Quantifying Cost-effectiveness of Systematic Leak Detection and Repair Programs Using Infrared Cameras

CL report CL-13-27

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Carbon Limits is a consulting company with long standing experience in climate change policies and emission reduction project identification and development. Our team works in close collaboration with industries, government, and public bodies to reduce greenhouse gas emissions, particularly in the oil and gas sector.

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EXECUTIVE SUMMARY

Overview

About 30% of the US anthropogenic methane emissions originate from the oil and natural gas sector. Emissions are partly *leaks* and partly engineered *vents*. Almost 30% of methane emissions from onshore oil and natural gas facilities are from leaks (1), which here means fugitive leaks past static seals on valves, connectors, regulators, or other components. This report presents results from an empirical analysis of real data on the costs and benefits of leak detection and repair (LDAR) programs at oil and natural gas facilities. These programs use infrared cameras to detect sources of gas emissions, which in addition to methane include volatile organic compounds (VOCs). Once emission rates are measured or estimated, repairs can be conducted, reducing emissions by 90% or more. The economic merits of a LDAR program depend on the amount and value of the gas otherwise leaked and the costs of the LDAR program, comprising both survey and repair costs.

The analysis presented is based on data from 4,293 surveys of oil and gas facilities in the USA and Canada. These surveys identified 58,421 components, which were either leaking or venting gas; leaks were detected from 39,505 components. A database was created with information on gas emission rates, repair costs, and repair lifetime for each emission source, in addition to average survey costs. This database allows calculation of the costs and benefits of LDAR programs with various designs, which is the main product of this work. In addition to repairs of leaks from static components, the economics and mitigation potential of addressing excess reciprocating compressor rod packing emissions are also examined in this study and the results are briefly presented in this report.

Main results

Costs and benefits of LDAR programs were analysed for three categories of facilities: *(i) gas processing plants, (ii) compressor stations* in gas transmission and gas gathering systems, and *(iii) well sites and well batteries,* including single well heads and multi-well batteries (up to 15 well heads).

There is considerable variability in leak rates across the facilities surveyed. Gas processing plants leak the most; well sites and well batteries leak more modestly, with about one third having no reported leaks and only 7% having leaks above 500 thousand standard cubic feet (Mcf) per year. Compressor stations leak more than well sites and well batteries, but less than gas plants.

Table 1: Distribution of facilities within each category by leak rate (in Mcf per facility and per year)

Category:	No leaks	≤99	100-499	500-1499	≥ 1500
(i) Gas processing plants	3%	17%	32%	25%	23%
(ii) Compressor stations	11%	30%	36%	15%	9%
(iii) Well sites & well batteries	36%	38%	18%	5%	2%

The vast majority of leaks are economic to repair once identified: even assuming a low value of gas (3 US dollars (USD) per Mcf), leaks amounting to more than 97% of total leak emissions are worth repairing. In addition, over 90% of the gas emissions are from leaks that can be repaired with a payback period of less than one year.

> **This means that once the survey has been performed, it is economic to repair almost every leak, even at low gas prices. This finding drives many of the results of this study**.

The costs and benefits of LDAR programs were analysed from both an individual facility perspective, where the distribution of net present values (NPV) for facilities of each category is examined, and a public or corporate perspective, where the aggregate cost-effectiveness of conducting LDAR programs for a number of facilities (in a jurisdiction or owned by a single company) is considered. For these analyses, a **base case scenario** has been defined based on the following assumptions:

(i) the value of recovered gas is 4 USD/Mcf;
(ii) in addition to the *external* cost of hiring a firm to survey facilities for emissions, owners of those facilities pay for *internal* costs (*e.g.*, administration, paperwork) equal to half of the external cost;
(iii) facility owners fix all leaks that the survey identifies.

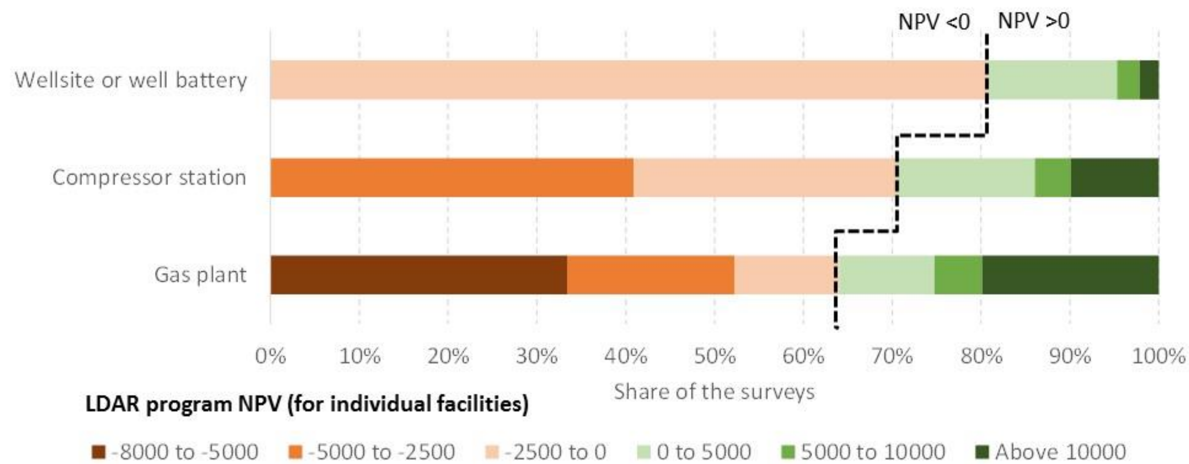
The base case presents results based on surveys as they were performed – with variable frequency. Alternative cases examined the cost-effectiveness of surveys at specific frequencies. Finally, changes in cost-effectiveness due to altering these and other assumptions, including the assumption that all leaks are fixed, were examined.

