AER Directive 060 Section 8.10.2.2 (periodic follow-ups can be thought of as having the same requirements as the currently existing AER D060 FEMP surveys, an OGI camera or portable analyzer is required)

Large Emitter Follow-up: Sites in which the stationary method registers a detection event >500m^3 of CH_4/day must receive follow-up within 30 days of the first alert. Note that programs with this work practice require the stationary method to be able to quantify emission rates. For Large Emitter Follow-ups, a first attempt at localizing and diagnosing the flagged emission can be made with an Audio Visual Olfactory (AVO) in combination with any other supporting data (screening data, SCADA data, etc.). If the emission cannot be localized and diagnosed by the supported AVO survey, the requirements of AER Directive 060 Section 8.10.2.2 must be followed.

Table 2. Equivalent alternative programs based on stationary alternative methods which are capable of emission rate quantification when compared to various scenarios.

Alternative Stationary Method	Current Facility AER D060 Survey Frequency Requirement	Alternative Program Equivalent with Current AER D060 Regulations	Alternative Program Equivalent with Scenario 1 *3x per year → 4x per year* *1x per year → 2x per year*	Alternative Program Equivalent with Scenario 2 *3x per year → 4x per year* *1x per year → 4x per year*
150 m^3 of CH_4 /day MDT Program 1 (Quantification)	3x per year	**Periodic follow-up** every 120 days (3x per year) + **Large emitter follow-up** (>500m^3 of CH_4/day) in up to 30 days.	**Periodic follow-up** every 90 days (4x per year) + **Large emitter follow-up** (>500m^3 of CH_4/day) in up to 30 days.	**Periodic follow-up** every 90 days (4x per year) + **Large emitter follow-up** (>500m^3 of CH_4/day) in up to 30 days.
	1x per year	**Periodic follow-up** every 360 days (1x per year) + **Large emitter follow-up** (>500m^3 of CH_4/day) in up to 30 days.	**Periodic follow-up** every 180 days (2x per year) + **Large emitter follow-up** (>500m^3 of CH_4/day) in up to 30 days.	**Periodic follow-up** every 60 days (6 per year) + **Large emitter follow-up** (>500m^3 of CH_4/day) in up to 30 days.
300 m^3 of CH_4 /day MDT Program 1 (Quantification)	3x per year	**Periodic follow-up** every 120 days (3x per year) + **Large emitter follow-up** (>500 m^3 of CH_4/day) in up to 30 days. + **Annual OGI**	**Periodic follow-up** every 90 days (4x per year) + **Large emitter follow-up** (>500 m^3 of CH_4/day) in up to 30 days. + **Annual OGI**	**Periodic follow-up** every 90 days (4x per year) + **Large emitter follow-up** (>500 m^3 of CH_4/day) in up to 30 days. + **Annual OGI**
	1x per year	**Periodic follow-up** every 360 days (1x per year) + **Large emitter follow-up** (>500m^3 of CH_4/day) in up to 30 days + **Annual OGI**	**Periodic follow-up** every 180 days (2x per year) + **Large emitter follow-up** (>500m^3 of CH_4/day) in up to 30 days + **Annual OGI**	**Periodic follow-up** every 60 days (6x per year) + **Large emitter follow-up** (>500m^3 of CH_4/day) in up to 30 days. + **Annual OGI**

Table 3. Equivalent alternative programs based on stationary alternative methods which are not capable of emission rate quantification when compared to various scenarios.

Alternative Stationary Method	Current Facility AER D060 Survey Frequency Requirement	Alternative Program Equivalent with Current AER D060 Regulations	Alternative Program Equivalent with Scenario 1 *3x per year → 4x per year* *1x per year → 2x per year*	Alternative Program Equivalent with Scenario 2 *3x per year → 4x per year* *1x per year → 4x per year*
150 m3 of CH_4/day MDT Program 2 (Non-Quantification)	3x per year	**Periodic follow-up** every 90 days (4x per year)	**Periodic follow-up** every 60 days (6x per year)	**Periodic follow-up** every 60 days (6x per year)
	1x per year	**Periodic follow-up** every 180 days (2x per year)	**Periodic follow-up** every 90 days (4x per year)	**Periodic follow-up** every 30 days (12x per year) **+Annual OGI**
300 m3 of CH_4/day MDT Program 2 (Non-Quantification)	3x per year	**Periodic follow-up** every 90 days (4x per year) **+Annual OGI**	**Periodic follow-up** every 60 days (6x per year) **+Annual OGI**	**Periodic follow-up** every 60 days (6x per year) **+Annual OGI**
	1x per year	**Periodic follow-up** every 180 days (2x per year) **+Annual OGI**	**Periodic follow-up** every 90 days (4x per year) **+Annual OGI**	**Periodic follow-up** every 30 days (12x per year) **+Annual OGI**

LDAR-Sim Overview

1.5. LDAR-Sim Overview

LDAR-Sim was used to compare various alternative programs with existing and other standard FEMP scenarios. 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 FEMPs 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 FEMPs, 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 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-wide weather data was used. All relevant LDAR-Sim information can be found on the LDAR-Sim GitHub page and a detailed description of LDAR-Sim can be found in Fox et al. 2019.[3,4]

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/behavior of the LDAR and alt-LDAR programs and methods (technology minimum detection threshold, travel speed, survey speed, operational weather envelopes, etc.). A full breakdown of LDAR-Sim operation and parameterization is outside this scope of this report; however, this section will describe the most relevant parameters to the modelling used to create the equivalency matrices presented in Sections 1.3 and 1.4.

Figure 2 presents a graphical overview of the LDAR-Sim virtual world, the programs which are applied to this virtual world and some of the parameters which inform both.

[3] LDAR-Sim GitHub page.
[4] Fox, T. A. et al. A methane emissions reduction equivalence framework for alternative leak detection and repair programs. Elem. Sci. Anthr. 7, 30 (2019)

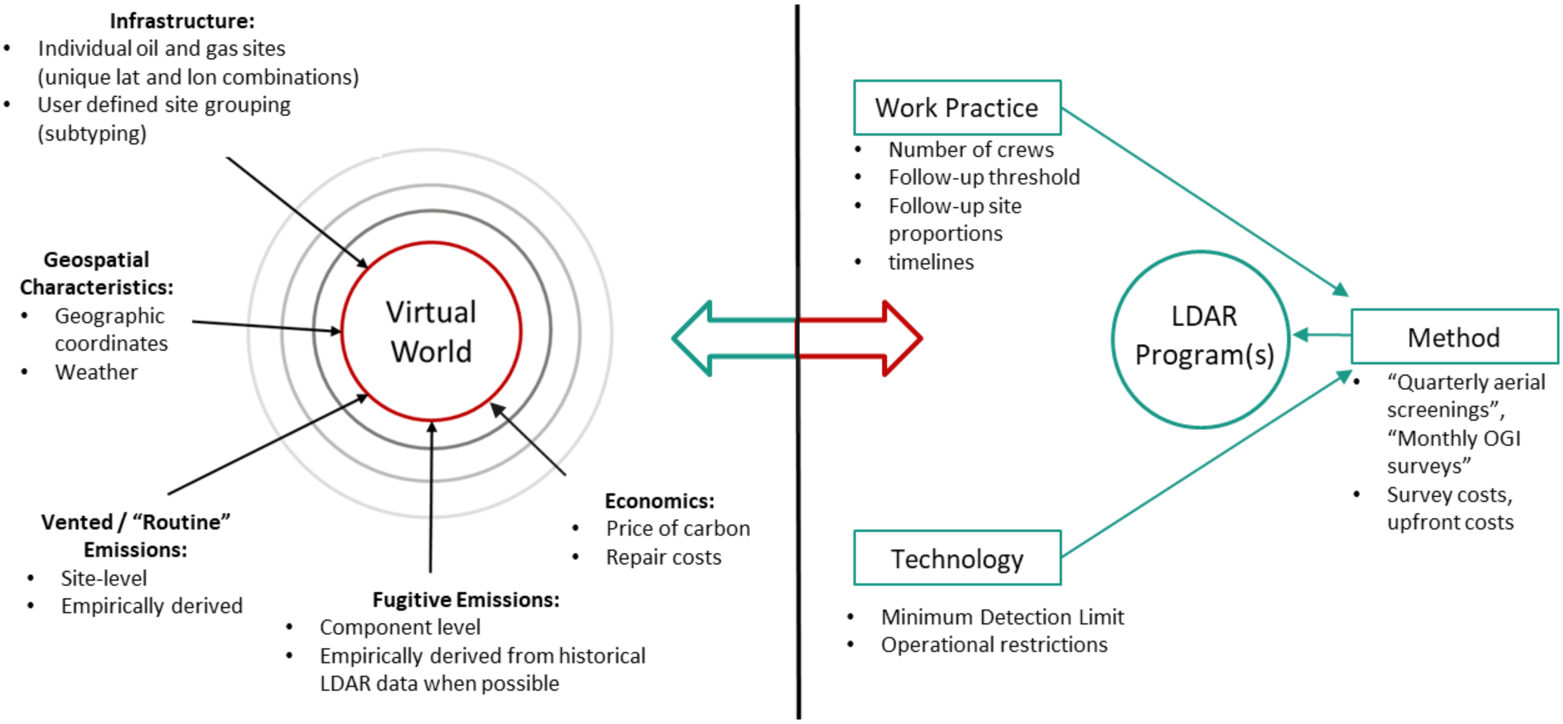


Figure 2: LDAR-Sim virtual world and program interaction. All bullet points are informed by the LDAR-Sim user using empirically derived data specific to the region and infrastructure being simulated whenever possible.

Figure 3 presents an overview of the processes which occur during each day of the simulation.

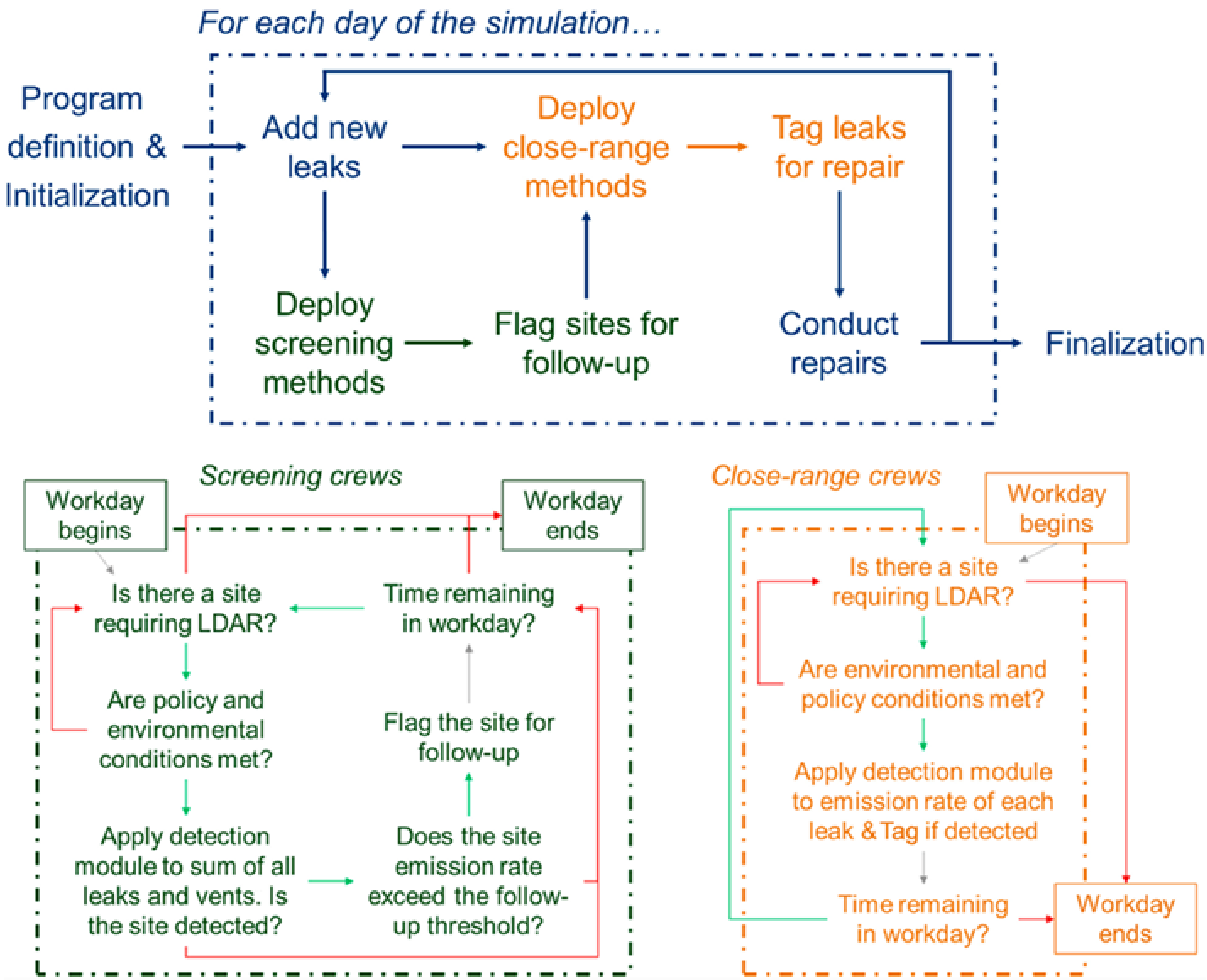


Figure 3: A detailed overview of the processes which occur in LDAR-Sim simulations each day of the simulated time, modified from Fox et al. 2019[3]. In the LDAR-Sim modelling undertaken to establish emissions reduction equivalency of alternative programs, screening methods (green text and arrows) are represented by “mobile” and “stationary” methods while close range surveys (orange text and arrows) are represented by OGI surveys.

1.6. LDAR-Sim Inputs and Assumptions

Sections 1.6.1 to 1.6.5 present an overview of the model inputs known by experienced modelers to have the most marked impact on model results.

1.6.1. Data Overview

A list of the data sources used to inform various model inputs follows:

- AER Alberta activity facility list.
- Select AER alt-FEMP data from AER approved alt-FEMPs.
- Aerial surveillance emission rate measurements gathered during AER compliance screenings.
- Aerial screening emission rate measurements gathered for Conrad et al.[5]

1.6.2. Modeled Infrastructure

A key process in LDAR-Sim modelling is establishing the virtual world sites (see glossary) which can emit and will be screened and surveyed by the modeled programs. Whenever possible, the virtual world sites are informed by real-world counterparts (the virtual world sites mirror their real-world counterpart's subtype, location, and emissions characteristics). In addition to the unique modeled sites, establishing accurate subtyping is important. Subtyping allows the user to group sites based on shared characteristics, typically, shared emissions characteristics. In the model, sites belonging to a subtype will behave similarly, but distinct from sites belonging to a different subtype. A common example of two generic subtypes would be compressor stations and wellsites. For the modelling used to construct the equivalency matrices described in this report, a publicly available list of Alberta facilities hosted on the AER website[6] was used to inform the virtual world sites. The following data cleaning and wrangling processes were applied to this list:

1. Filter out non-active facilities.
2. Filter out facilities which do not require a FEMP program as per AER Directive 060 were considered.
3. Define each facility's "main facility", and unique location. LDAR-Sim requires a unique location and subtype for each modeled site and the available AER data occasionally had multiple co-located (at the same UWI) subtypes.

