CARBON LIMITS

Statistical Analysis of leak detection and repair in Canada

Summary report

This report was prepared by Carbon Limits AS.

Project title:
Statistical Analysis of leak detection and repair in Canada

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Carbon Limits is a consulting company with long standing experience in supporting energy efficiency measures in the petroleum industry. In particular, our team works in close collaboration with industries, government, and public bodies to identify and address inefficiencies in the use of natural gas and through this achieve reductions in greenhouse gas emissions and other air pollutants.

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Acronym

cfm	cubic feet per min
CH4	Methane
ECCC	Environment and Climate Change Canada
LDAR	Leak detection and Repair
OGAED	Oil, Gas and Alternative Energy Division
PRV	Pressure Relief Valve

1. Introduction

1.1 Project context and objective

Oil and gas facilities represent the largest source of methane emissions in Canada. Methane is a potent GHG and represents the largest share of natural gas.

The Government of Canada is planning to introduce national regulations that will require oil and gas facilities to implement leak detection and repair programs in order to reduce fugitive emissions of methane. The Oil, Gas and Alternative Energy Division (OGAED) at Environment and Climate Change Canada (ECCC) has been tasked with developing these national regulations. However, OGAED requires information from surveys of existing LDAR programs in order to design requirements that will reflect the best possible balance between cost-effectiveness and environmental outcomes.

Carbon Limits, based in Oslo, Norway, is a consulting company with deep experience in climate change issues, particularly related to monitoring and reporting of emissions and analysis of mitigation options. The company has developed a unique database of the results of LDAR surveys in North America. In total, data from **4,378 surveys** were included in the database, covering all potential sources of emissions (both leaks and vents), and included **58,181 sources** with quantified emission rates. The database contains information on the emitting component, the gas emissions rate, the type of gas emitted, the type of repair required, the repair costs, and the repair lifetime for each individual emission source detected in the surveys. Facility specific information such as age, size, operating mode and the technology used are not available.

ECCC asked the support of Carbon Limits to answer specific questions concerning leak detection and repair programs, based on the information contained in the database and the company's analysis of the data.

1.2 General methodology and approach

As mentioned above, Carbon Limits has developed a database of results of LDAR surveys. The database is based on figures collected during surveys[1] carried out by two private firms that provide gas emission detection and measurement services to the oil and gas industry. The data were made available to Carbon Limits in an anonymous form and checked for quality/consistency before being entered into a database.

As part of the surveys, facilities were first screened using infrared (IR) cameras to locate hydrocarbon gas emissions. Identified emissions were then either measured or estimated. An emission register, which includes estimations of the costs of repairs to reduce emissions, was then produced by the company conducting the survey and delivered to the facility owner.

[1] Performed before 2014

For the analysis presented in this report, only Canadian data have been used and are presented. Table 1 presents the number of emission surveys available for the analysis and the number of emission points detected during these surveys.

Table 1: Number of surveys and emissions points in the database

	Number of emission points	Number of surveys performed
Canada	40 344	3 913
Canada – only main facilities categories[2]	37 316	3 828
Full dataset (including all US data)	58 181	4 378

In all this analysis, sites are grouped into 5 main categories:

- Gas plants; Gas treatment and processing plants
- Compressor stations: This category includes both booster stations and compression stations in the transmission network;
- Wellsite: Wellsites typically include only a well head and associated equipment. Equipment on sites may include controllers, pumps, valves, connectors, odor pots, PRV[3];
- Single well battery: Single well battery is a well battery with only one well head. Contrary to a wellsite, it would usually have some additional equipment on site other than the well head (typically an oil/liquids storage tank, and/or separator, etc.);
- Multi well battery: Multi well battery is a gathering point for more than one wellhead. Typically a well battery includes oil/liquids storage tank, and/or separator;

Wellsite, multi well battery, and single well battery are together referred as «Wellsite and well batteries» or «production sites».
Emission points are classified into two main categories: leaks (unintended emission points) and vents (engineered emission points). It is important to highlight that some component which typical vents (e.g. controllers) may also present some additional leaks[4].

All the classification of emission points in the database have been performed by the survey company and are thus, to some extent, subject to personal interpretation. The database has however undergone a thorough QC process to limit human bias.

Finally, it is important to highlight that the facilities in the database are regularly surveyed. As a result, the analysis does not reflect the potential emission reductions for facilities which are not regularly surveyed.

1.3 Report Structure

The report is organized into 5 main sections, each section covering one of the five main themes/questions identified by ECCC:

- Frequency of occurrence of leakages
- Emission profile from Wellsite and well batteries
- Categorization of type of repair and their relative frequency
- LDAR abatement cost depending on the repair timeline
- Leak profile depending on the LDAR frequency

The five sections are structured as follows:

[2] Facilities such as Bitumen processing, Sagd and Straddle plants are excluded
[3] Pressure Relief Valve
[4] Note: In this analysis, excessive vents due to malfunctionning equipment are classified as vents.

- Objective and approach for this analysis: The main question targeted by the analysis is presented. The methodology applied in each specific case is also described including an assessment of the number of data points available for each analysis.
- Results: Key results are presented, typically as a series of figures and tables. Limitations to the analysis are highlighted when relevant.
- Conclusion: Finally, conclusions, main trends and relevant discussions are presented.

2. Frequency of occurrence of leakages

2.1 Objective and approach for this analysis

This first analysis aims at understanding what is the number of leaking points by type of facility. Given the variability of the results, the minimum, maximum, and average number of leaking points by facility type are presented. In addition a full distribution analysis has been performed.

For this analysis, the results of 3828 surveys and information on 21 471 emission points were used (see Table 2).

Table 2: Number of data points used for the analysis on the frequency of occurrence of leakages

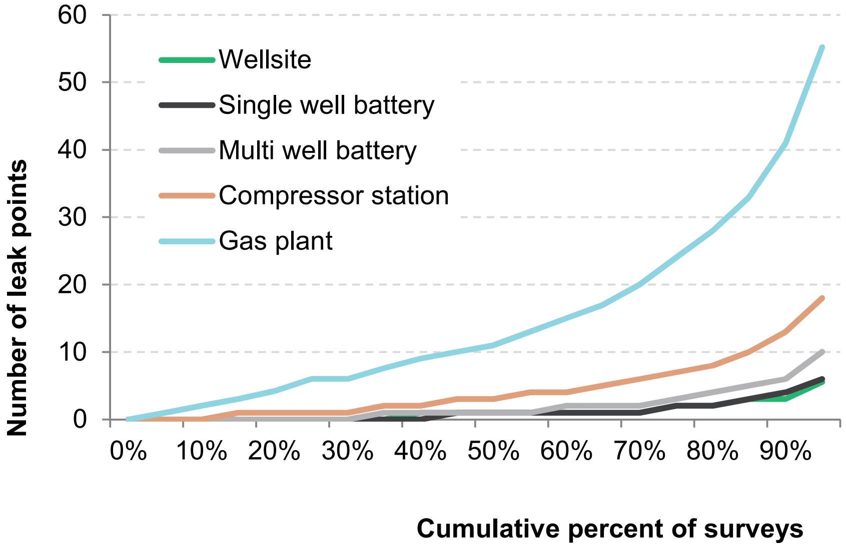
	Number of surveys	Number of leak points
Compressor station	1661	9357
Gas plant	437	8188
Multi well battery	1113	2664
Single well battery	511	728
Wellsite	106	189

Given the measurement campaign procedure (section1.2), emission points with an emission rate below the detection limit of the IR camera (typically 0.8g/hr for methane) were not reported in the database. Very small emission points may have thus been missed by this analysis.

2.2 Results

The number of leak points per facility is highly variable in the database analyzed, ranging from 267 leaks in one gas plant to no leaks (only vent) detected in 863 surveys. The number of leak point depends on the type of facility surveyed, with the largest concentration of leak points in gas plants and compressor stations. On average, 19 leak points are identified in each gas plant, about 6 leak point per compressor station, and about 2 per production site (**Error! Reference source not found.** and Figure 1). However, given the type of distribution (see Figure 2 and Figure 3), the average number of points should always be considered with care as it is highly influenced by the few outliers.

Figure 1: Distribution of the number of leak per survey. [5]



The following two figures present the distributions of survey depending on the number of leaks detected. Distribution for wellsite and well batteries and other sites (compressors and gas plants) are presented with two different scales.

Figure 2: Wellsite and well batteries – Distribution of surveys depending on the number of leaks detected per survey

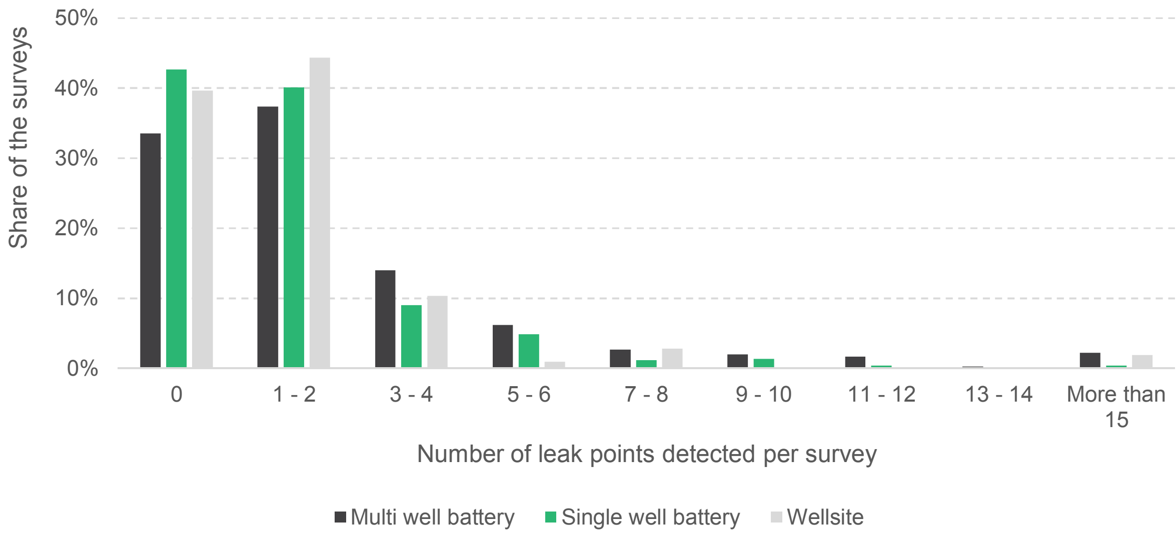
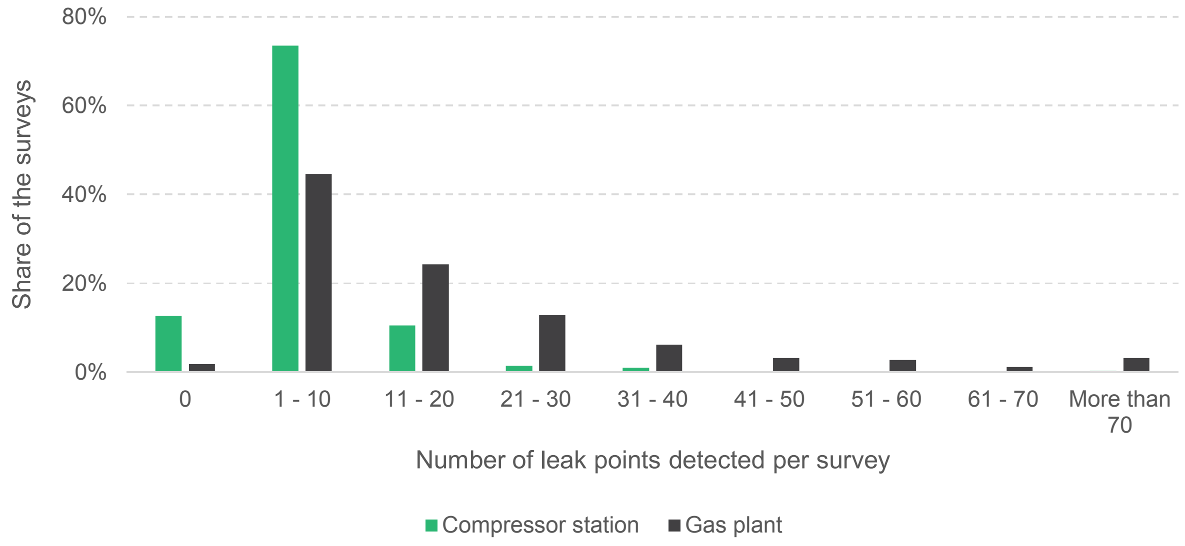


Figure 3: Gas plants and compressor sites – Distribution of surveys depending on the number of leaks detected per survey

[5] The 100th percentile (i.e the maximum) is not presented to make the figure more readable



2.3 Conclusion

The number of leak points per facility varies widely. A few key conclusions can be drawn from the analysis performed:

Production facilities (well battery, wellsites): Though a few production facilities have a large number of leak points, the vast majority (75%) of facilities present less than 2 leak points. For 37% of the surveys reviewed, the measurement team only identified vents (i.e. no leaks). In only 3% of the surveys, more than 10 leaks point were detected.

Compressor stations: Compressor stations present on average a larger number of leak points compared to production sites. In 86% of the surveys performed, less than 10 leak points were detected. No leak points were detected in about 13% of the facilities covered, whereas 8% of the compressor stations have more than 15 leak points.

Gas plants: Unsurprisingly, Gas plants include the highest concentration of leak points. In total 54% of the facilities had more than 10 leak points, and 16% had more than 30 leak points. While gas plants typically represent a high concentration of leak, 2% of the gas plants did not present any leak at all (i.e. only vents).

Finally it is important to highlight that a LDAR survey may also allow detecting important and /or improper vent points (e.g. open hatches) which can be easily fixed. The benefits of these are not included in the analysis presented here.

3. Emission profile from wellsite and well batteries

3.1 Objective and approach for this analysis

This analysis aims at understanding in more detail the emissions patterns from production sites. Productions sites are presented into three subcategories: multi well batteries, single well batteries, and wellsites. For each subcategory, the statistical review aims at evaluating the number of emitting components and the emission rates per survey (distinguishing vents and leaks).

For this analysis 1730 survey results were analyzed (Table 3)

Table 3: Number of data points used for the analysis on the emission profiles from wellsite and well batteries

	Number of surveys	Number of emission points (leak and vent points)
Multi well battery	1113	5918
Wellsite	106	474
Single well battery	511	2044

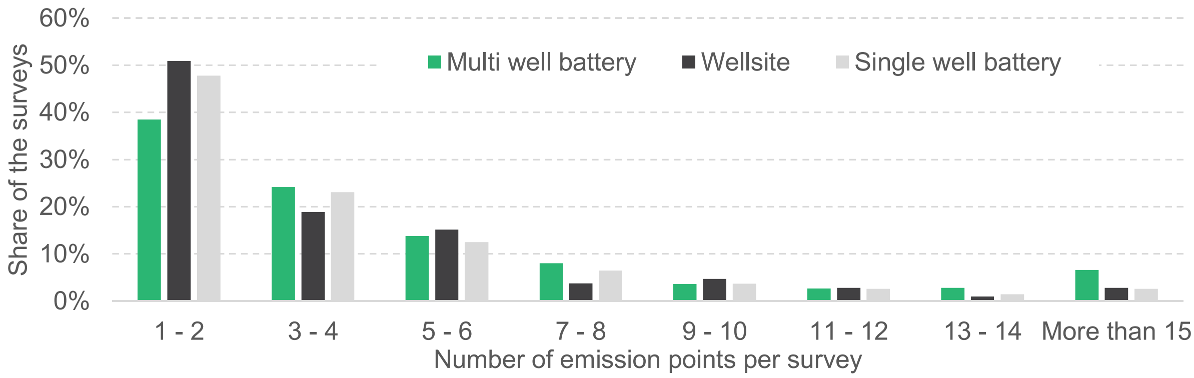
It is important to highlight that the classification of production sites into subcategories is performed by the measurement team and is thus subject to a certain level of personal appreciation.

3.2 Results

Number of emission points

The project team first evaluated the number of emission points per survey, independently of the magnitude of the emission. The median number of points detected is 3 for both multi well battery and single well battery, while it is only 2 for wellsites. The distribution of the number of emission points is presented in Figure 4.

Figure 4: Wellsite and well batteries – Distribution of surveys depending on the number of emission point detected per survey



Focusing on leaks, there are more leak points per multi well battery than for either single well battery or wellsites, the last two showing a similar trend (Table 4). In terms of vents, the number of vent emission points follows a similar pattern for all three subcategories (Table 5) (please refer to section 3.3 for more details)

Table 4: Number of leaks detected per survey

	Min Value	Percentile - 20%	Percentile - 40%	Percentile - 60%	Percentile - 80%	Max
Multi well battery	0	0	1	2	4	29
Wellsite	0	0	1	1	2	42
Single well battery	0	0	0	1	2	25

Table 5: Number of vents detected per survey

	Min Value	Percentile - 20%	Percentile - 40%	Percentile - 60%	Percentile - 80%	Max
Multi well battery	0	1	1	2	4	37
Wellsite	0	1	1	2	4	38
Single well battery	0	1	1	2	4	23

Magnitude of emissions

Figure 5 presents the distribution in terms of emission rate per survey for the three production facility subcategories, while Figure 6 illustrates the average emission rate per subcategory[6]. Emissions from multi well batteries are significantly higher than emissions from both wellsite and single well battery.