[5] Conrad, B., Tyner, D., Li, H., Xie, D., & Johnson, M. (2023). Measurement-Based Methane Inventory for Upstream Oil and Gas Production in Alberta, Canada Reveals Higher Emissions and Starkly Different Sources than Official Estimates.
[6] https://www.aer.ca/providing-information/data-and-reports/statistical-reports/st102

The main facility in a unique location was defined based on the co-located facility with the highest leak frequency. Leak frequency is defined in Section 1.6.4.. For example, if a compressor station and a battery were co-located in a site, the site would be classified as a compressor station. After this stage, the infrastructure consisted of individual “sites” (see glossary).

4. Define each site subtype. While the available AER data provided AER standard subtypes at each location, these subtypes are too granular for accurate modelling (not enough data is available to accurately inform the emissions behavior of each AER subtype). The AER Subtypes were grouped into LDAR-Sim subtypes which are summarized in Table 4.

Table 4. Site subtype proportion in simulation infrastructure.

Site Subtype (in LDAR-Sim)	D60 Subtype Code	Required Survey Frequency (Current D60)	Infrastructure Proportion
Compressor Stations	601,621	3**	21.6%
Gas Multiwell Battery	361,362,363,364	1	6.8%
Gas Plant	401	3	1.8%
Gas Single-Well Battery	351	1	19.2%
Oil Multiwell Battery	321,322,341,342	1	16.0%
Oil Multiwell Battery (w/ controlled tank)*	-	3	1.7%
Oil Single-Well Battery	311,331	1	27.8%
Other	*all others*	1	5.0%

* Through working sessions between the AER and Highwood, it was established that 1.7% of total sites have controlled tanks. It was assumed that these tanks are primarily present at oil multiwell batteries.
** Under AER D060, sour and sweet compressor stations have different survey frequency requirements, however, there was not sufficient available data to build out unique emissions behavior for these two subtypes. As ~80% of compressor stations are sweet facilities, they were assigned the “compressor station” site subtype and were assumed to require triannual surveys under the current AER D060.

5. Convert the UWI coordinated to latitude and longitude coordinates using an in-house program.

1.6.3. Emissions Size

Emissions size (emission rate) in the LDAR-sim virtual world is informed by empirical Alberta data. There are two categories of emissions in LDAR-Sim, leaks (fugitive emissions) and other emissions (“routine”, or “allowable” emissions). These emissions categories behave differently and the inputs from each are from different sources.

Leaks

Fugitive emissions in LDAR-Sim are informed by the Leak Rate Source. The Leak Rate Source can either be a statistical distribution fit to known leak rates, or a “raw” file of leak rates, both of which are randomly sampled from to inform the emission rate of randomly generated leaks. For this investigation, a raw file of leak rates was sampled from to inform simulated leak rates. Leaks in LDAR-Sim are component-level; therefore, a site can have more than one leak present at a given time. This can be important as most alternative methods have site-level measurements, so they will “see” the summation of all leaks at a site if there are multiple.

There is an accepted discrepancy between emission rates recorded via top-down and bottom-up methods. This discrepancy is highlighted in both peer reviewed studies (Tyner and Johnson (2021)[7], Johnson (2023)[8]) and the alt-FEMP and AER compliance screening data which was made available to Highwood for this modelling exercise. Tyner and Johnson (2021) show that tank emission measurements from aerial surveys (top-down) were ~37 times larger than measurements of those same tanks with OGI (bottom-up). Accurately representing this discrepancy in modelling is difficult. If the Leak Rate Source was constructed exclusively with bottom-up methods, the large sources typically captured by top-down methods would be missed, conversely, a Leak Rate Source constructed exclusively with top-down methods is limited by the MDT of the top-down method, which is consistently less sensitive than bottom-up methods MDTs, resulting in small individual emissions being omitted. These “small” emissions, while not as impactful as super-emitters, need to be considered. To represent both sources of measurement this modelling exercise saw a Leak Rate Source populated with measurements from both top-down and bottom-up methods.

The source of top-down measurements used was from the results of AER’s aerial surveillance completed 2019-2022. The source of bottom-up measurements was the records of all OGI follow-up surveys in which the source was measured (predominantly by quantitative OGI but occasionally by metering) in completed alt-FEMPs (AER alt-FEMP requirements call for record keeping around follow-up surveys). In the Leak Rate Source, 60% of leak rates are from bottom-up measurements and 40% are from top-down measurements. This ratio was used because of the findings of Johnson (2023) which stated that “*The ground team qualitatively observed vented emissions from 96% (26/27) of uncontrolled electric drive compressors, whereas only 37% (10/27) of these units were detected from the air, suggesting that non combustion compressor package emissions were captured in the aerial measurements ~40% of the time”.* This ratio of bottom-up to top-down emission rates was investigated through a sensitivity analysis.

Figure 4 shows the Leak Rate Source used in modelling compared to the “raw” AER compliance flyover measurements. For the purposes of visualization, Figure 4 shows the Leak Rate Source and the “raw” AER compliance flyover

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[7] Tyner, D. R., & Johnson, M. R. (2021). Where the methane is—Insights from novel airborne LiDAR measurements combined with ground survey data. *Environmental Science & Technology*, *55*(14), 9773-9783.
[8] Johnson, M. R., Tyner, D. R., & Conrad, B. M. (2023). Origins of oil and gas sector methane emissions: on-site investigations of aerial measured sources. Environmental Science & Technology, 57(6), 2484-2494.

measurements fit to lognormal distributions, visualized as cumulative density functions (CDFs), however, during modelling the Leak Rate Source is randomly sampled from, not fit to a distribution, and then sampled from. Sample from a file as opposed to fitting the emission rates to a distribution is based on the findings Rutherford et al, 2023. which state that in practice, most leak rate distributions do not fit to a lognormal or power law distribution[9].

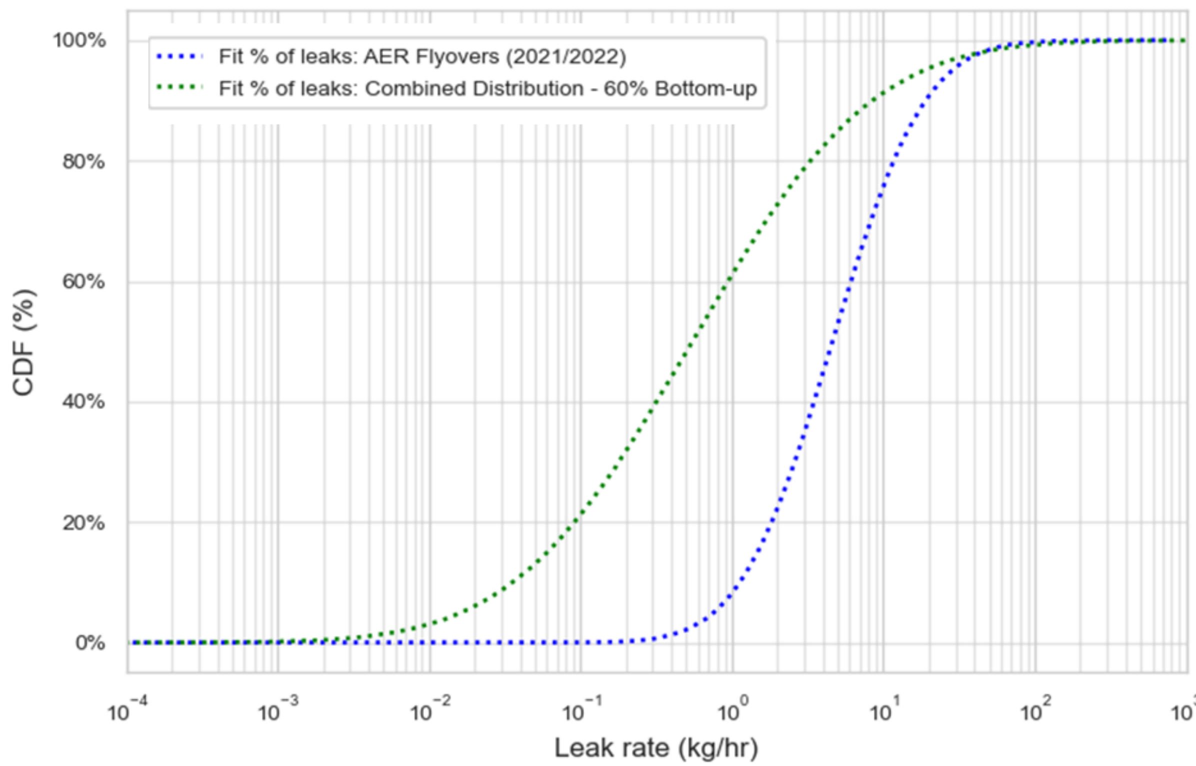


Figure 4: Emission rates fit to a lognormal distribution and visualized as a Cumulative Density Function (CDF). Blue curve: Original ("raw") AER compliance flyover measurements. Green curve: The Leak Rate Source used in modelling (40% top-down rates via AER compliance screening measurements and 60% bottom-up rates collected through alt-FEMPs) fit to a lognormal distribution. Combining bottom-up and top-down measurements (green curve) "pulls" the original distribution (blue curve) upwards into the left (there is a larger probability of an emission rate being small) but the large emission rates remain consistent. Note that in modelling the rates are not fit to a lognormal distribution, they are randomly sampled from.

To verify that the AER's compliance screening data is in line with other available top-down measurements, the AER compliance screening data was compared to the Bridger Photonics screening measurements, collected at 508 upstream oil and gas production sites in BC, Canada for Johnson et al, 2023. Figure 5 shows this comparison in which we can see

[9] Sherwin, E., Rutherford, J., Zhang, Z., Chen, Y., Wetherley, E., Yakovlev, P., & Cusworth, D. (2023). Quantifying oil and natural gas system emissions using one million aerial site measurements.

the two collections of measurements are very similar, with the measurements collected via AER compliance screenings slightly smaller than the measurements collected for Johnson et al, 2023.

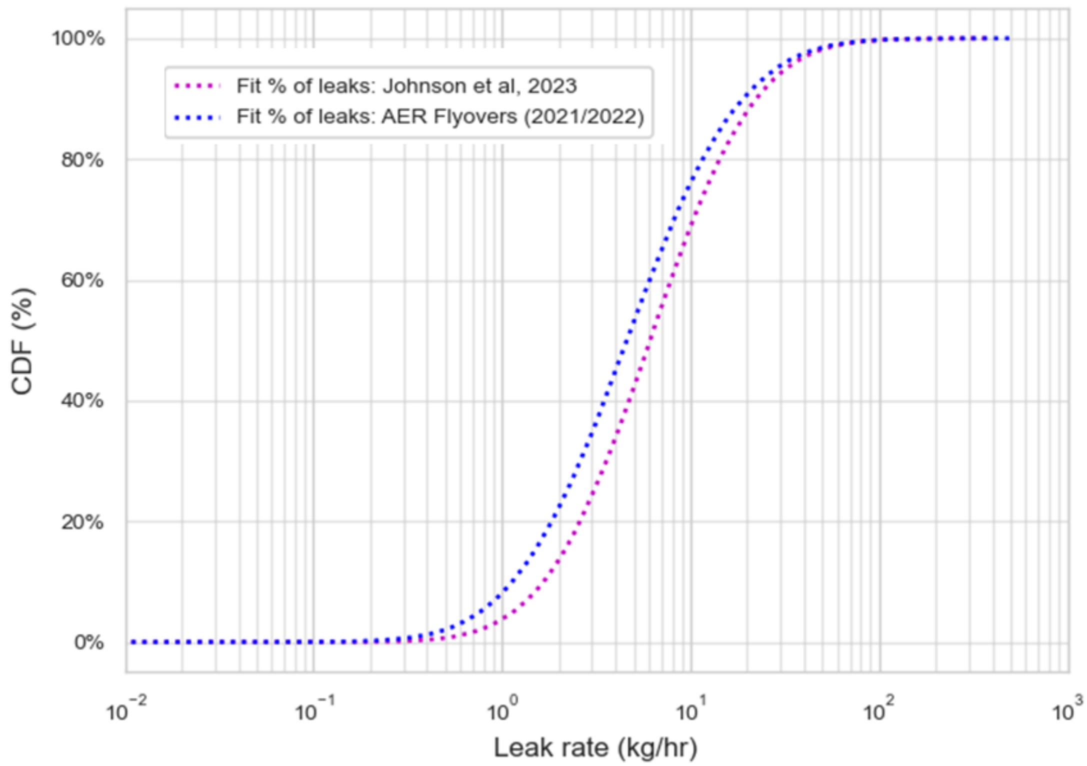


Figure 5: Emission rates fit to a lognormal distribution and visualized as a Cumulative Density Function (CDF). Blue curve: Original ("raw") AER compliance flyover measurements (Bridger Photonics). Pink curve: "raw" Bridger Photonics measurements collected for Johnson et al, 2023. The two leak rate sources are very similar with the AER compliance survey measurements being slightly "smaller", shown by the close-ness of the CDFs but the blue curve being slightly to the left of the pink curve. The AER compliance flyover measurements had a 60% chance of being smaller than 5 kg CH_4/hr while the Bridger Photonics measurements collected for Johnson et al, 2023 had a 60% chance of being smaller than 7 kg CH_4/hr.

The assumed bottom-up / top-down proportions of the Leak Rate Source of 60% and 40% respectively were investigated through a sensitivity analysis the results of which are shown in Figure 6.

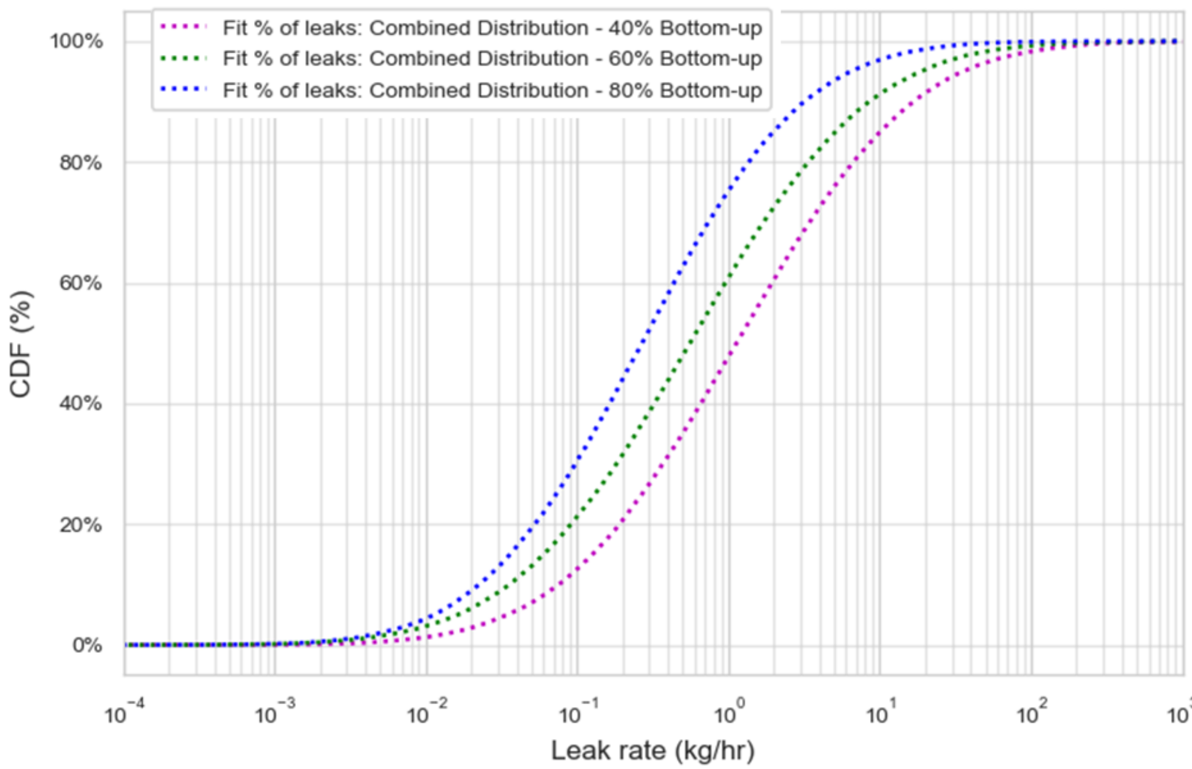


Figure 6: Emission rates fit to a lognormal distribution and visualized as a Cumulative Density Function (CDF). The curves show the sensitivity analysis of adjusting the proportion of top-down to bottom-up measurements in the Leak Rate Source. While the Leak Rate Source with the smallest proportion of bottom-up measurements (40%) is the "largest", it is not a wide enough margin for concern with this proportion-based approach to constructing the Leak Rate Source.

Intentional or Vented Emissions

Intentional or vented emissions in LDAR-Sim are informed by a tabular input, the Vent File. Intentional emissions are site-level, a single emission rate from the Vent File is sampled to inform the site's vented emission rate during a screening or survey. The emission rates which inform the Vent File are also sourced from the AER's compliance flyover screening data.

1.6.4. Emission Frequency

Leaks

Leak frequency is defined by the Leak Production Rate (LPR) LDAR-Sim parameter. The LPR is the probability a new leak will arise at a given site each day. Operational FEMP data from Alberta (routine OGI surveys) was used to calculate the

LPR for each of the modeled subtypes. These LPR values were verified against leak frequency values from public BC LDAR data[10], and they were found to be similar. Table 5 summarizes the calculated LPR values for the modeled subtypes.

Table 5. Leak Rate Production of the modeled subtypes

Site Subtype	Leaks (per site, per year)
Oil Multiwell Battery	0.17
Oil Multiwell Battery (with controlled tanks)	0.17
Oil Single-Well Battery	0.14
Gas Multiwell Battery	0.78
Gas Single-Well Battery	0.30
Compressor Station	3.21
Gas Plant	15.47

A sensitivity analysis included in the appendix which explores emissions mitigation if the LPR was 1.5x and 0.5x the values in Table 5.

Vented Emissions

During a screening or survey of a given site, there is a 25.8% chance that the site will be venting. This 25.8% chance is informed by a preprint by Conrad et al.[11] which collected top-down measurements of 3,454 unique Alberta facilities using Bridger Photonics. The preprint found that 34% of sites screened had an emission source above MDT, and 24% of these emission sources were classified as fugitive in nature. For example, in modelling, considering 100 sites, during a hypothetical screening, on average 34 of these sites will be emitting and 9 of these sites will have a fugitive emission.

Considering the assumption that all source emission rates (fugitive and venting) follow a similar distribution, we assume that 24% of all emission sources are fugitive in nature. Therefore, 8.2% of sites screened in the preprint had a fugitive emission source large enough to be detected by the MDT of the aerial detection method from the study (~4 kg CH_4/hr 90% PoD under standard operating conditions) and 25.8% were venting (that are detectable by the aerial detection method). In summary, during modeling, each time a site is screened or surveyed there is a 25.8% chance this site is

[10] BCER 2021 Equivalence Report.

[11] Conrad, B., Tyner, D., Li, H., Xie, D., & Johnson, M. (2023). Measurement-Based Methane Inventory for Upstream Oil and Gas Production in Alberta, Canada Reveals Higher Emissions and Starkly Different Sources than Official Estimates.

venting, and the venting rate is randomly sampled from the top-down measurements collected by the aerial detection technology used during AER compliance screenings.

1.6.5. Other Key Inputs

The most relevant parameters used in the modeling are described in the following list. This is a summarized version focused on important parameterizations to interpret simulation modelling results, a full list of LDAR-Sim inputs can be provided upon request.

- **Minimum Detection Threshold (MDT)**: The smallest methane emission rate a particular technology can detect. While as per AER Directive 060, the regulatory comparison programs can be completed with either an OGI camera or a portable analyzer, OGI cameras were exclusively modeled due to a better publicly available understanding of their detection capabilities. For OGI methods, the MDT was parameterized with a PoD curve informed by Zimmerle et al.[12]which accounts for operator experience and has a 95% PoD at an emission rate of 0.66 kg/hr. Zimmerle et al. represents the most comprehensive study on typical, handheld OGI detection capabilities. All alternative methods MDTs are a single value associated with the method's 90% CH_4 probability of detection established via controlled release testing.
- **Spatial coverage:** A representation of the average proportion of a facility a method can effectively survey. When the model is running, every time a new leak is created, a "weighted coin" is flipped representing a methods 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. This parameter is intended to represent locations on a facility where a method may have difficulty screening / surveying. The modelling conducted for this report assumed a coverage of 85% for comprehensive OGI surveys and 90% for alternative technologies (mobile and stationary methods). Alternative technologies were parametrized with higher spatial coverage due to their ability to detect sources that close-range surveys can typically miss (e.g., sources hidden from view). OGI follow-up methods were parametrized with 100% spatial coverage.

[12] Zimmerle, D., Vaughn, T., Bell, C., Bennett, K., Deshmukh, P., & Thoma, E. (2020). Detection limits of optical gas imaging for natural gas leak detection in realistic controlled conditions. *Environmental science & technology*, *54*(18), 11506-11514.

- **Repair Delay**: Time that a leak exists from being tagged to repair. This delay was estimated as 30 days, an assumed average between rapid repairs and larger repairs requiring facility shut down. Repair delay affects all programs equally, so it is moot from a mitigation comparison standpoint.

- **Natural Repair Delay**: Defines how long a leak will last at site before it is repaired by "natural causes" which could include: retrofits, operators finding leaks outside of the established LDAR program, etc. While it is commonly agreed that leaks do have a natural lifespan, very little empirical data is available to parameterize this lifespan and the natural repair delay input. An assumption of 1 year is used but investigated in sensitivity analysis of the Appendix of this report. Natural repair delay affects all programs equally, so it is moot from a mitigation comparison standpoint.

- **Deployment Cost:** The cost of an alternative method or OGI to conduct screenings / surveys. Cost does not play a role in the equivalency matrices but an investigation into assumed program cost is presented in Section 0. **Cost model inputs rely on assumptions agreed upon collaboratively between the AER and Highwood. Alternative mobile and stationary screening methods each assume a single cost, but in practice will vary based on the vendor. Furthermore, cost assumptions are from the date of publication and could change over time, potentially decreasing as technology deployment becomes better understood and optimized. Ultimately, true costs could vary greatly from the assumptions presented here.**

  - **OGI Methods:** Table 6 summarizes the assumed OGI costs (cost per survey) in Alberta.

Table 6: Assumed costs of OGI surveys at modeled Alberta subtypes

Subtype Site	Estimated Cost per Survey (CAD)
Single well Battery	$233
Multi well Battery	$1,438
Compressor Station	$1,635
Gas Plants	$2,269
Others	$233

  - **Alternative mobile screening methods:** $1,040 CAD per site (estimated as 20% higher than the average OGI survey cost per site).

  - **Stationary Methods:** Assumptions on stationary method costs are based on publicly available Project Canary cost data.
    - Upfront cost (all associated processes around installation): $1,600 CAD per site (The quoted installation price is $250 USD per device, and we have assumed an average of 5 devices per site for a total of $1,250 USD per site.)
    - Monthly Subscription: $100 CAD per site ($75 USD per site)

Modeling Results

The following Section presents the simulation modelling results which informed the equivalent alternative programs and comparison standard FEMP scenarios presented in the matrices of Section 3.

1.7. Mobile Methods Matrix

Sets of modelling results are shown corresponding to the three comparison standard FEMP scenarios referenced as columns in the equivalency matrix of Section 1.3. These comparison standard FEMP scenarios are:

- **Current AER D060** (sites in simulation receive the appropriate number of simulations their subtype requires, either 1x or 3x per year).
- **Scenario 1** (triannual (3x) survey requirements become 4x per year survey requirements and annual (1x) survey requirements become 2x per year survey requirements).
- **Scenarios 2** (all sites require 4x per year surveys).

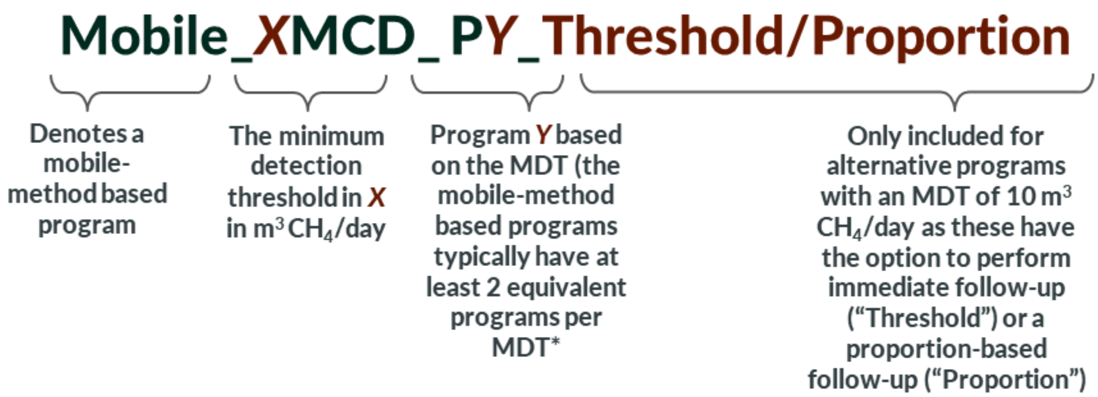
For each standard FEMP scenario two plots are shown:

- **Emissions Mitigation**: A bar graph where bar length is the % of mitigation each program achieves. % mitigation is based on a comparison to a program devoid of any LDAR. For example, if this program devoid of LDAR led to 100 kg of CH_4 emissions, and a given program mitigated 60 kg CH_4 emissions, that program's bar would be 60%.
- **Cost**: A stacked bar chart where total bar heigh represents total program cost and stacked bar height represents method cost. Cost assumptions summarized in Section 1.6.5.

Finally, mobile method-based programs which are *not* capable of quantification are inherently more conservative than those capable of quantification as they do not allow for follow-up proportions (any flagged site must receive a follow-up). As such, only the results of the quantification capable mobile-method based programs are shown.

1.7.1. Program Nomenclature

All modeled mobile method-based programs correspond to a row in the equivalency tables of Section 1.2. The modeled program names employ the following nomenclature (orange text varies program-to-program):



*Note: In the case of comparison regulatory Scenario 2, program 1 and program 2 are synonymous for 10 m^3 CH_4/day, so Y is shown as "1/2".

The comparison standard FEMP scenario is the only program to not follow this nomenclature, but the program name does change depending on the modeled standard FEMP scenario.

1.7.2. Current Standard FEMP Scenario (AER D060)

1.7.2.1 Emissions Mitigation

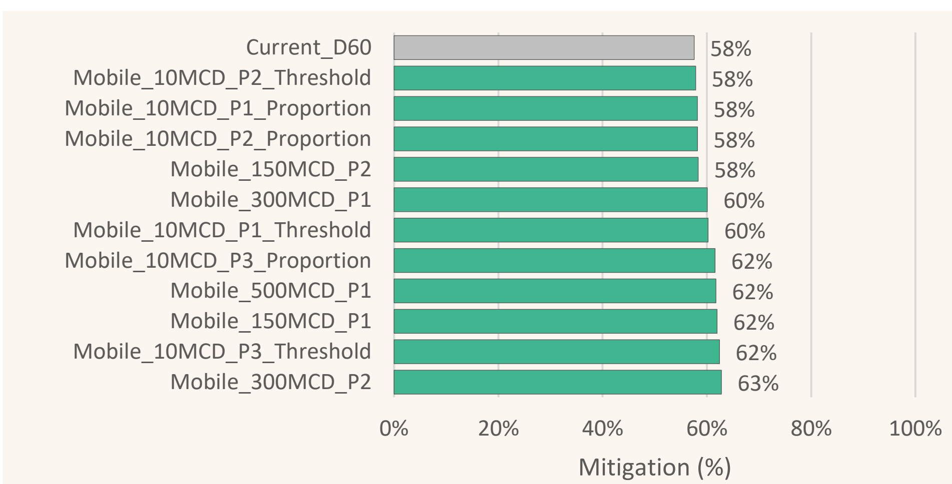


Figure 7. Emissions mitigation of mobile method-based programs and a comparison standard FEMP scenario based on current AER D060 FEMP requirements. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH_4 from fugitive emissions the program mitigates.

Only mobile method-based programs capable of quantifying emission rates are shown as the equivalent programs required from non-quantitative mobile method-based programs are inherently more conservative (more follow-ups are required).

1.7.2.2 Cost

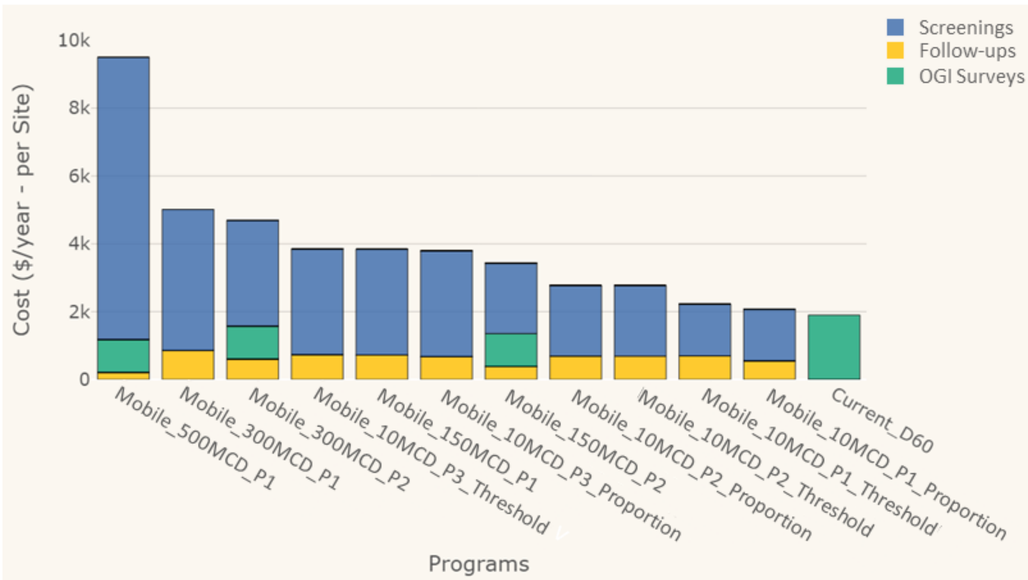


Figure 8. Program cost. Total bar heigh represents the average annual program cost per year per site for mobile method-based programs. Stacked components represent individual method costs. The comparison program is based on current AER D060 FEMP requirements.

1.7.3. Scenario 1

Scenario 1 is a potential scenario where Alberta sites which currently require 3x surveys per year now require 4x survey per year, and sites which currently require 1x surveys per year now require 2x survey per year. Note the change in the scenario name of the modeled comparison program.