Figure 5: Distribution of surveys depending on the total emission rate per survey

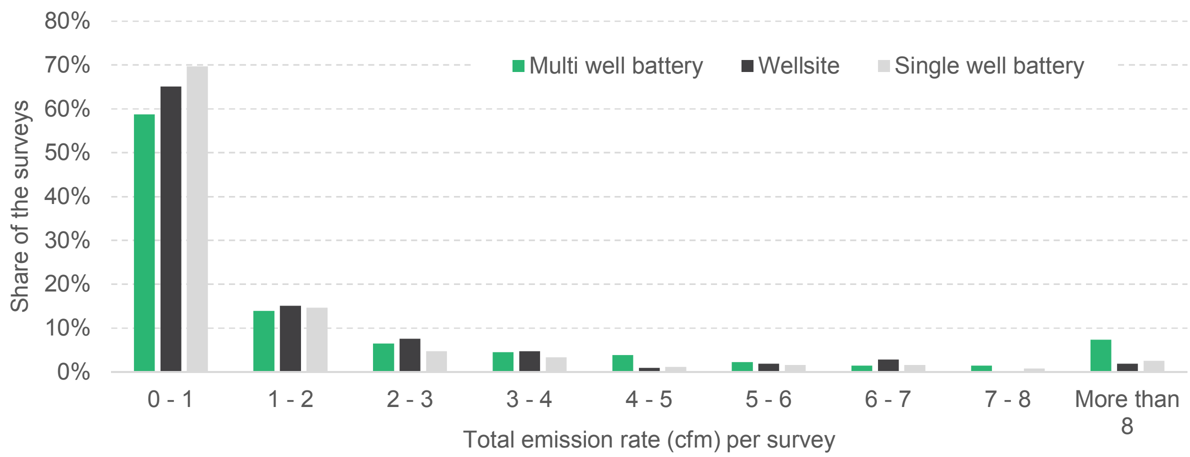


Figure 6: Average emission rate per survey

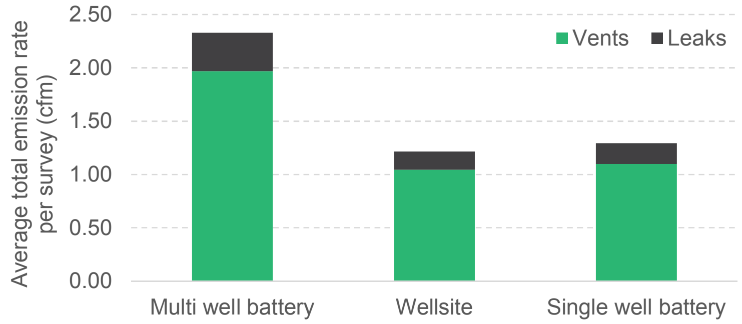


Figure 8 and Figure 7 illustrate the distribution of vent rates and leak rates per survey. Both wellsite and single well batteries follow fairly similar statistical distribution, while emissions from multi well batteries are higher.

Figure 7: Leak rate per survey (cfm) - Distribution[7]

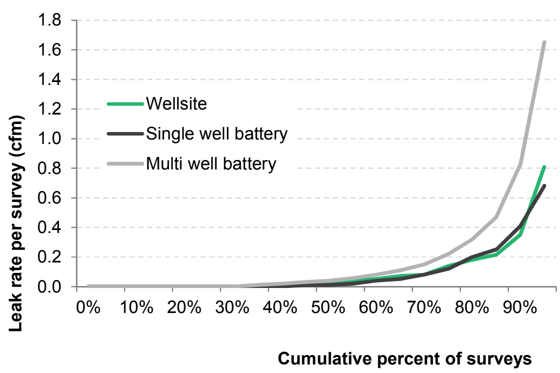
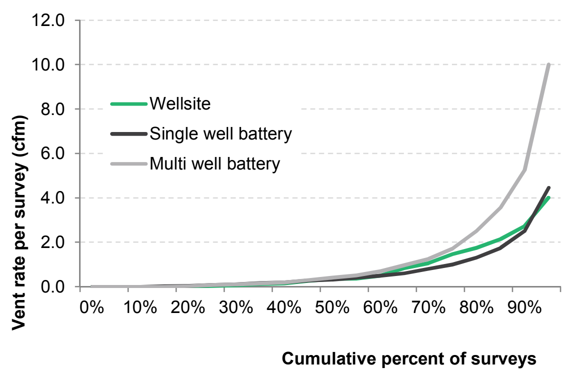


Figure 8: Vent rate per survey (cfm) - Distribution



[6] Important note: Given the heavy tailed distribution of the emission rate per site, the average emission rate is highly dependent on the emission rate of the few highest emitting sites.

[7] The 100th percentile is not presented to make the figure more readable

3.3 Conclusion

Multi well batteries present the largest emissions rate of the three facilities subcategories, while the two other subcategories have relatively similar emission profile. Overall the median number of emission points is 1 leak point and 2 vent points per production site. In terms of emission rate, the median rate of leaks varies from 0.01 to 0.04 cfm per production site and the median rate of vents varies from 0.3 to 0.4 cfm per production site.

The behavior of single well batteries compared to wellsites deserves additional investigation. Indeed, as single well batteries include additional equipment on-site (in particular storage tanks) compared to wellsites, it would have been natural to expect a higher number of vent points (and higher rates) for single well batteries.

A closer look at the vent type breakdown, however, provides additional insights on the results:

- The instrument controller is the largest source of vent occurrence in all 3 subcategories;
- Batteries (single well and multi wells) present a very high occurrence of tank hatch/vent emission points while this emission source is non-existent on wellsites. This is simply due to the fact that wellsites do not typically include tanks;
- Open lines and other vent points (including odor pot) venting represent an important share of the vents on wellsites and are not as predominant in well batteries. These two categories "compensate" for the storage tanks emission points. And as a result, the wellsite and the single well battery emission are more similar than originally expected.

Finally it is important to highlight that the sample size for wellsites is smaller than for batteries (single well and multi wells), which may have had some bearing on the conclusion.

4. Categorization of repair types and their relative frequency

4.1 Objective and approach for this analysis

During the measurement campaign, the measurement team documented not only the emission source and magnitude but also the recommended[8] repair required to reduce or eliminate the emission detected. As part of this analysis, the project team explored the repair types and their relative frequency. Some of these repairs can be performed on the spot immediately after detection, while others may require partial of full shut down of the facilities (and thus may be postponed to the next maintenance scheduled). This section thus also aims at documenting the relative frequency and share of repairs requiring shutdown, depending on facility type.

To perform this analysis, the long list of repairs descriptions have been classified into 9 repairs types described in Table 6.

Table 6: Repair type description

Repairs types	Description
Reseal	Open the connection, apply sealing material, re-tighten
Replace seal/gasket	Remove the old seal or gasket, and replace with new, re-tighten
Tightening	Simply tighten the joint/thread/connection
Replacing whole component	Replace the leaking component with a brand new one

[8] It is important to highlight that the recommended repair strategy proposed is not approved or validated by the operator. However, measurement companies, by the nature of their business, aim at providing high quality recommendations to their clients, the operator.

Service the component	Remove the component, service it and re-install it
Shut-in or disconnect the component	Take the component out of service by shutting in or disconnecting
Welding or patching	Perform welding or patching at the leaking point
Other	Other[9] or uncertain repair.

The project team then defined five different "repair timeline categories" presented in Table 7.

Table 7: Repair timeline categories description

Repairs timeline Categories	Description
Quick fix	Stop the leak immediately, with no interruptions in operations
No shutdown	Leaking component, or seal can be repaired/replaced with no interruptions in operations. Some material may be required (i.e. it may not be feasible to perform the repair during the LDAR but the repair can be performed in the next few weeks)
Equipment shutdown, standby or bypass	The facility or unit could be operational if a bypass line or standby unit could be used. If neither of these conditions are met, partial of full shutdown might be required.
Shutdown	The facility or a unit in the facility should be shut-down in order to perform repair/replacement
Uncertain	No or inconclusive information

To classify each leak point into a "repair timeline category", the project team evaluated the repair types as well as the component/equipment affected by a repair; since some equipment/components are more critical for the operation than others. For example storage tanks, building heaters and equipment that can temporarily put out of service can typically be repaired without any major interruptions on the main operation. At the opposite end of the spectrum, servicing a compressor (when no standby compressor is available) may require full or partial shutdown of a facility."