1.7.3.1 Emissions Mitigation

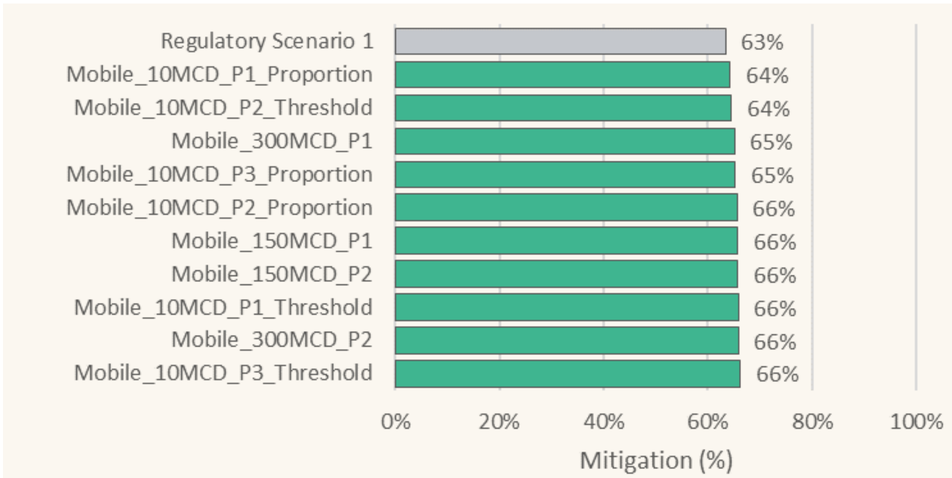


Figure 9. Emissions mitigation of mobile method-based programs and a comparison standard FEMP scenario based on a potential setting in which more frequent OGI surveys are required (Scenario 1). Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH_4 from fugitive emissions the program mitigates. Only mobile method-based programs capable of quantifying emission rates are shown as the equivalent programs required from non-quantitative mobile method-based programs are inherently more conservative (more follow-ups are required).

1.7.3.2 Cost

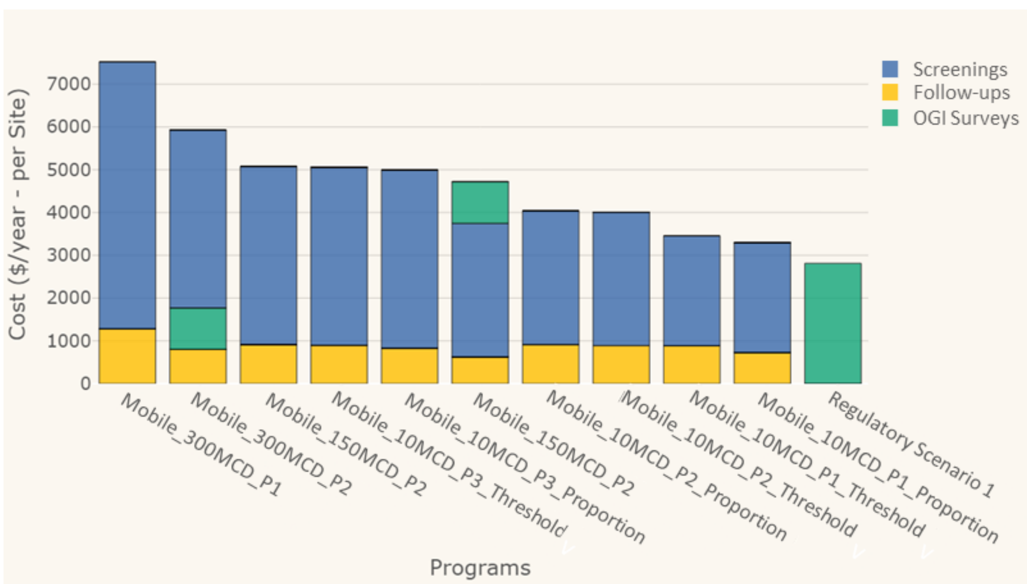


Figure 10. Program cost. Total bar heigh represents the average annual program cost per year per site for mobile method-based programs. Stacked components represent individual method costs. The comparison program is based on various standard FEMP scenarios in which sites in Alberta require additional OGI surveys (Scenario 1).

1.7.4. Scenario 2

Standard FEMP Scenario 2 is a potential scenario where all Alberta sites require 4x surveys per year.

1.7.4.1 Emissions Mitigation

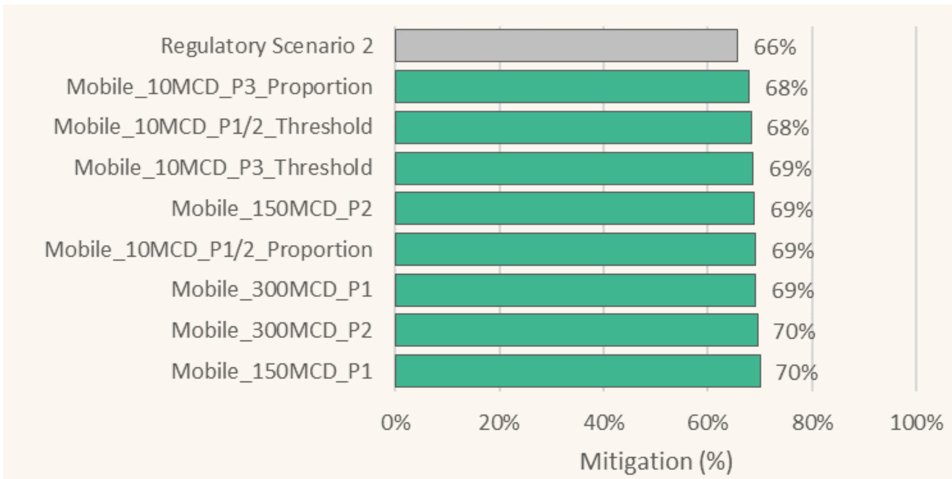


Figure 11. Emissions mitigation of mobile method-based programs and a comparison standard FEMP scenario based on a potential setting in which more frequent OGI surveys are required (Scenario 2). Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH_4 from fugitive emissions the program mitigates. Only mobile method-based programs capable of quantifying emission rates are shown as the equivalent programs required from non-quantitative mobile method-based programs are inherently more conservative (more follow-ups are required).

1.7.4.2 Cost

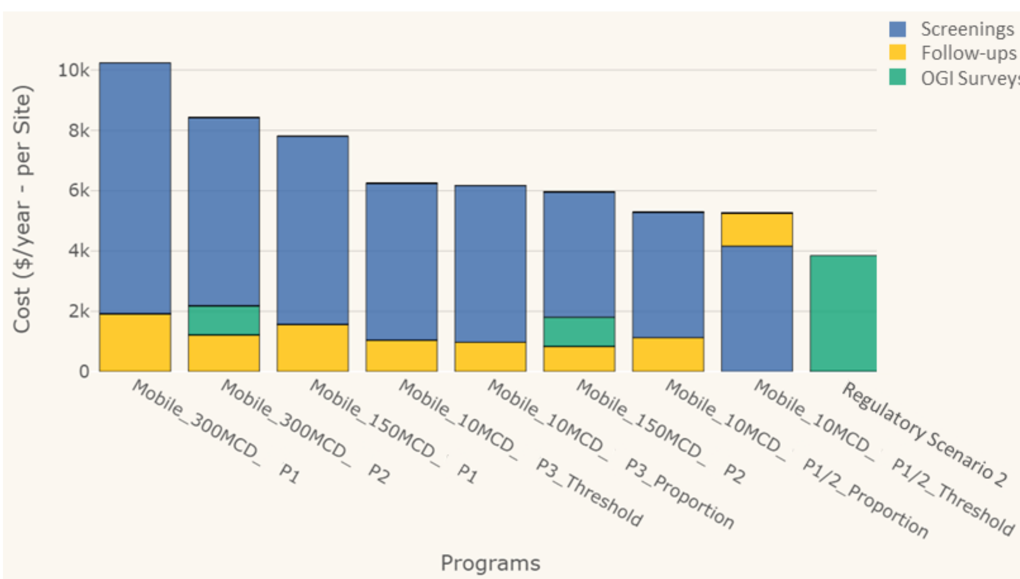


Figure 12. Program cost. Total bar heigh represents the average annual program cost per year per site for mobile method-based programs. Stacked components represent individual method costs. The comparison program is based on a potential standard FEMP scenario in which sites in Alberta require additional OGI surveys (Scenario 2).

1.8. Stationary Methods Matrix

As discussed in more detail in Section 1.4 and 1.6.2, the key difference between simulation modelling of the mobile method-based programs and the stationary method-based programs is the modelled infrastructure / "virtual world". Mobile modelling saw a virtual world with representative proportions of Alberta subtypes, while stationary modelling saw separate model runs where the virtual world was populated with a single subtype. These subtypes were represented by a "Model Plant", a site with emissions characteristics representative of the given subtype. The evaluated subtypes / Model Plants and their current AER D060 survey requirements are:

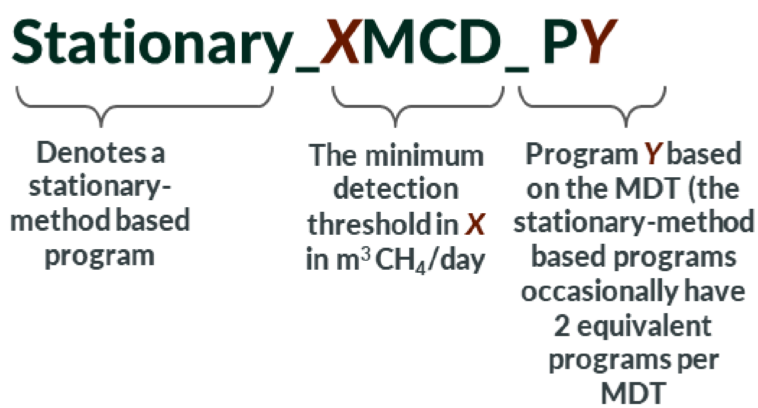
- Gas Multiwell Battery (1x per year survey requirement)
- Gas Single well Battery (1x per year survey requirement)
- Oil single well Battery (1x per year survey requirement)
- Oil Multiwell Battery (1x per year survey requirement)
- Gas Plant (3x per year survey requirement)
- Compressor Station (3x per year survey requirement)
- Other (1x per year survey requirement)

Sets of modelling results are shown corresponding to each of the three comparison standard FEMP scenarios referenced as columns in the equivalency matrices of Section 1.4. For each standard FEMP scenario two plots are shown:

- **Emissions Mitigation**: A bar graph where bar length is the % of mitigation each program achieves. % mitigation is based on a comparison to a program devoid of any LDAR. For example, if this program devoid of LDAR led to 100 kg of CH_4 emissions, and a given program mitigated 60 kg CH_4 emissions, that program's bar would be 60%. Separate visualizations are shown for subtypes which currently require 1x per year surveys and those which currently require 3x per year surveys.
- **Cost**: A stacked bar chart where total bar heigh represents total program cost and stacked bar height represents method cost. Cost assumptions summarized in Section 1.6.5. As cost is subtype specific, a cost plot is shown for each subtype within each potential standard FEMP scenario.

1.8.1. Nomenclature

All modeled stationary method-based programs correspond to a row in the equivalency matrices of Section 1.4. The modeled program names employ the following nomenclature (orange text varies program-to-program)



1.8.2. Current Standard FEMP Scenario (AER D060)

1.8.2.1 Emissions Mitigation

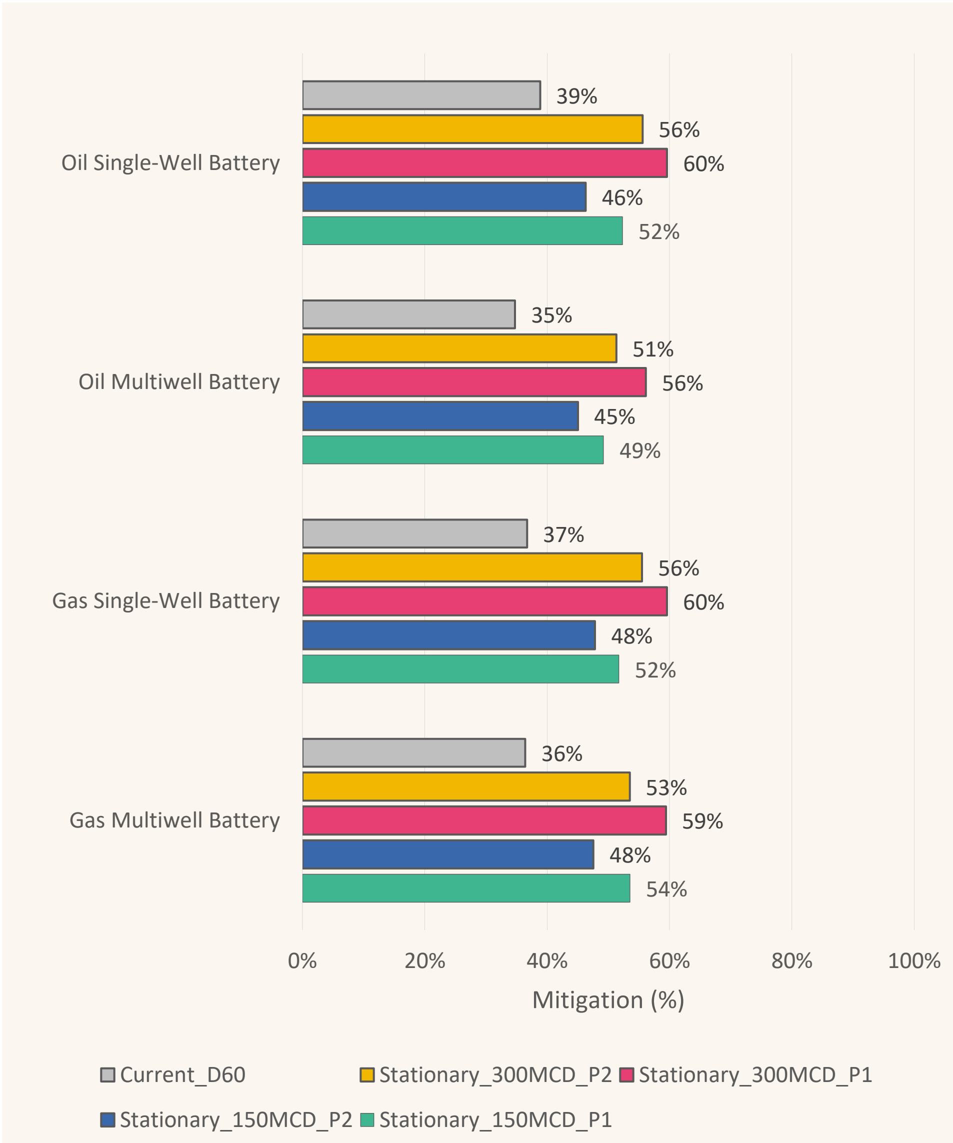


Figure 13. Emissions mitigation of stationary method-based programs and a comparison standard FEMP scenario based on current AER D060 FEMP requirements for subtypes which currently require 1x survey per year. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH_4 from fugitive emissions the program mitigates.

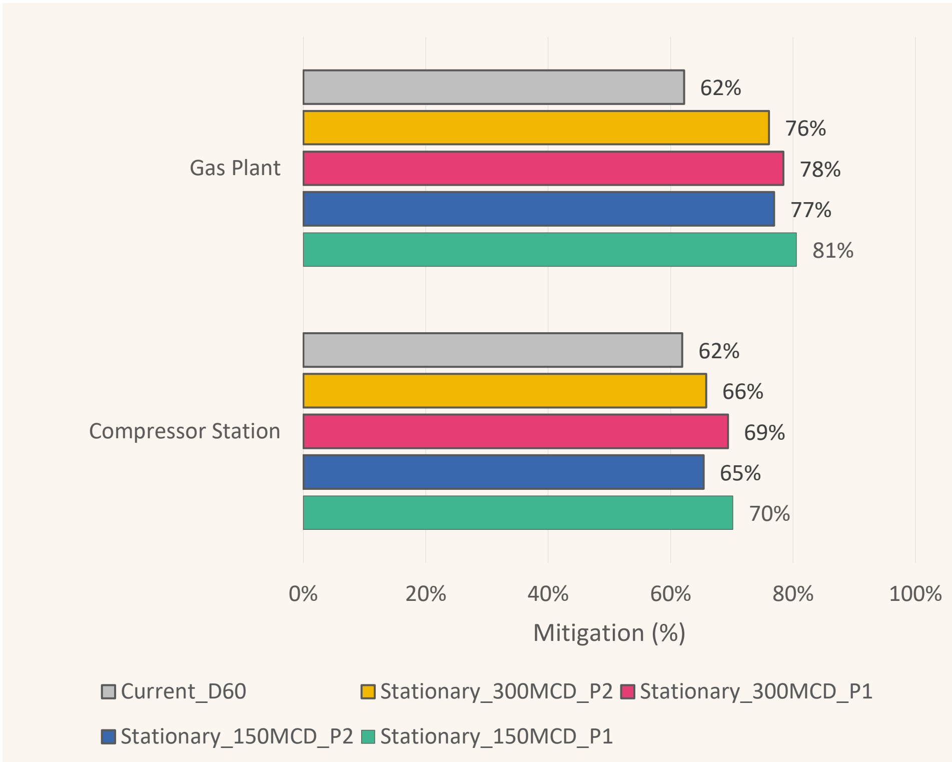


Figure 14. Emissions mitigation of stationary method-based programs and a comparison standard FEMP scenario based on current AER D060 FEMP requirements for subtypes which currently require 3x survey per year. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH_4 from fugitive emissions the program mitigates.

1.8.2.2 Cost

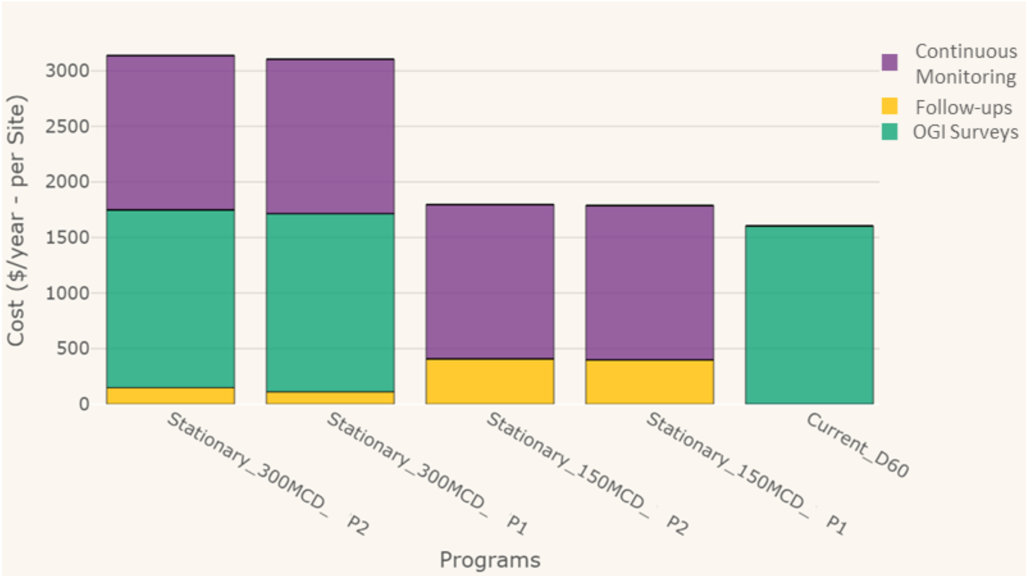


Figure 15. Program cost for the Gas Multiwell Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on current AER D060 FEMP requirements.

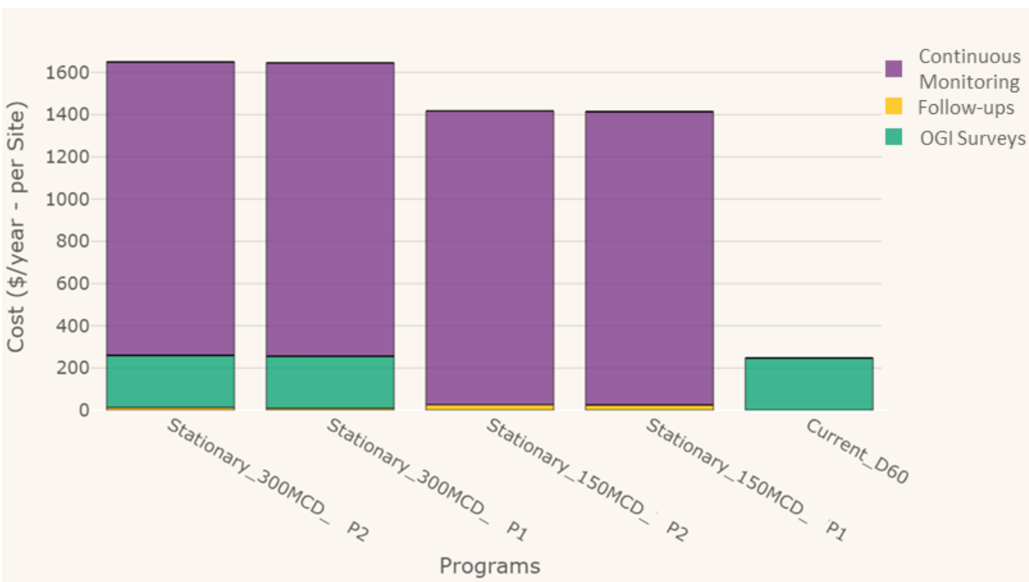


Figure 16. Program cost for the Gas Single Well Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on current AER D060 FEMP requirements.

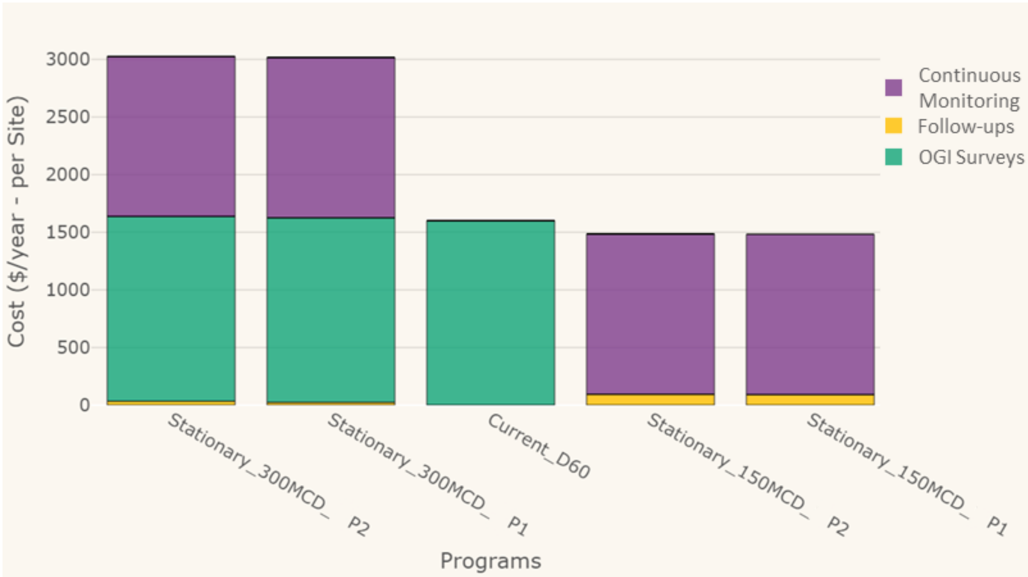


Figure 17. Program cost for the Oil Multiwell Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on current AER D060 FEMP requirements.

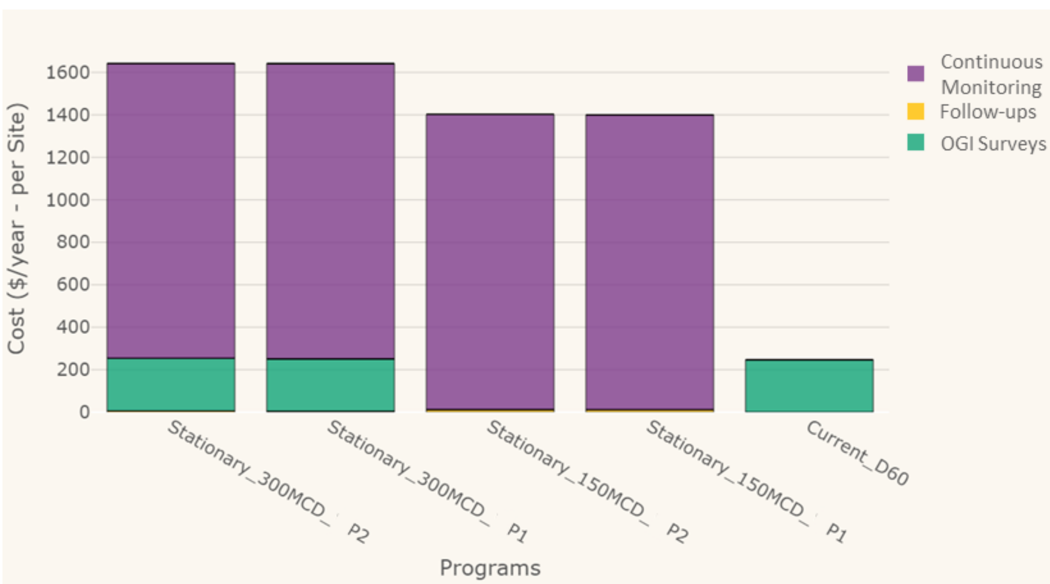


Figure 18. Program cost for the Oil Single Well Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on current AER D060 FEMP requirements.

Figure 19. Program cost for the Compressor Station subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on current AER D060 FEMP requirements.

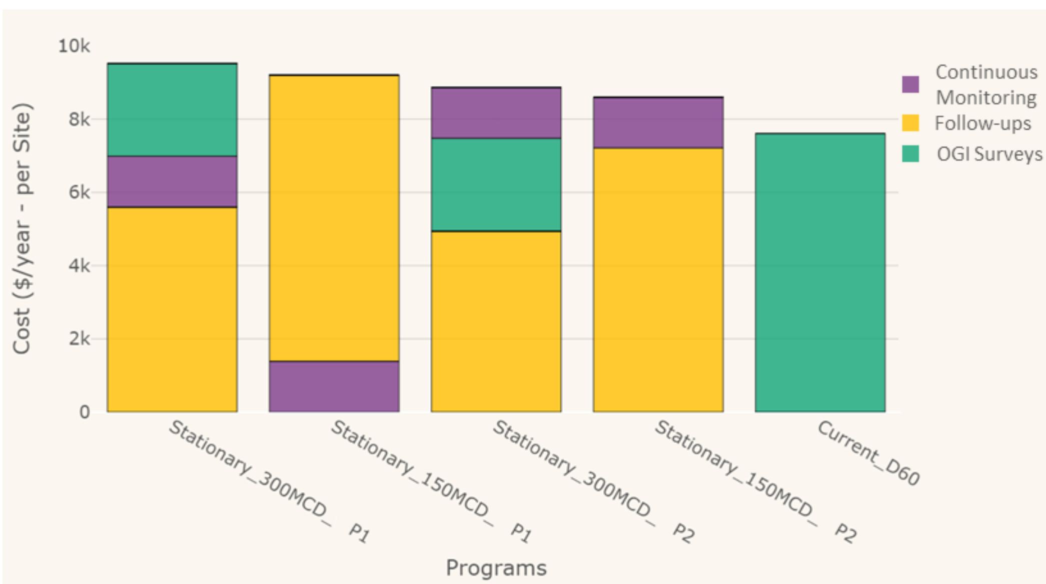


Figure 20. Program cost for the Gas Plant subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on current AER D060 FEMP requirements.

1.8.3. Scenario 1

1.8.3.1 Mitigation

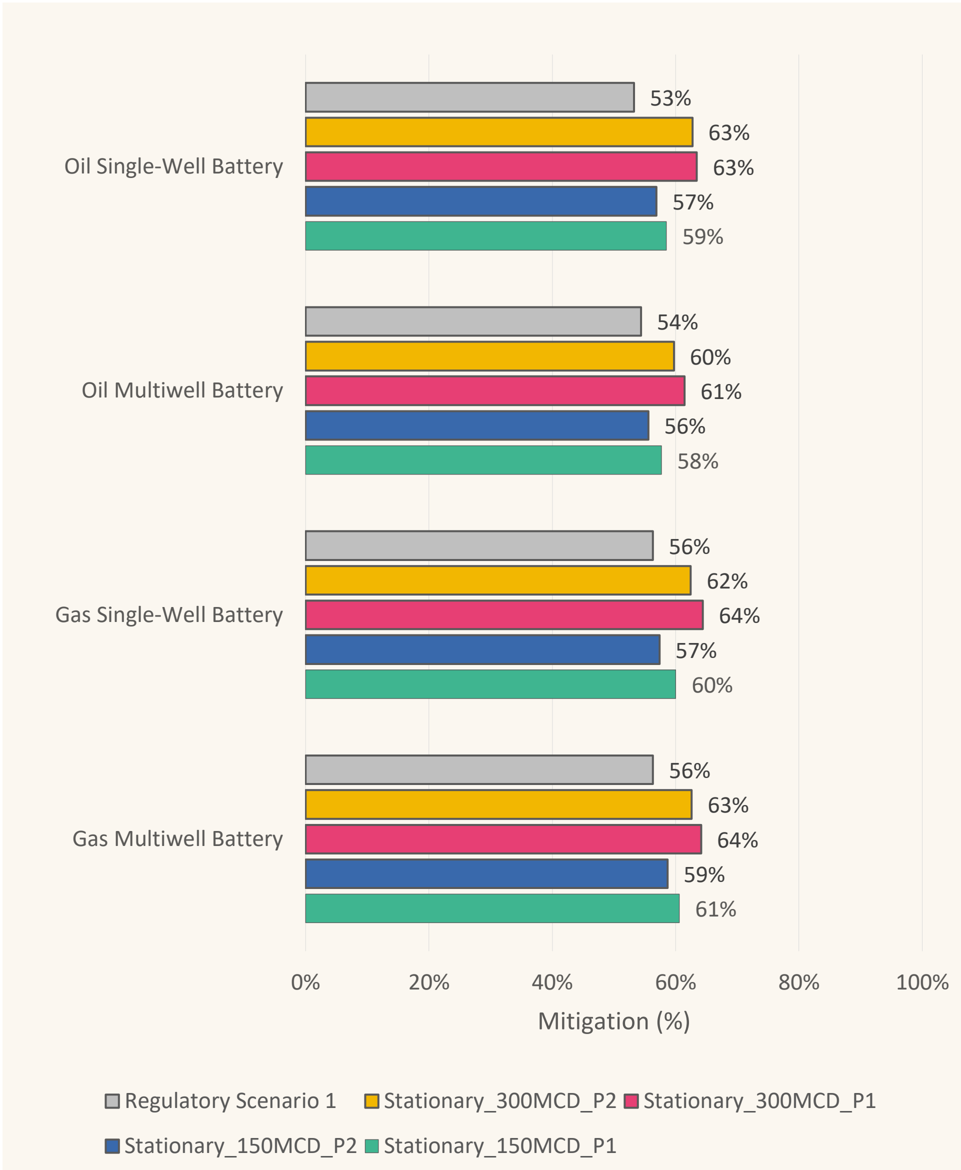


Figure 21. Emissions mitigation of stationary method-based programs and a comparison regulatory scenario based on a potential setting in which more frequent OGI surveys are required (Regulatory Scenario 1) for subtypes which currently require 1x survey per year. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH_4 from fugitive emissions the program mitigates.