Overall 117 combinations of "component type" and "repair type" were analyzed. Each combination was associated to a repair timeline category (Table 7). The classification is based on expert assessment and aims at analyzing statistically the database in terms of repair timeline. Local circumstances may impact how each individual repair can be performed.

Based on this categorization, the relative occurrence and emission share per repair category and repair timeline category was calculated. For this analysis, the full dataset (leaks only) was analyzed.

4.2 Results

Figure 9 presents the relative frequency of leaks depending on the repair type category. The category "tightening" presents the largest frequency for all the facility type with about 50% of the leak points requiring tightening. The repair category "reseal" represent 15% of the leaks and the category "replace seal/gasket" represent 18% of the leaks. The LDAR service provider proposed to replace the component for only 3% of the leak points.

In terms of share of emission (Figure 10), the picture is more balanced with the repair category "tightening" representing only about 30% of the total leak rate. For 6 % of the total leak rate, a full

[9] In the following figures, the repair type with very limited occurrence are presented together in the section other.

component replacement is required. It is interesting to note that the average leak rate per leak point varies significantly depending on the repair category. While the average emission rate for the leaks in the category “tightening” is only 0.1 cfm, the components which need to be replaced leak on average 0.5 cfm.

The split varies between different facilities types (up to 18% difference). For example, tightening represents about 19% of the leak rate for production sites and 37% for gas plants. However, some pattern are similar for all facility types, for example, replacing a component represents a minor share of the leak rate for all the facilities types.

Figure 9: Relative frequency of different repair type depending on the facility type

Figure 10: Share of leaks for the different repair type depending on the facility type

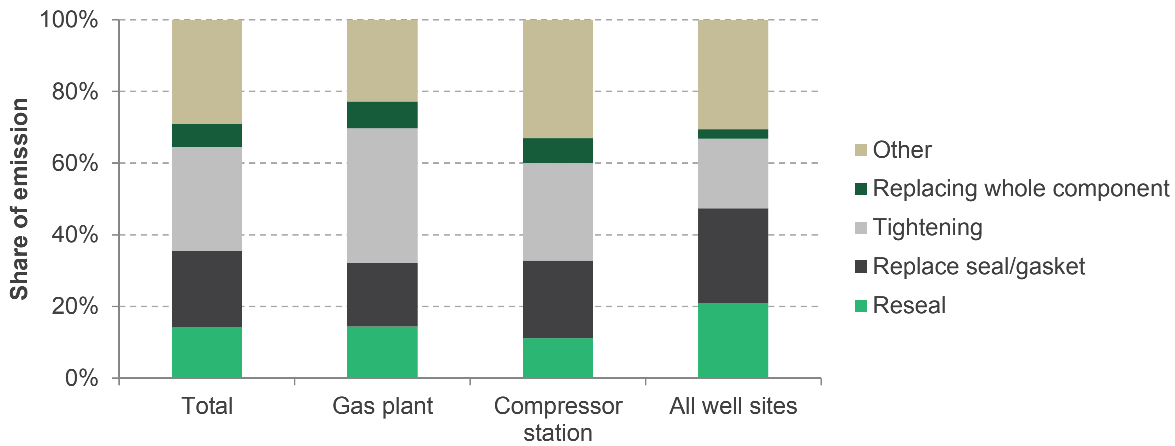


Figure 11 and Figure 12 present the relative frequency and share of leak for different repair timeline categories as defined in Table 7. This analysis demonstrates that about half of the leak points detected can be fixed on the spot, while another 15% of the leak points can be fixed without any shutdown. It may be required to perform a full or a partial shutdown for about 26% of the leak points detected. These proportions do not vary significantly between installation types but quick fix leak points are slightly more frequent in gas plants than in other types of installations.

In terms of share of emission (Figure 12), about 30% of the leak rate detected can be fixed on the spot and another 22% can be fixed without shutdown. It may be required to perform a full or a partial shutdown for about 33% of the total leak rate. The assessment was uncertain for 16% of the leak rate.

Figure 11: Relative frequency of different re pair timeline category depending on the facility type

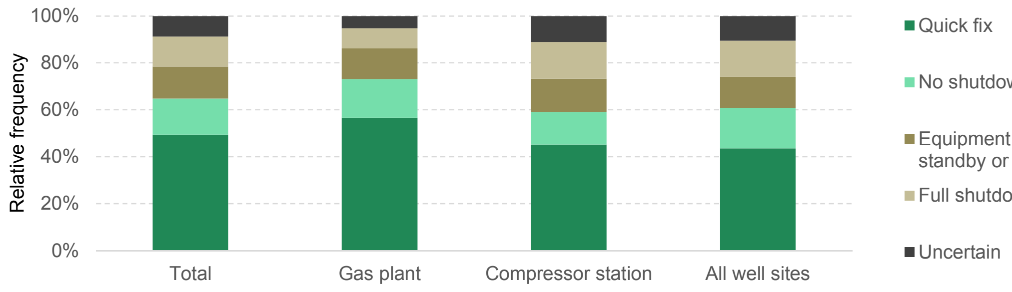
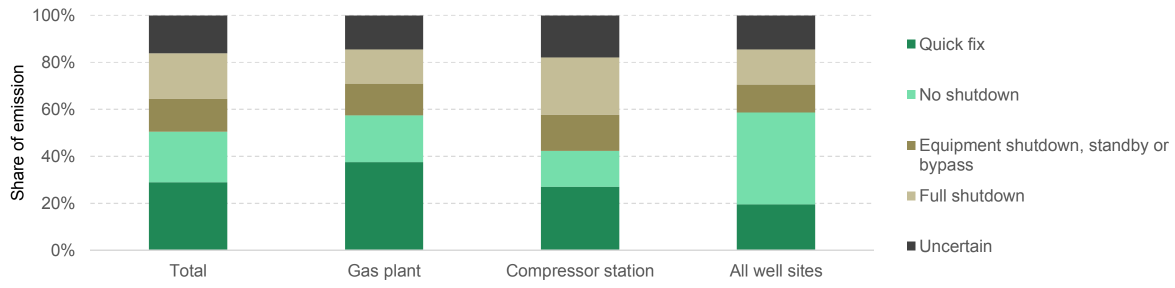


Figure 12: Share of leaks for the different repair timeline category depending on the facility type



4.3 Conclusion

A detailed review of the repairs recommendations depending on the component/equipment type has allowed to understand in more detail the types of repairs which can be performed without shutdown and the repairs which may need to be postponed to the next maintenance.

Overall, 65% of the leak points detected and 50% of the leak rate can be fixed either immediately or without partial or full shutdown. This proportion varies from 42% in compressor stations to 57% for gas plants.
For 26% of the leak points and 33% of the leak rate, partial or full shutdown may be required. In a number of cases, the facility or unit could be operational during the repair if a bypass line or standby unit could be used, these numbers thus represent an upper bound estimate.
Finally, the classification was inconclusive for 9% of the leak points detected and 16% of the leak rate.

5. LDAR Abatement cost depending on the repair timeline

5.1 Objective and approach for this analysis

In the report «Quantifying cost-effectiveness of systematic Leak Detection (LDAR) using infrared cameras»[10], the abatement costs were estimated based on the assumption that repairs will be performed immediately after the LDAR survey. As presented in the previous section, a detailled review of the repair types underlined the fact that a portion of the leaks may only be fixed during a partial or a full shutdown and may thus be postponed until the next scheduled maintenance.

This section thus aims at evaluating the abatement cost depending on the delay of the repairs. Three scenarios have been constructed (Table 8):

- No delay: all the leaks are repaired just after the LDAR survey
- Partial delay: On the spot repair and repairs which can be performed without operation interruption are performed immediately after the LDAR. All the other repairs (including unclassified repairs) are performed one year after the LDAR.

[10] http://carbonlimits.no/project/quantifying-cost-effectiveness-of-systematic-leak-detection-ldar-using-infrared-cameras/

- All delay: All the repairs are performed one year after the original LDAR. This case is presented as a conservative extreme, as operators have a strong incentive to repair "easy fix" leaks as early as possible.

Table 8: introduction to the delay scenario

		NO DELAY	PARTIAL DELAY	ALL DELAY
1	**Quick fix**	Immediately after LDAR	Immediately after LDAR	One year after LDAR
2	**No shutdown**	Immediately after LDAR	Immediately after LDAR	One year after LDAR
3	**Equipment shutdown, standby or bypass**	Immediately after LDAR	One year after LDAR	One year after LDAR
4	**Full shutdown**	Immediately after LDAR	One year after LDAR	One year after LDAR
5	**Uncertain**	Immediately after LDAR	One year after LDAR	One year after LDAR

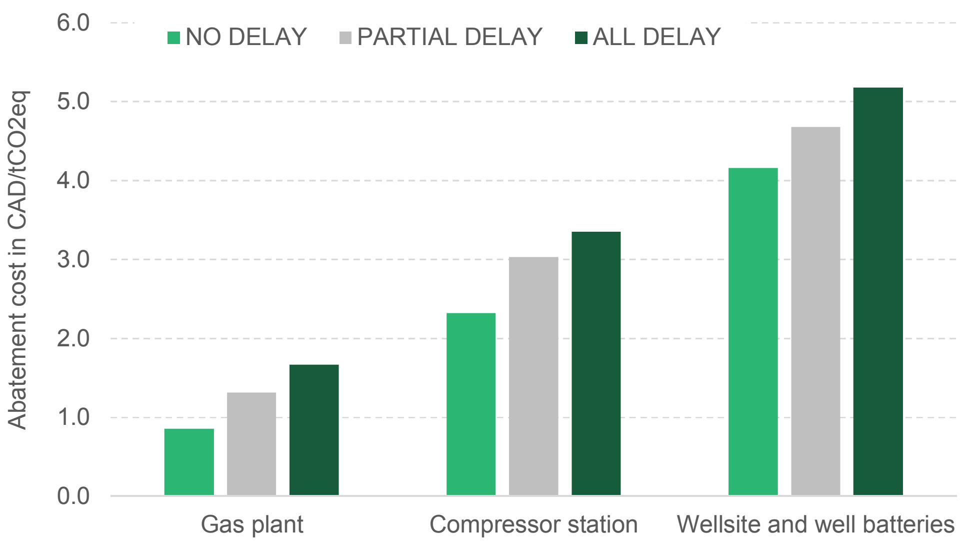
For the abatement cost calculation, an interest rate of 7% and a gas price of 3 CAD/Mscf have been assumed. The GWP of methane used for this analysis is 25. The methodology applied is described in the original report section 3.2[11]. For this analysis, it is assumed that the repairs from categories 3 to 5 are performed during a planned shutdown. Scheduling a shutdown to repair these leaks would impact heavily the cost and thus the abatement cost calculated.

5.2 Results and conclusions

The following figure presents the aggregated abatement cost depending on the delay scenario and on the facility type. As expected, delaying repairs have a negative impact (i.e. increase) the abatement costs. In the "partial delay" scenario, abatement costs increase by 0.5 to 0.7 CAD/tCO_2eq depending on the facility type. Delaying all the repairs by one year (conservative scenario) increases the abatement costs by 0.8 to 1 CAD/tCO_2eq. Overall the impact of the delay is quite modest and all abatement costs calculated remains below 5 CAD/tCO_2eq.

Though the abatement cost is only slightly impacted by the delay, the cumulative emissions is, of course, heavily impacted by this delay. (see section 6.3)

Figure 13: Abatement cost depending on the delay scenario and the facility type[12]



[11] http://carbonlimits.no/project/quantifying-cost-effectiveness-of-systematic-leak-detection-ldar-using-infrared-cameras/
[12] Benefits from improper vent fixing (closing open hatches) are not included in these estimates.

6. Leak profile depending on the LDAR frequency

6.1 Objective and approach for this analysis

This analysis aims at evaluating how the frequency of survey impacts the leak rate and occurrence. Assuming that repairs are performed after each LDAR, frequent LDAR should result in lower leak rate over time.

The database used in this report includes surveys performed at a variety of facilities. Some of the facilities are surveyed once every year or once every two years, while others are surveyed less frequently. It was possible to extract definitive information[13] on the survey frequency for 10% of the total surveys in the database (i.e. 543 surveys)[14]. Almost 80% of these repeat surveys were performed one year since the last survey. The following table presents the number of surveys available depending on frequency information. The size of the sample for this analysis is therefore much smaller than that used in previous analysis.

Table 9: Summary of the number of survey depending on the frequency information

	No information available on the date of the last survey	1 year since the last survey	2 years since the last survey	More than 2 years since the last survey
Gas plant	337	76	16	8
Compressor station	1372	221	62	6
Multi well battery	1047	51	13	2
Single well battery	502	8	1	0
Wellsite	104	2	0	0
Wellsite and well batteries	1653	61	14	2
Total	5015	419	106	18

It is important to highlight that the database includes only surveys commissioned by oil and gas companies to the two measurement companies. An oil and gas operator may choose to terminate his contract with a specific provider but may continue to perform surveys using internal resources or using a different service provider. An operator may also have run surveys internally and then decided to subcontract the LDAR. As a result, and by nature, the database provides an incomplete snapshot of the frequency of the LDAR survey for a given facility.

6.2 Results

Figure 14 presents the average number of leaks per survey for different categories of survey frequencies. Given the low number of surveys available, the two categories with 2 or more years since the last survey are presented together. The median number of leaks is also presented for all the categories (Figure 15).

[13] i.e. clear reference that the same installation has been surveyed at a specific date
[14] While definitive frequency information is only available for 10% of the surveys, it is clear, based on interviews that the facilities in our database are typically surveyed every one or two years.

Figure 14: Average number of leaks per survey depending on the frequency

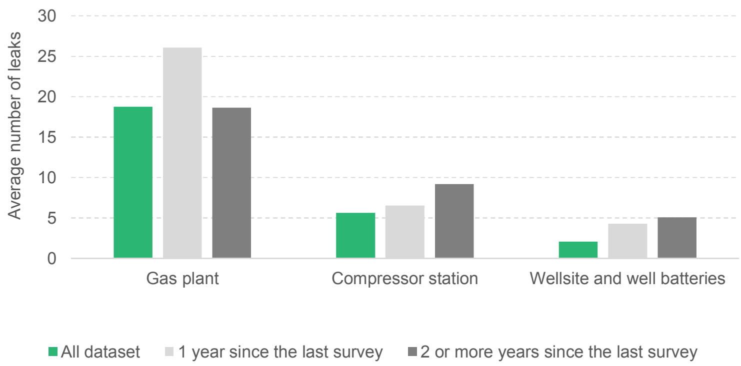
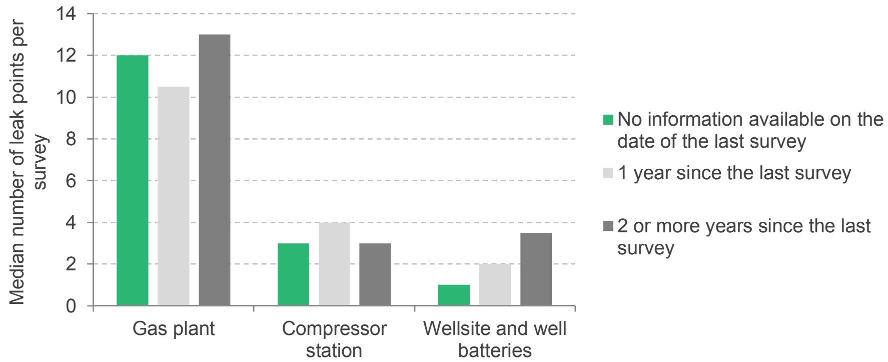


Figure 15: Median number of leaks per survey depending on the frequency



The next two graphs present the average and the median leak rate per survey for the different categories. For all these four figures, it would be expected that both the number and the rate of the leak will be higher for sites surveyed less than once a year. However, the expected trend is not confirmed by the analysis (see next section for further analysis).