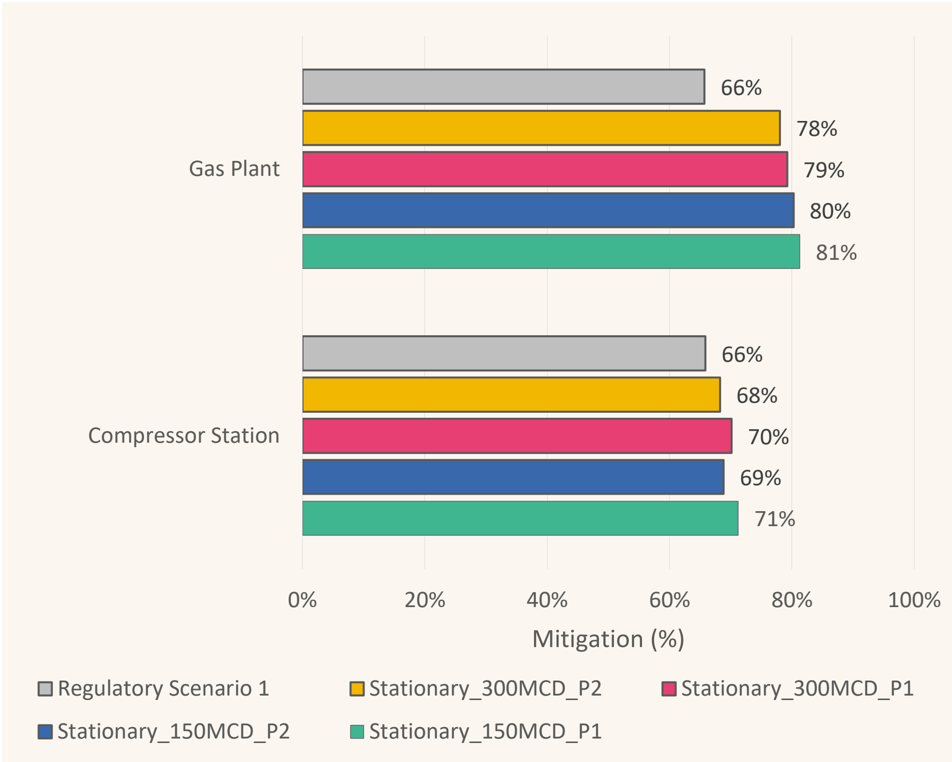


Figure 22. Emissions mitigation of stationary method-based programs and a comparison standard FEMP scenario based on a potential setting in which more frequent OGI surveys are required (Scenario 1) for subtypes which currently require 3x survey per year. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a “program” devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH_4 from fugitive emissions the program mitigates.

1.8.3.2 Cost

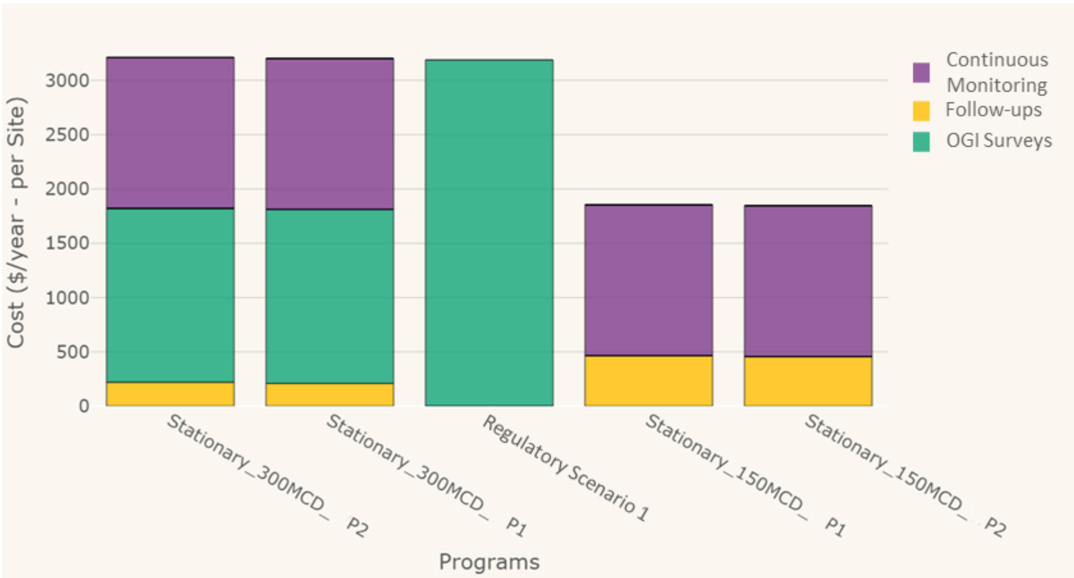


Figure 23. Program cost for the Gas Multiwell Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on a potential standard FEMP setting in which sites in Alberta require additional OGI surveys (Scenario 1).

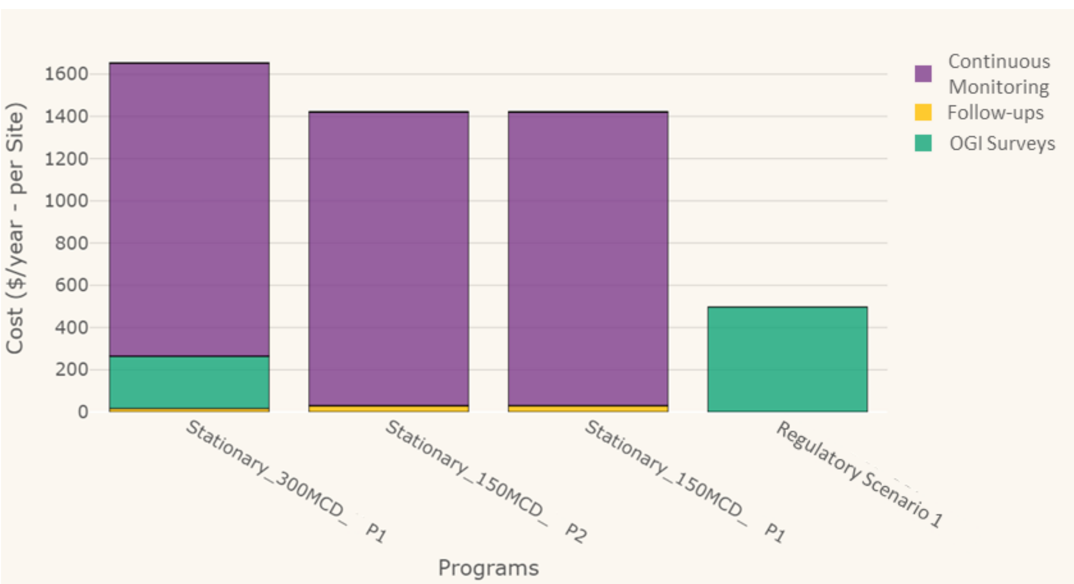


Figure 24. Program cost for the Gas Single Well Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on a potential standard FEMP setting in which sites in Alberta require additional OGI surveys (Scenario 1).

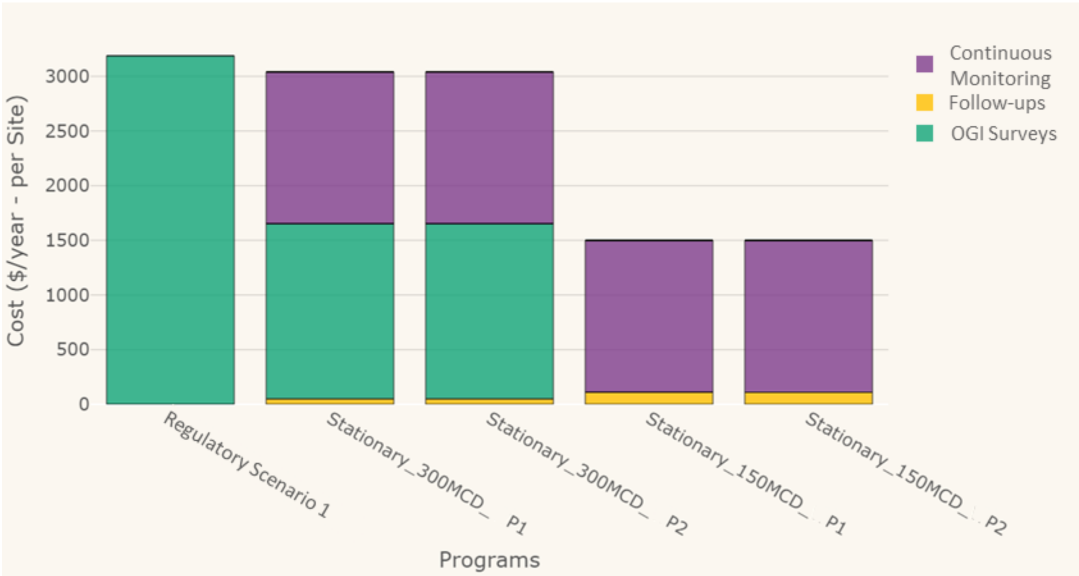


Figure 25. Program cost for the Oil Multiwell Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on a potential standard FEMP setting in which sites in Alberta require additional OGI surveys (Scenario 1).

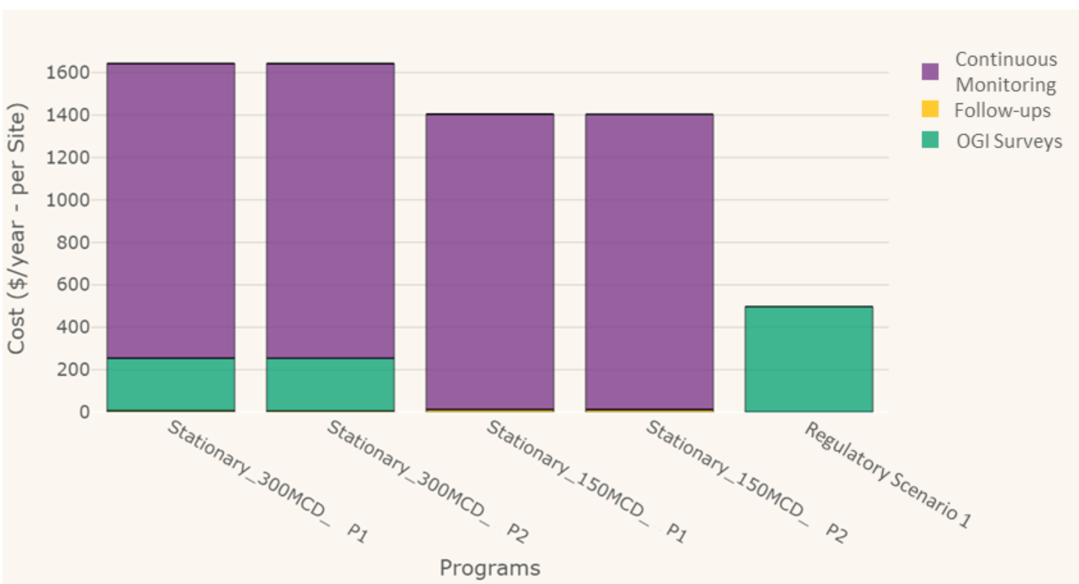


Figure 26. Program cost for the Oil Single Well Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on a potential standard FEMP setting in which sites in Alberta require additional OGI surveys (Scenario 1).

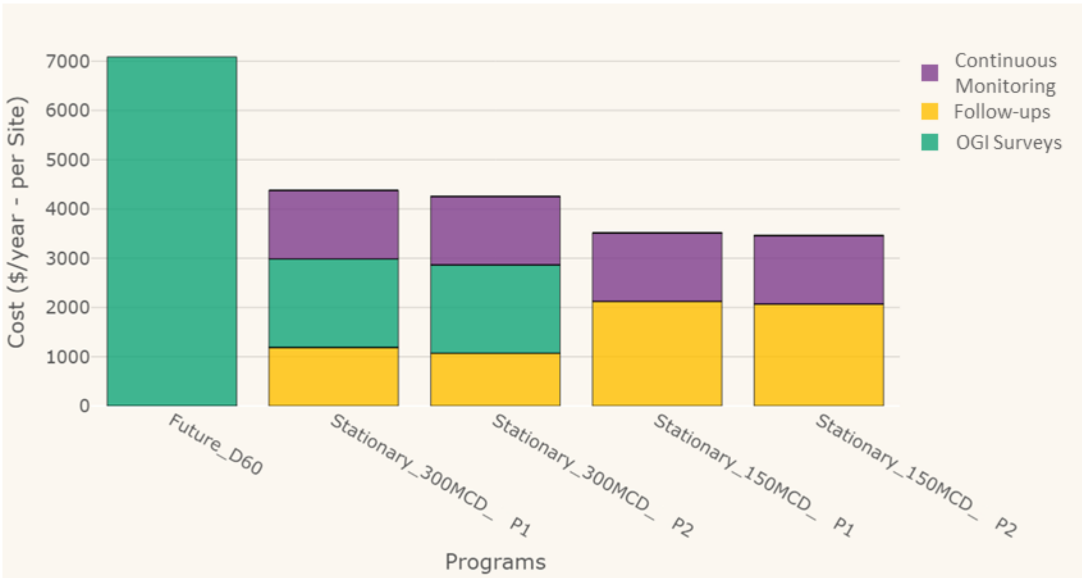


Figure 27. Program cost for the Compressor Station subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on a potential standard FEMP setting in which sites in Alberta require additional OGI surveys (Scenario 1).

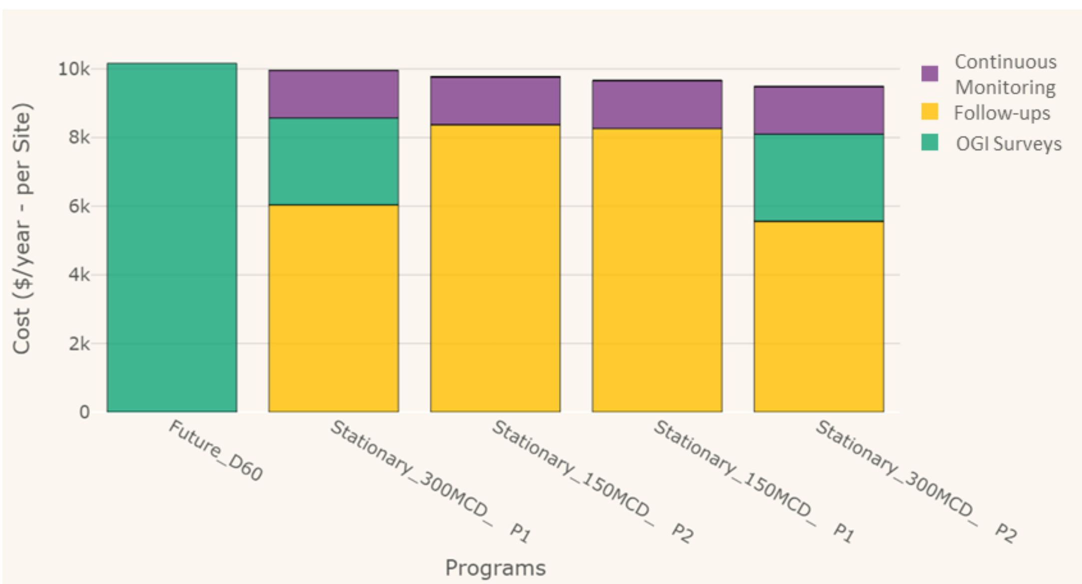


Figure 28. Program cost for the Gas Plant subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on a potential standard FEMP setting in which sites in Alberta require additional OGI surveys (Scenario 1).