Figure 16: Average leak rate per survey depending on the frequency of survey

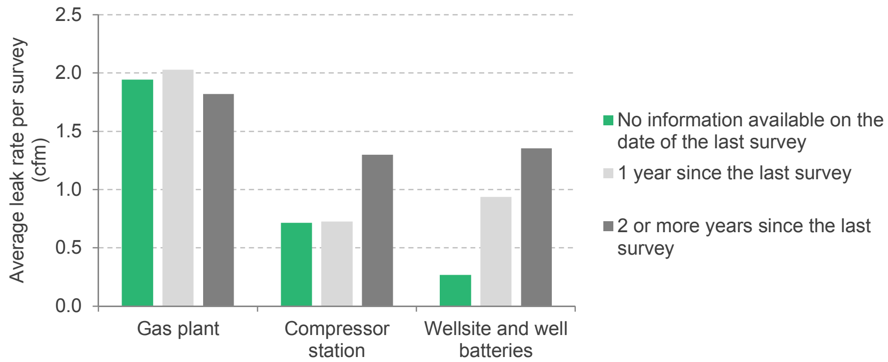
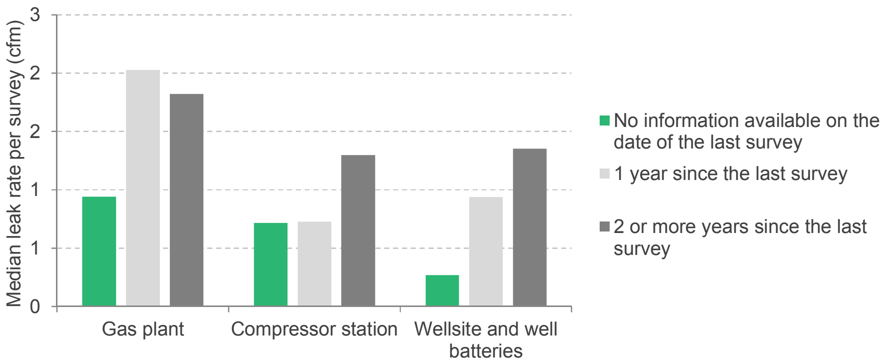


Figure 17: Median leak rate per survey depending on the frequency of survey



The project team also wanted to evaluate if the frequency of survey influenced the number and rate of the largest emitters (for this analysis, large emitter are leaks with a rate higher than 0.3 cfm), to confirm the hypothesis that regular LDAR may prevent the formation of the largest leaks. The following analysis aims at evaluating this assumption. Table 10 and Table 11 present both the number of large emitters and the average leak rate from these high emitters depending on the frequency of survey[15].

For this analysis, the trend is much clearer, with lower frequency being associated with both larger number of leak large emitters and larger leak rate from large emitters.

Table 10: Average number of large leak (>0.3 cfm) per survey

	No information available on the date of the last survey	1 year since the last survey	2 or more years since the last survey
Gas plant	1.2	1.1	1.1
Compressor station	0.4	0.5	1.1
Wellsite and well batteries	0.2	0.3	0.3

Table 11: Average leak rate from large leak (>0.3 cfm) per survey (cfm)

	No information available on the date of the last survey	1 year since the last survey	2 or more years since the last survey
Gas plant	1.1	0.9	0.9
Compressor station	0.4	0.3	0.6
Wellsite and well batteries	0.2	0.7	1.1

6.3 Conclusion

The analysis performed does not show any strong correlation between the frequency (information available in the database) and the number of leak points or the rate of leakage detected. Three main reasons can explain the lack of trend:

- **The dataset does not represent the full history of facilities:** As mentioned above, facilities may have been surveyed by internal staff or by another measurement company. In addition, surveys may not always be followed by repairs of all the emission points identified;
- **Potential bias by size of facility:** Size of the facility is not available in the database. It would not be surprising for an operator to survey more frequently large facilities (in particular gas plants and compressor stations) than smaller ones. This would create a bias and limit the possibility to compare on the same level depending on the frequency.

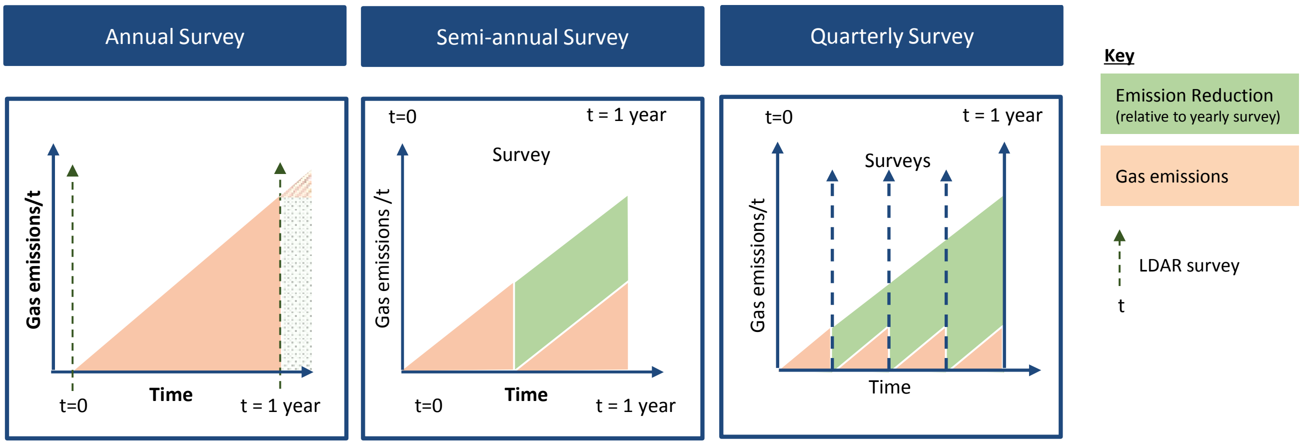
[15] Median are not interesting to present here as many sites (fortunately) do not present any large leak.

- **Size of the sample**: The sample size for facilities with 2 or more years since the last survey is relatively small for many facility types. As a result, this analysis may not be as statistically representative as the other analyses presented in this document;

To conclude, the database does not allow confirming (or rebutting) the assumption «more frequent LDAR leads to lower leak rate detected at each survey». The analysis compared annual surveys to survey performed less frequently.

Finally, the Figure 18 below presents a theoretical model on how survey frequency impacts emission over time. In this model, it is assumed that leaks appear randomly and linearly over one year. The database does not allow to confirm or rebut this assumption, however the experience from a large sample of LDAR demonstrates that a **number of leaks are identified when annual survey are performed.**
In this context, increasing the frequency of the leak detection and repair survey will have a positive impact on the emission reduction that can be achieved, as the leaks are detected and can be repaired earlier. Obviously, the abatement cost increase with the survey frequency (see p 22 on the report: http://catf.us/resources/publications/files/Carbon_Limits_LDAR.pdf)

Figure 18: theoretical overview on how emissions over time depending on the survey frequency.[16]



7. Key conclusions from the analysis

The analysis of the results of 3 828 surveys in Canada representing 37 483 emission points shed some light on a number of aspects of repeated LDAR. The following list presents the key conclusions from the analysis:

- In average, through the large sample of information, six leak points were identified during each survey. The number of leak points per facility varies widely:
  - The vast majority of wellsite and well batteries (75%) present less than 2 leak points and 37% presented no leak points (e.g. only vents)
  - 86 % of the compressor stations present less than 10 leaks and
  - 84 % of gas plants present less than 30 leaks
  - A small number of facilities, however, present an important number of leaks (up to 267 leaks for one of the facilities surveyed).
- Multi well batteries present the largest emissions rate of the production sites:

[16] It is important to highlight that we assumed, in this simple sketch, that all the leaks are repaired quickly after the survey. This assumption is not realistic for leaks which cannot be repaired without shutdown of the facility or process unit (generally, repair of those leaks will be delayed until the next planned shutdown) . As a result, emissions reduction are overestimated in regards to this aspect.

  - The median number of leaks is 1 per production site and the median number of vents is 2 per production site
  - The median total vent rate per survey is 0.3 cfm per production site, while the median leak rate is inferior to 0.1 cfm
  - Instrument controllers, tanks, open lines and odor pots are the most frequent sources of vent in wellsite and well batteries.
- A detailed review of the repairs recommendations depending on the component/equipment type has allowed to understand in more details the types of repairs which can be performed without shutdown and the repairs which may need to be postponed to the next maintenance.
  - Overall, at least 64% of the leaks detected and 50% of the leak rate can be fixed either immediately or without shutdown.
  - For 26% of the leak points and 33% of the leak rate, partial or full shutdown may be required.
  - Delaying all the repairs by one year increase the aggregate abatement cost by only up to 1 CAD/tCO2eq. Though the abatement cost is only slightly impacted by the delay, the cumulative emissions is, of course, heavily impacted by the delay.
- Comparing facilities surveyed annual or less frequently, the database did not allow to confirm (or rebut) the assumption «more frequent LDAR leads to lower leak rate detected at each survey». However the experience from a large sample of LDAR demonstrates that a number of leaks are identified when annual surveys are performed. In theory, increasing the survey frequency will reduce the cumulative emission over time but will increase the abatement costs.

CARBON LIMITS

Statistical Analysis of leak detection and repair in Canada

Extension

CARBON LIMITS

This report was prepared by Carbon Limits AS.

Project title:
Statistical Analysis of leak detection and repair in Canada

Client:	Environment Canada
Project leader:	Stephanie Saunier
Project members:	Stephanie Saunier, Hesam Darani
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Carbon Limits is a consulting company with long standing experience in supporting energy efficiency measures in the petroleum industry. In particular, our team works in close collaboration with industries, government, and public bodies to identify and address inefficiencies in the use of natural gas and through this achieve reductions in greenhouse gas emissions and other air pollutants.

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Acronym

cfm	cubic feet per minute
CH_4	Methane
ECCC	Environment and Climate Change Canada
LDAR	Leak Detection and Repair
OEL	Open Ended Line
OGAED	Oil, Gas and Alternative Energy Division
PRV	Pressure Relief Valve

1. Comparison of the distribution of emissions per component between US and Canada

1.1 Objective and approach for this analysis

This section aims at evaluating whether US and Canada components have statistically similar emission profiles. To perform a robust comparison, the project team selected four different component types based on the following criteria:

- Only typical leak emission sources were considered
- Only components which could be fully categorized were considered[1]
- Only components with a sample size higher than 200 for both US and Canada were considered

For each of the components selected, a distribution curve was prepared for both US and Canada and the two distribution curves were presented together.

Finally two different "tests" have been performed to compare quantitatively the two distributions:

- **Two samples Kolmogorov-Smirnov Test or k-s test**[2]: The two sample Kolmogorov-Smirnov test is used to test whether two samples (here US and Canada components) come from the same distribution.
- **Gini coefficient**[3]: The Gini coefficient is a measure of statistical dispersion. The Gini coefficient measures the inequality among values of a frequency distribution (for example, levels of income and here emission per component). A Gini coefficient of zero expresses perfect equality, where all values are the same (all components within one category emit exactly the same). A Gini coefficient of 100% expresses maximal inequality among values (e.g. if one component emits highly while all the other components emits nothing the Gini coefficient would then be very nearly one). The Gini coefficient has been used to compare how "skewed" the US and the Canada distribution are.[4] The approach was first presented in Zavala-Araiza et al.[5]

1.2 Results

The following graphs present the distribution of emissions (on the left in normal scale and on the right on log scale) for the four types of components selected for both US and Canada.

[1] In particular non classified valve and connection were not considered.
[2] http://www.real-statistics.com/non-parametric-tests/two-sample-kolmogorov-smirnov-test/
[3] https://en.wikipedia.org/wiki/Gini_coefficient
[4] For our analysis we have used the formula developed by Angus Deaton (Princeton) https://fastexcel.wordpress.com/2011/05/21/fast-gini/
[5] Zavala-Araiza D, Alvarez RA, Lyon DR, Allen DT, Marchese AJ, Zimmerle DJ, Hamburg SP. Super-emitters in natural gas infrastructure are caused by abnormal process conditions. Nature Communications. 2017;8

Figure 1: Emission distribution - Connection - flange

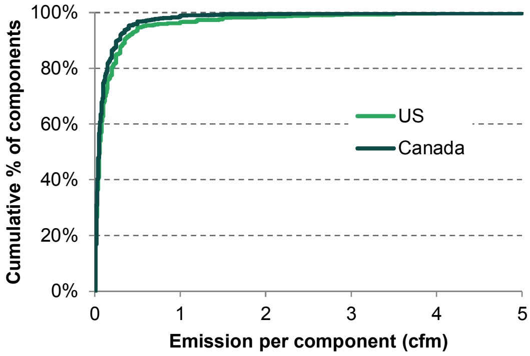


Figure 2: Emission distribution - Connection - flange

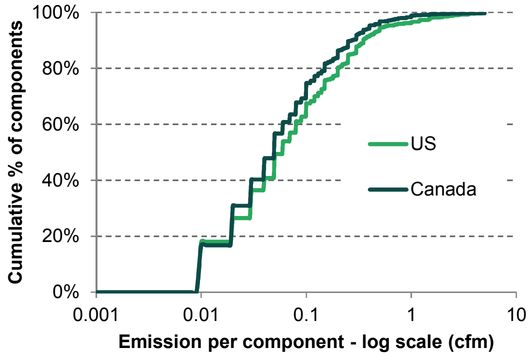


Figure 3: Emission distribution - Connection - Threaded

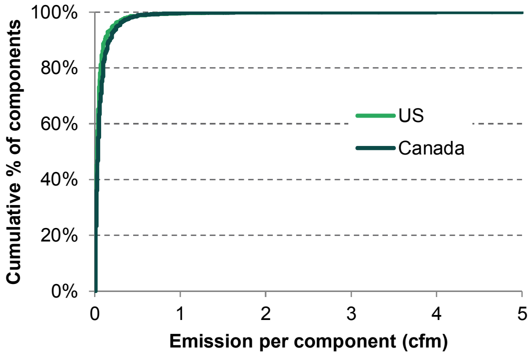


Figure 4:Emission distribution - Connection - Threaded

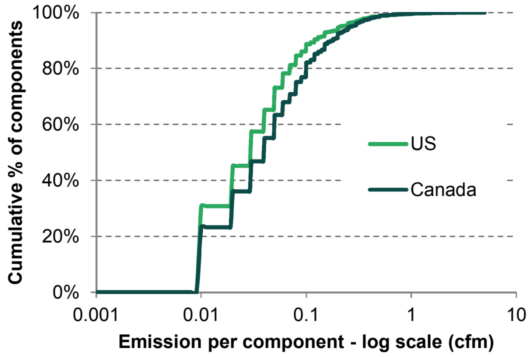


Figure 5: Emission distribution - PRV

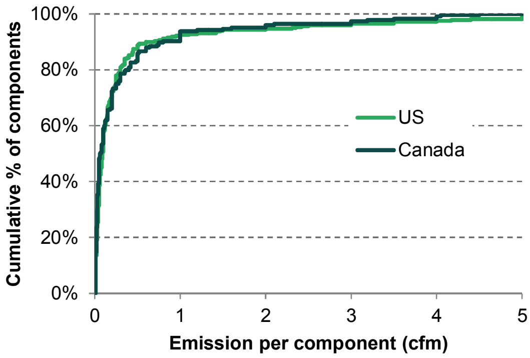


Figure 6: Emission distribution - PRV

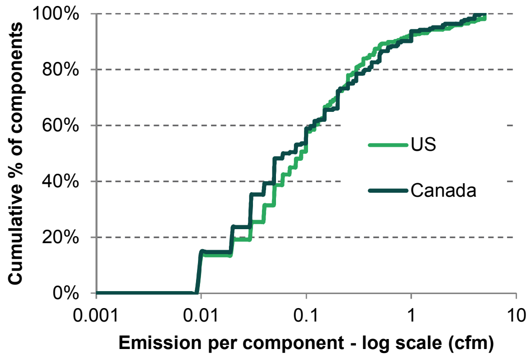


Figure 7: Emission distribution - Block Valve

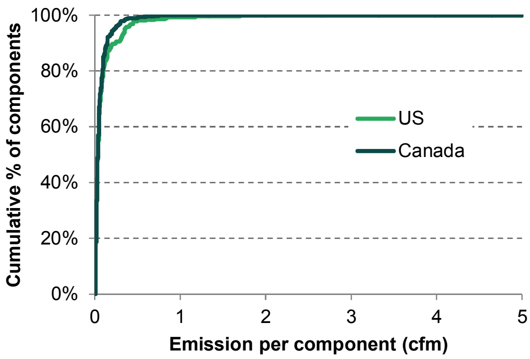
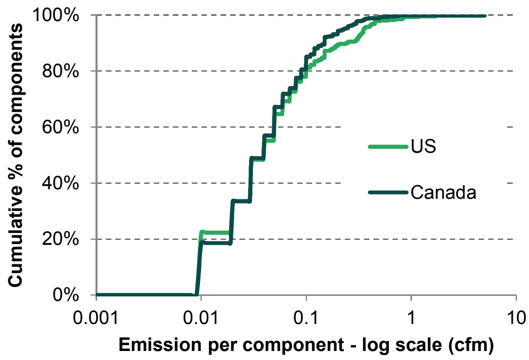


Figure 8: Emission distribution - Block Valve



The following table presents the results of the different tests evaluated for each of the four components. In the left part of the table, the results of the K-s test are presented. "YES" means the two samples comes from the same distribution. On the right part of the table, the Gini test results are presented as a percentage. The difference between the Gini test for US and for Canada is further calculated (right column). The following can be concluded from this table:

- **K-s test:**
  - PRV and Block Valve: We can conclude that the two samples (here US and Canada components) come from the same distribution.
  - Connection (flange and threaded): The k-s test indicates that there is a significant difference between the distributions for the samples
- **Gini coefficient**
  - All the Gini coefficients calculated for both US and Canada are higher than 62%. This highlights that the distributions are extremely skewed.
  - The Gini coefficients for connections or PRV are very close (within a few percent). Block valve Gini coefficient for US and Canada present a difference of 8%.