1.8.4. Scenario 2

Subtypes which currently require 3x surveys per year have the same potential survey requirements (4x) for scenarios 1 and 2 and as such are not shown here.

1.8.4.1 Mitigation

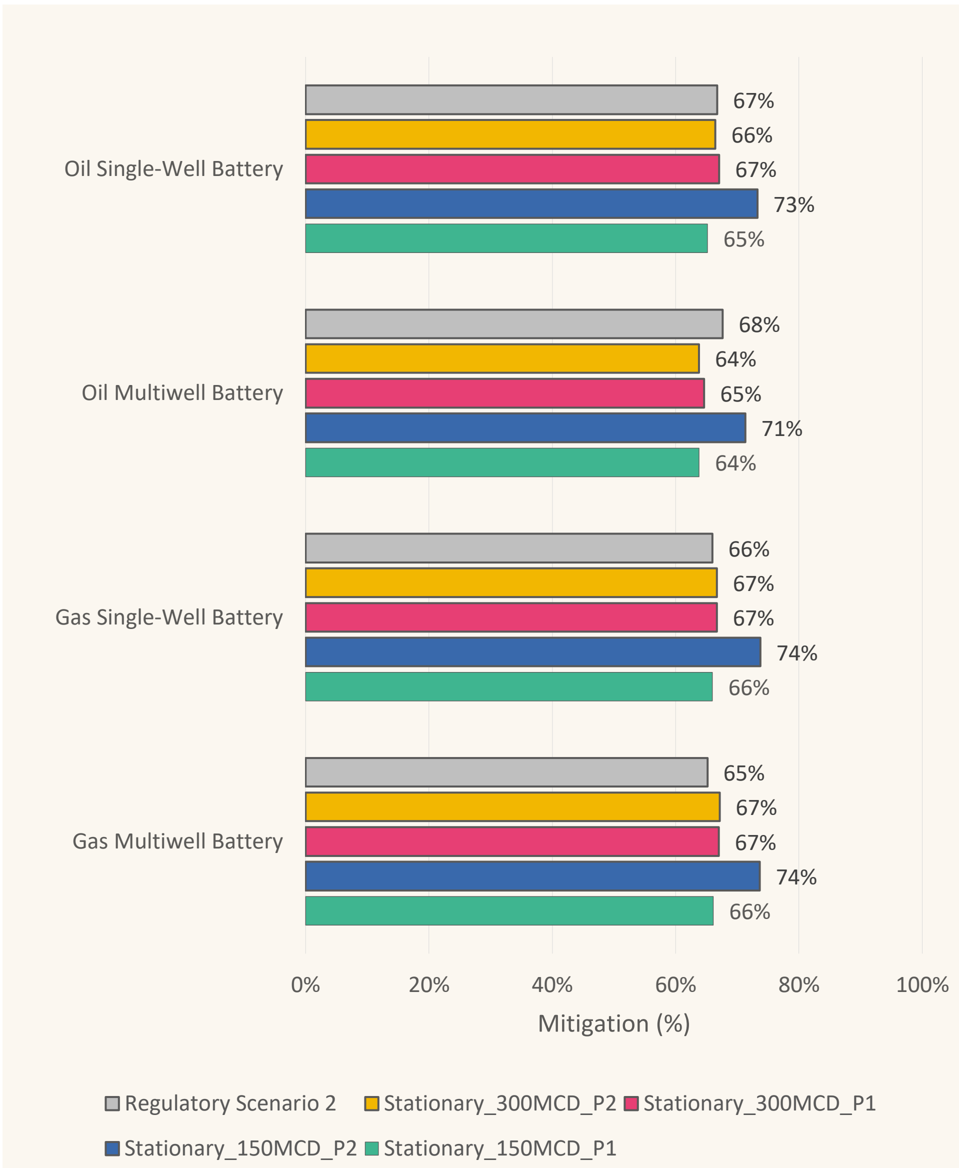


Figure 29. Emissions mitigation of stationary method-based programs and a comparison standard FEMP scenario based on a potential setting in which more frequent OGI surveys are required (Scenario 2) for subtypes which currently require 1x survey per year. Bar distance represents the % mitigation each program achieves from an emissions baseline established by applying a "program" devoid of formal LDAR to the modeled infrastructure. The larger the mitigation %, the more CH_4 from fugitive emissions the program mitigates.

For Oil Single-Well Batteries only "CM_150MCD_WP2 and CM_300MCD_WP1 are equivalent with the comparison standard FEMP scenario modeled under scenario 2. For Oil Multi-Well Batteries, only CM_150MCD_WP2 is equivalent. However, overall mitigation is still very close. Achieving equivalency for oil batteries under scenario 2 was challenging as these sites have a very low leak frequency. In the simulation, every time a leak arises, simulator draws a rate from a leak dataset, which predominantly consists of small leaks. Consequently, sites with low leak frequency have a reduced likelihood of encountering a high-volume emitter, diminishing the efficiency of a stationary method-based program, which requires leaks higher than the "lowest" MDT of (150/300 m^3 of CH_4/day) to trigger a follow-up.

Oil wells and Oil multiwells contribute minimally to the overall Alberta emissions. Despite their being many of these sites in the infrastructure, leaks at these locations occur infrequently, typically averaging between 1 to 2 leaks per 10 sites annually, in contrast to gas plants, which experience 150 leaks per 10 sites per year, and compressor stations, which record 30 leaks per 10 sites annually. See Section 1.6 for more details.

1.8.4.2 Cost

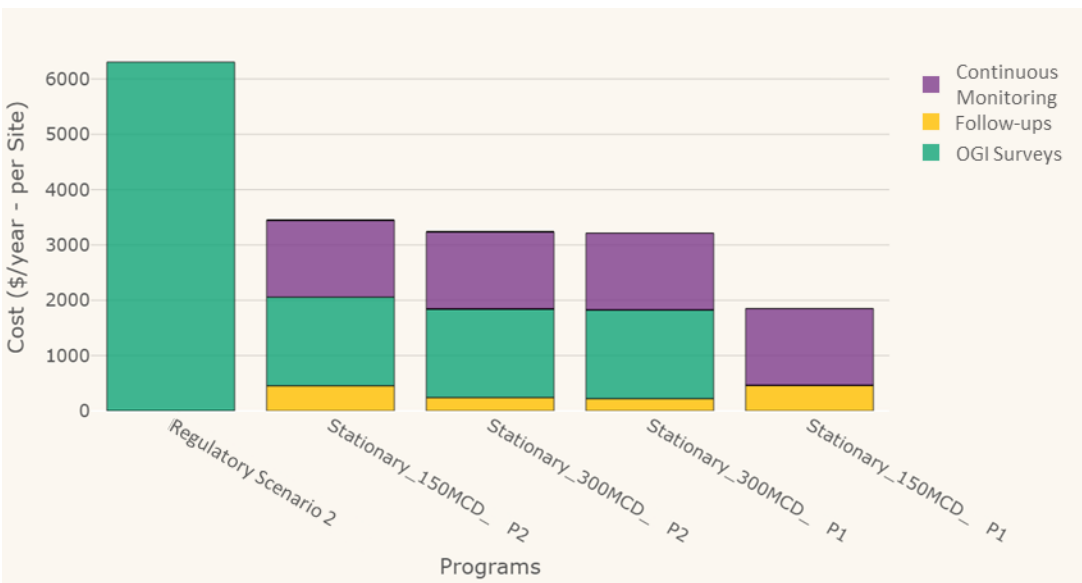


Figure 30. Program cost for the Gas Multiwell Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on a potential standard FEMP setting in which sites in Alberta require additional OGI surveys (Scenario 2).

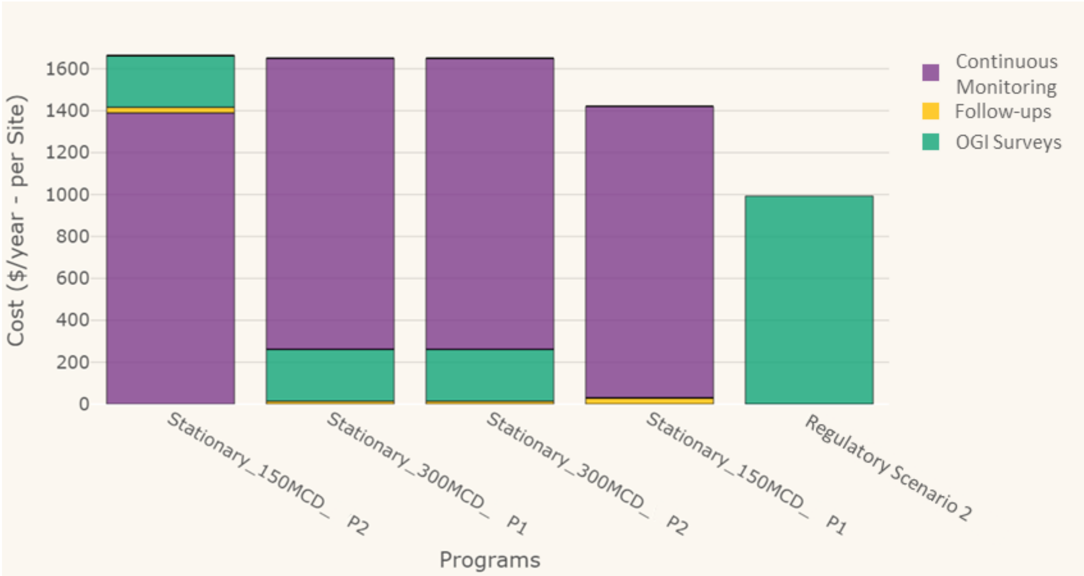


Figure 31. Program cost for the Gas Single Well Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on a potential standard FEMP setting in which sites in Alberta require additional OGI surveys (Scenario 2).

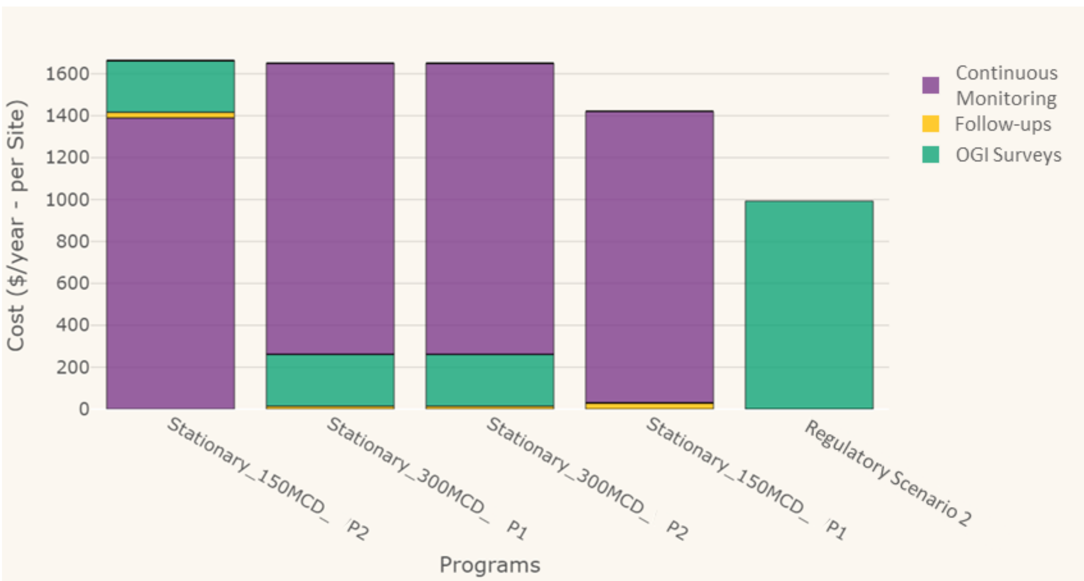


Figure 32. Program cost for the Oil Multiwell Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on a potential standard FEMP setting in which sites in Alberta require additional OGI surveys (Scenario 2).

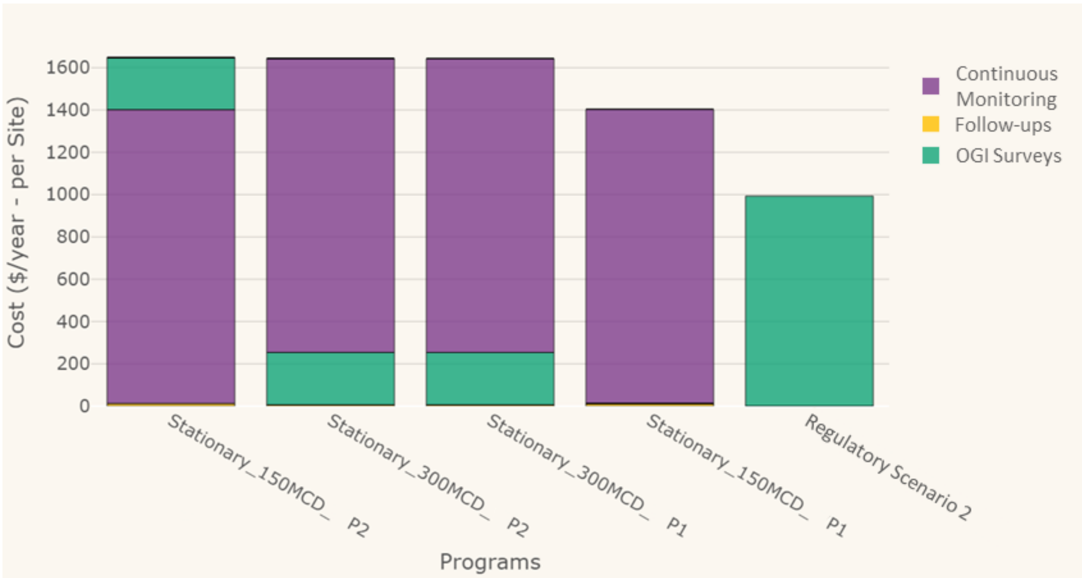


Figure 33. Program cost for the Oil Single Well Battery subtype. Total bar heigh represents the average annual program cost per year per site for stationary method-based programs. Stacked components represent individual method costs. The comparison standard FEMP scenario is based on a potential standard FEMP setting in which sites in Alberta require additional OGI surveys (Scenario 2).

Appendix

The appendix presents a series of sensitivity analyses where key LDAR-Sim modelling parameters were adjusted and resultant changes in program mitigation were observed.

1.9. Mobile Matrix Sensitivity Analysis

The following sensitivity analyses were conducted for the modelling which informed the mobile method equivalency matrix.