Table 1: Comparison between US and Canada components distributions

	k-s test	Gini Coefficient		
	α =0.1, 0.05 or 0.01	Canada	US	Difference
Connection	NO	64%	66%	2%
Connection	NO	71%	73%	2%
PRV	YES	77%	81%	3%
Block Valve	YES	62%	70%	8%

1.3 Conclusions

This analysis provides a number of new insights on the behavior of four emitting components in US and Canada:

- All the samples evaluated present a skewed distribution: A small share of the emitting components represent the majority of the emissions. This conclusion is true for both US and Canadian components.
- It seems that some components (e.g. PRV) tend to have a distribution more skewed than others (e.g. Threaded connection)
- Emissions distributions are fairly similar between US and Canada[6]

Based on the analysis, we can conclude that it is very likely that the results of leak distribution analysis performed in US at the component level are applicable to Canada[7]. It is however important to also underline that emission rates are determined by a large number of factors (for example type of maintenance, weather, pressure, etc), and that each of these factors may be very different between US and Canada.

2. Large emitters

2.1 Objective and approach for this analysis

As presented in the previous section, a small share of the components represents a large portion of the emissions. This section aims to understand and document which of the component types are the most likely to be large emitters and where the large emitters are located.

There is currently not one single definition for large or super emitters. Large emitters can be defined as the components emitting more than a certain threshold. They can also be defined as exceeding a certain a percentile threshold (for example the 1% of the component emitting the most) or can be defined vis-a-vis an average emission factor (e.g. 5 times the average emission factor). For our analysis, large emitters include all the components emitting more than 1 cfm. For Canada, about 6% of the emitting components in the database meet this threshold.[8]

As the database contains only the emitting components (and not the full list of component on the sites surveyed) it was not possible to evaluate the share of the existing components which emit more than 1 cfm. In the follow up analysis, only the share of the emitting components which emit more than 1 cfm is presented.

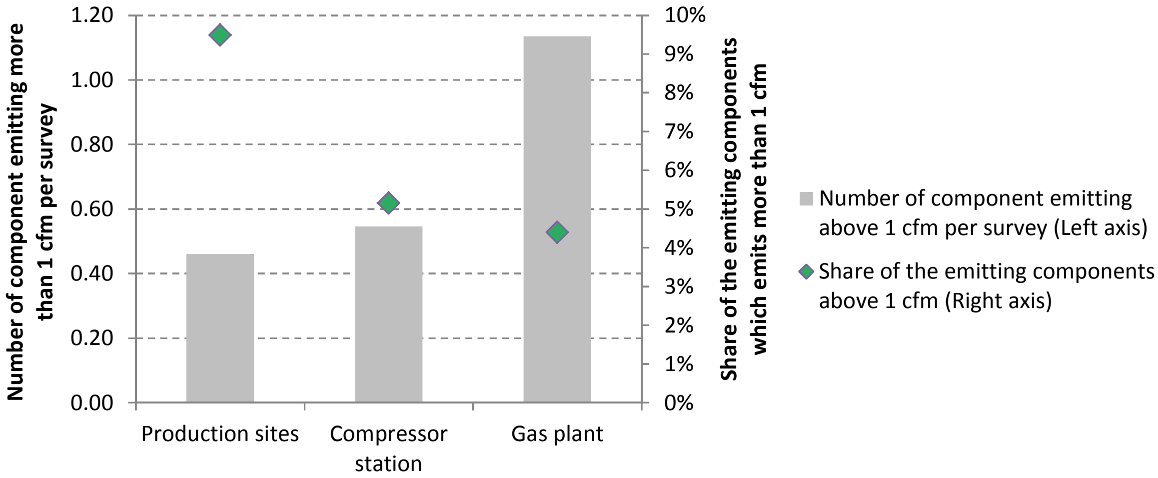
[6] Either the k-s test is positive which means that the two samples come from the same distribution or the gini coefficient are very close or both.
[7] Note: This analysis does not compare emissions profile per facility.
[8] Note: Different threshold are also tested in Table 2

2.2 Results

The following figures present the key results depending on the facility type (Figure 9) and on the component type (Figure 10). Two different metrics are presented on these graphs:

- The number of components emitting more than 1 cfm detected per survey. For example, 0.5 components emitting more than 1 cfm have been detected on average during each production site survey,
- The share of emitting components which emit more than 1 cfm[9]: this metric is more relevant for vents categories (where most of the components emit) than for leaks categories (where the vast majority of components do not emit).

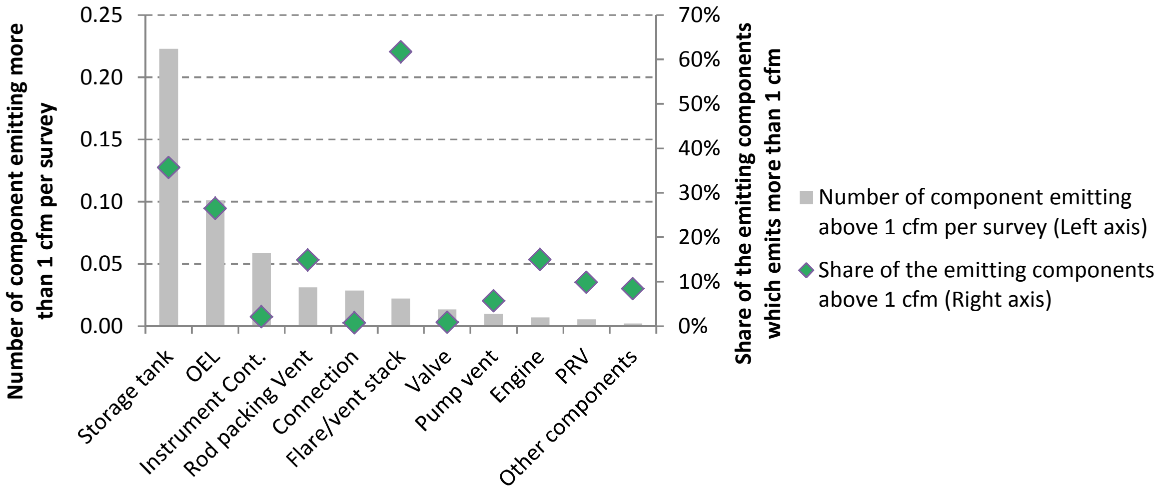
Figure 9: Large emitters per facility type[10]



The analysis per facility type reveals that there are on average about twice as many large emitters per gas plant survey compared to other types of facilities. This difference can be explained by the difference in the overall number of components between gas plants and other types of facilities. It is interesting however to note that the share of high emitting components is higher for well sites (almost 10%) than for gas plants (or compressor stations). A number of reasons could explain this difference, but we could assume that maintenance on gas plants may typically be more frequent and that large emission points may be addressed more often.

[9] See comment in the previous section
[10] Here the category well site include all the production sites subcategories (including well battery)

Figure 10: Large emitters per component type[11]



The analysis per component reveals important differences between different types of components. The three first categories of component (storage tanks vents, open ended lines and instrument controllers) represents together 0.4 large emitter per survey. Only 1% of the emitting connectors emit more than 1 cfm, while at the other end of the spectrum, more than 60% of the emitting vent/flare stack[12] exceeds 1 cfm. It is important to underline that different emission points may be gathered and emitted together on an open ended line or a vent/flare stack, which explains the large weight of these two types of components in the large emitter analysis.

Finally the Table 2 presents the share of emitting components and the share of emission depending on the threshold defined. The table demonstrates e.g. that only 3 % of the emitting components emit more than 2 cfm and that together they represent more than 40% of the emissions.

Table 2: Share of emitting components and share of emissions depending on the emission threshold.

Emission threshold (cfm)	0.8	1	1.2	1.4	1.6	1.8	2
Share of emitting components exceeding the threshold	6%	6%	4%	4%	3%	3%	3%
Share of the emission exceeding the threshold	58%	55%	49%	47%	44%	43%	42%

2.3 Conclusion

This analysis aimed at providing an understanding on where components emitting more than 1 cfm are located. In the dataset analyzed, only about 6% of the emitting components emit more than 1cfm, but these components represent more than 50% of the emissions.

The most important conclusion that can be drawn from this analysis is that these large emitters can be found in all types of facilities and for all types of components. Though some components are more likely to become large emitters, large emitters were identified in all the component categories and subcategories defined. As pointed out in previous documents, identifying as early as possible these large emitters will have a significant positive impact on the emissions.

[11] It is important to highlight that the emissions from storage tanks are particularly uncertain due to the typical measurement protocol for this source of emission.
[12] In this category only un-combusted gas is considered. The flare stacks are typically categorized as "unlit".