- **Leak Production Rate (LPR) sensitivity analysis**
  - Aimed to evaluate mitigation that would be achieved by alternative programs if LPR considered for subtypes were 50% lower (LPR X 0.5) or 50% higher (LPR X 1.5x).
- **Natural Repair Delay (NRD) sensitivity analysis**
  - The NRD assumed was 1 year. This sensitivity analysis evaluates mitigation that would be achieved by alternative programs if natural repair delay was increased to 2 years (NRD=2 years) or 5 years (NRD = 5 years).
- **Leak rate sensitivity analysis**

   - Aimed to evaluate mitigation that would be achieved by alternative programs if different leak rates were assumed. Two inputs were evaluated:
     - Site-level measurement source: In the main analysis, we considered the impact of emission rates measured at the source and site level (top-down and bottom-up respectively). The source of site-level emission rates was AER aerial surveillance flyovers. As a comparison, here we investigate the impact of assuming the source of site-level measurements are the rates collected and described in Johnson (2023)[13]
     - Proportion of site-level to source-level emissions in modelling: In the main analysis we considered 60% of emission sources are those from source-level measurements. Sensitivity evaluates the impact of assuming this contribution of source-level measurements was 40% and 80%.

- **Spatial coverage sensitivity analysis**
   - Aimed to evaluate mitigation that would be achieved by alternative programs if all methods (screenings and OGI surveys) were modeled with 100% spatial coverage. The modelling presented in the body of this report assumed a spatial coverage of 90% for alternative methods (mobile and stationary), and a spatial coverage of 85% for standard FEMP OGI methods.

The sensitivity analyses are summarized in a series of tables. The values in the table indicate the mitigation % the program achieves under a given adjusted parameter, denoted by the column. Note, each mitigation % is a result of only changing 1 parameter value. It becomes much too difficult to investigate the results of modifying multiple assumed inputs at once. Values in red indicate the mitigation achieved by the alternative program was lower than the mitigation achieved by the comparison standard FEMP program.

[13] Johnson, M. R., Tyner, D. R., & Conrad, B. M. (2023). Origins of oil and gas sector methane emissions: on-site investigations of aerial measured sources. Environmental Science & Technology, 57(6), 2484-2494.

1.9.1. Current Standard FEMP Scenario (AER D060) Sensitivity Analysis

Table 7. Program mitigation sensitivity analysis when considering the current standard FEMP scenario. Table values show the % mitigation the program achieves when the given parameter (denoted by each column) is adjusted. Note all mitigation % values are based on only changing 1 parameter input at a time.

	Mitigation (%)								
Program Name	Base Case	LPR X 0.5	LPR X 1.5	NRD =2 years	NRD=5 years	Top-down Rate Source, Johsons et al., 2023	Bottom-up Proportion 40%	Bottom-up Proportion 80%	Methods Spatial Coverage =1
Current_D60	57.6%	58.9%	57.8%	70.5%	77.7%	59.3%	58.3%	57.7%	67.2%
Mobile_10MCD_WP2_Threshold	60.1%	57.6%	61.0%	74.3%	86.8%	63.6%	61.4%	56.9%	60.5%
Mobile_10MCD_WP2_Proportion	62.8%	61.9%	63.6%	78.5%	88.4%	64.2%	63.4%	60.8%	60.7%
Mobile_10MCD_WP3_Threshold	58.2%	55.3%	59.8%	76.9%	88.4%	58.7%	59.5%	56.6%	65.6%
Mobile_10MCD_WP3_Proportion	60.2%	59.6%	62.3%	77.4%	87.8%	63.5%	62.1%	57.3%	64.5%
Mobile_10MCD_WP1_Threshold	62.0%	60.4%	63.4%	76.8%	88.1%	64.7%	62.9%	58.1%	62.4%
Mobile_10MCD_WP1_Proportion	61.7%	57.0%	63.5%	76.9%	87.2%	64.2%	63.3%	58.6%	59.9%
Mobile_150MCD_WP2	58.2%	55.9%	59.4%	74.8%	86.4%	59.2%	58.5%	56.7%	62.6%
Mobile_150MCD_WP1	61.6%	58.8%	64.1%	77.5%	88.4%	63.3%	63.0%	58.8%	65.2%
Mobile_300MCD_WP2	57.9%	55.9%	59.5%	75.9%	87.4%	58.7%	59.5%	54.7%	66.0%
Mobile_300MCD_WP1	58.3%	57.5%	58.3%	76.5%	87.7%	59.6%	59.3%	57.6%	62.5%
Mobile_500MCD_WP1	62.4%	61.6%	64.6%	77.5%	88.2%	64.9%	64.3%	59.0%	65.5%

1.9.2. Scenario 1 Sensitivity Analysis Results

Table 8. Program mitigation sensitivity analysis when considering a potential standard FEMP scenario with increased required surveys (Scenario 1). Table values show the % mitigation the program achieves when the given parameter (denoted by each column) is adjusted. Note all mitigation % values are based on only changing 1 parameter input at a time.

Program Name	Mitigation (%)								
	Base Case	LPR X 0.5	LPR X 1.5	NRD =2 years	NRD=5 years	Top-down Rate Source, Johsons et al., 2023	Bottom-up Proportion 40%	Bottom-up Proportion 80%	Methods Spatial Coverage =1
Future_D60_SC1	63.4%	64.4%	63.3%	73.8%	79.3%	63.2%	63.8%	63.6%	74.3%
Mobile_10MCD_WP3_Threshold	66.3%	63.4%	68.2%	80.5%	89.2%	68.7%	68.0%	62.0%	69.3%
Mobile_10MCD_WP2_Threshold	64.5%	62.4%	66.0%	79.3%	89.3%	66.3%	66.4%	61.5%	67.5%
Mobile_10MCD_WP2_Proportion	65.6%	62.0%	66.4%	80.3%	89.5%	66.7%	66.4%	64.1%	68.1%
Mobile_10MCD_WP3_Proportion	65.2%	62.0%	66.6%	80.5%	89.4%	67.4%	67.1%	62.7%	68.7%
Mobile_10MCD_WP1_Threshold	65.8%	64.0%	68.2%	80.9%	89.4%	69.0%	68.0%	62.9%	69.2%
Mobile_10MCD_WP1_Proportion	64.2%	62.4%	64.8%	79.2%	88.6%	65.9%	65.3%	62.0%	67.1%
Mobile_150MCD_WP2	65.8%	64.0%	66.1%	80.5%	89.8%	67.3%	67.1%	64.5%	69.4%
Mobile_150MCD_WP1	65.7%	64.3%	66.2%	79.2%	89.1%	68.3%	67.9%	63.0%	68.4%
Mobile_300MCD_WP2	65.9%	65.2%	66.2%	80.2%	89.8%	68.1%	67.1%	64.2%	69.2%
Mobile_300MCD_WP1	65.1%	63.8%	65.8%	78.7%	88.6%	68.4%	67.2%	62.3%	67.5%

1.9.3. Scenario 2 Sensitivity Analysis Results

Table 9. Program mitigation sensitivity analysis when considering a potential standard FEMP scenario with increased required surveys (Scenario 2). Table values show the % mitigation the program achieves when the given parameter (denoted by each column) is adjusted. Note all mitigation % values are based on only changing 1 parameter input at a time.

Program Name	Mitigation (%)								
	Base Case	LPR X 0.5	LPR X 1.5	NRD =2 years	NRD=5 year	Top-down Rate Source, Johsons et al. , 2023	Bottom-up Proportion 40%	Bottom-up Proportion 80%	Methods Spatial Coverage =1
Future_D60_SC2	65.7%	65.7%	65.3%	73.4%	79.9%	65.5%	66.3%	65.3%	77.2%
Mobile_10MCD_WP1/2_Threshold	68.3%	66.7%	69.4%	81.6%	89.9%	69.8%	69.9%	63.8%	71.1%
Mobile_10MCD_WP1/2_Proportion	69.1%	66.3%	70.3%	82.5%	90.8%	69.8%	69.7%	67.2%	71.9%
Mobile_10MCD_WP3_Proportion	68.7%	66.9%	69.8%	81.1%	89.9%	71.0%	70.2%	64.0%	71.5%
Mobile_10MCD_WP3_Proportion	68.0%	65.8%	69.1%	81.2%	90.1%	69.6%	69.2%	65.2%	71.0%
Mobile_150MCD_WP2	68.9%	69.1%	69.4%	82.3%	90.7%	70.4%	69.9%	66.6%	72.9%
Mobile_150MCD_WP1	70.1%	69.5%	71.8%	83.0%	90.8%	73.0%	72.3%	68.2%	73.3%
Mobile_300MCD_WP2	69.5%	69.6%	70.1%	83.0%	91.0%	71.9%	70.6%	68.4%	73.2%
Mobile_300MCD_WP1	69.1%	68.7%	70.5%	81.7%	90.0%	72.7%	71.1%	66.4%	72.0%

1.10. Stationary Matrix Sensitivity Analysis

The same sensitivity analysis conducted for mobile method-based programs was conducted for stationary method-based programs. The sensitivity analysis was carried out across two subtypes: Gas Plants and Gas Multiwell Battery. These subtypes were chosen as in practice, they are a common deployment target for stationary methods.

1.10.1. Current Regulations (AER D060)

Table 10. Program mitigation sensitivity analysis when modelling the Gas Multiwell Battery subtype considering the current standard FEMP scenario (AER D060). Table values show the % mitigation the program achieves when the given parameter (denoted by each column) is adjusted. Note all mitigation % values are based on only changing 1 parameter input at a time.

	Mitigation (%)								
Program Name	Base Case	LPR X 0.5	LPR X 1.5	NRD =2 years	NRD=5 years	Top-down Rate Source, Johsons et al. , 2023	Bottom-up Proportion 40%	Bottom-up Proportion 80%	Methods Spatial Coverage =1
Current_D60	36.4%	37.1%	36.4%	58.7%	36.4%	36.4%	34.8%	36.0%	40.6%
Stationary_150MCD_WP1	53.5%	52.2%	53.5%	67.3%	53.5%	53.5%	58.0%	50.6%	55.9%
Stationary_150MCD_WP2	47.6%	46.8%	47.6%	60.0%	47.6%	47.6%	51.4%	44.9%	51.1%
Stationary_300MCD_WP1	59.4%	59.5%	59.4%	75.9%	59.4%	59.4%	61.4%	59.6%	63.5%
Stationary_300MCD_WP2	53.5%	52.9%	53.5%	72.0%	53.5%	53.5%	55.0%	53.3%	58.7%

Table 11. Program mitigation sensitivity analysis when modelling the Gas Plant subtype considering the current standard FEMP scenario (AER D060). Table values show the % mitigation the program achieves when the given parameter (denoted by each column) is adjusted. Note all mitigation % values are based on only changing 1 parameter input at a time.

	Mitigation (%)								
Program Name	Base Case	LPR X 0.5	LPR X 1.5	NRD =2 years	NRD=5 years	Top-down Rate Source, Johsons et al. , 2023	Bottom-up Proportion 40%	Bottom-up Proportion 80%	Methods Spatial Coverage =1
Current_D60	62.2%	62.0%	62.3%	72.5%	78.7%	62.3%	62.1%	61.9%	73.1%
Stationary_150MCD_WP1	80.6%	76.1%	82.5%	88.4%	92.9%	82.0%	82.7%	75.3%	81.6%
Stationary_150MCD_WP2	76.9%	72.1%	78.6%	84.7%	89.4%	78.1%	78.9%	71.5%	78.0%
Stationary_300MCD_WP1	78.4%	73.8%	81.0%	88.0%	93.6%	80.5%	81.4%	72.9%	80.3%
Stationary_300MCD_WP2	76.1%	70.7%	78.7%	86.4%	92.7%	78.3%	79.0%	70.2%	78.6%

1.10.2. Regulations (Scenario 1)

Table 12. Program mitigation sensitivity analysis when modelling the Gas Multiwell Battery subtype considering a potential standard FEMP scenario with increased required surveys (Scenario 1). Table values show the % mitigation the program achieves when the given parameter (denoted by each column) is adjusted. Note all mitigation % values are based on only changing 1 parameter input at a time.

	Mitigation (%)								
Program Name	Base Case	LPR X 0.5	LPR X 1.5	NRD =2 years	NRD=5 years	Top-down Rate Source, Johsons et al. , 2023	Bottom-up Proportion 40%	Bottom-up Proportion 80%	Methods Spatial Coverage =1
Future_D60_SC1	56.3%	55.9%	56.3%	67.9%	56.3%	56.3%	56.5%	55.9%	65.0%
Stationary_150MCD_WP1	60.6%	59.3%	60.6%	70.5%	60.6%	60.6%	64.8%	57.0%	63.2%
Stationary_150MCD_WP2	58.7%	57.4%	58.7%	66.8%	58.7%	58.7%	62.1%	54.2%	63.1%
Stationary_300MCD_WP1	64.1%	63.7%	64.1%	78.8%	64.1%	64.1%	66.4%	62.4%	67.3%
Stationary_300MCD_WP2	62.6%	63.5%	62.6%	77.2%	62.6%	62.6%	64.4%	61.9%	67.3%

Table 13. Program mitigation sensitivity analysis when modelling the Gas Plant subtype considering a potential standard FEMP scenario with increased required surveys (Scenario 1). Table values show the % mitigation the program achieves when the given parameter (denoted by each column) is adjusted. Note all mitigation % values are based on only changing 1 parameter input at a time.

Program Name	Mitigation (%)								
	Base Case	LPR X 0.5	LPR X 1.5	NRD =2 years	NRD=5 years	Top-down Rate Source, Johsons et al. , 2023	Bottom-up Proportion 40%	Bottom-up Proportion 80%	Methods Spatial Coverage =1
Future_D60	65.7%	65.2%	65.3%	74.3%	79.3%	65.9%	65.8%	65.1%	77.0%
Stationary_150MCD_WP1	81.3%	77.0%	83.1%	88.7%	93.1%	82.6%	83.4%	76.2%	82.2%
Stationary_150MCD_WP2	80.3%	75.3%	82.3%	87.2%	91.4%	81.7%	82.6%	74.8%	81.7%
Stationary_300MCD_WP1	79.2%	74.6%	81.8%	88.3%	93.7%	81.3%	82.1%	73.6%	80.7%
Stationary_300MCD_WP2	78.1%	73.0%	80.9%	87.6%	93.3%	80.5%	81.1%	72.2%	80.6%

1.10.3. Regulations (Scenario 2)

Table 14. Program mitigation sensitivity analysis when modelling the Gas Multiwell Battery subtype considering a potential standard FEMP scenario with increased required surveys (Scenario 2). Table values show the % mitigation the program achieves when the given parameter (denoted by each column) is adjusted. Note all mitigation % values are based on only changing 1 parameter input at a time.

Program Name	Mitigation (%)								
	Base Case	LPR X 0.5	LPR X 1.5	NRD =2 years	NRD=5 years	Top-down Rate Source, Johsons et al. , 2023	Bottom-up Proportion 40%	Bottom-up Proportion 80%	Methods Spatial Coverage =1
Future_D60_SC2	65.2%	67.0%	65.2%	74.7%	65.2%	65.2%	66.7%	67.8%	76.9%
Stationary_150MCD_WP1	66.1%	65.6%	66.1%	75.1%	66.1%	66.1%	69.6%	62.5%	68.3%
Stationary_150MCD_WP2	73.7%	73.6%	73.7%	84.0%	73.7%	73.7%	75.7%	70.6%	78.3%
Stationary_300MCD_WP1	67.0%	67.3%	67.0%	80.8%	67.0%	67.0%	69.3%	65.1%	69.7%
Stationary_300MCD_WP2	67.2%	67.2%	67.2%	80.9%	67.2%	67.2%	69.8%	64.4%	72.0%