Economic assessments – Individual facilities

We first calculated the distribution of NPVs of LDAR programs conducted at individual facilities. We note that the detection surveys identified emissions from both leaks and vents. However, while this analysis considers the entire cost of surveys, it focuses on the potential benefits of leak repairs for static components. We also consider the benefits that can be realized through cost-effective reductions of excess emissions from reciprocal compressors. However, the potential benefits that can be realized through cost-effective reductions of other excess emissions identified by the surveys are not considered due to a lack of empirical information. As a result of this omission, this report underestimates the value of LDAR programs.

The NPV of a LDAR program is highly dependent on the number of identified emission sources and their leak rates. **Figure 1** shows the distribution of NPVs for individual facilities in the base case scenario. Overall, the majority of facilities have negative LDAR program NPV (net cost) with the well sites and batteries having the lowest percentage of facilities with positive NPV (net gain). This is because leak rates for well sites and batteries are generally smaller than that for gas plants or compressor stations. However, even when implementing a LDAR program represents a net cost for an individual facility, the overall cost for the facility owner will always be relatively low. This is because surveys are relatively inexpensive, and any identified leaks are generally economic to repair. For example, for the well sites and batteries surveyed, the *lowest* NPV was -3,000 USD, while the *mean* NPV for the 340 well surveys having a positive NPV was +4,704 USD. For the 600 gas plants surveyed, the *lowest* NPV was -8,000 USD, while the *mean* NPV for the 221 gas plant surveys having a positive NPV was +34,412 USD.

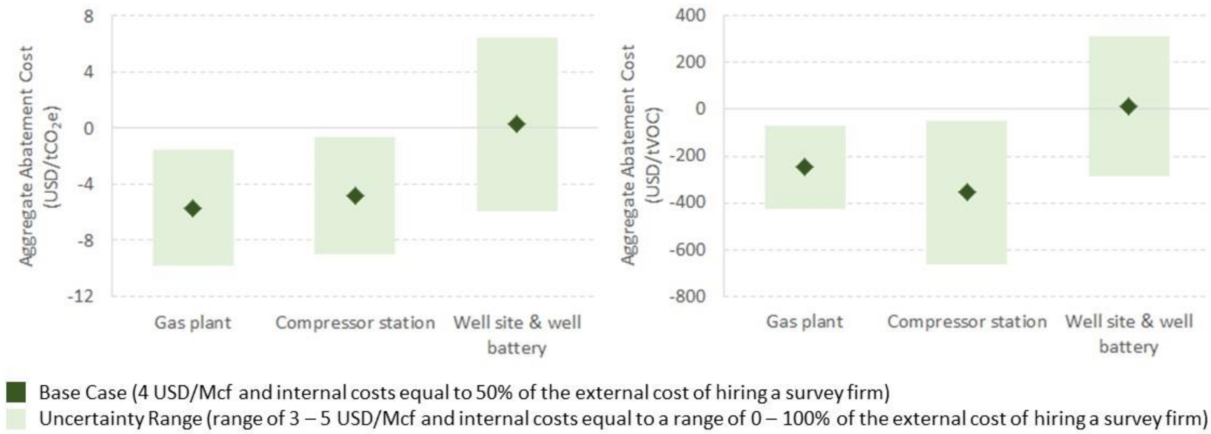
Figure 1: Distribution of Project NPV (base case assumptions) per survey for different types of facilities



Economic assessments – Aggregate cost effectiveness of LDAR programs

The aggregate economic result of conducting LDAR programs can be presented in terms of abatement cost per metric ton of CO_2e or VOC reduced by the program. A negative abatement cost means that the aggregate NPV is positive (net benefit for facility owners). LDAR programs in both gas plants and compressor stations have negative abatement costs, even with low gas prices. For well sites and batteries, the abatement cost is about zero USD/tCO_2e in the base case scenario and +6 USD/tCO_2e or +300 USD/tVOC in the most conservative scenario we considered (assuming a value of recovered gas of 3 USD/Mcf and that the *internal* cost of obtaining a survey is equal to 100% of the *external* cost of hiring the surveying firm). These abatement costs are low compared to many other GHG or VOC mitigation measures.

Figure 2: Aggregate VOC and CO_2e abatement cost for different types of facilities



In addition to the base case results, we have also evaluated whether requiring repair only of leaks that are economic to repair, or only of leaks with an emissions rate over a certain threshold, would reduce the abatement costs of systematic LDAR programs. As the vast majority of the identified leaks are economic to repair once the survey has been performed, it is most economic and environmentally effective to repair almost all the leaks. Adding an economic threshold to decide whether to undertake individual repairs only very marginally improves the economics of the overall LDAR program, by reducing the abatement cost by less than 15 USD/tVOC, while significantly reducing emissions abatement from the program.

The cost-effectiveness of surveying at different frequencies was also evaluated. **Figure 3** shows the effect of survey frequency on abatement cost. Increasing the survey frequency from annual to quarterly reduces the remaining emissions by 68%, as shown in **Figure 4**, but increases the abatement costs. The aggregate abatement costs for quarterly surveys, however, remain below 15 USD/tCO_2e and 800 USD/tVOC. Monthly surveys increase the maximum abatement cost to 55 USD/tCO_2e and 3,400 USD/tVOC. We note that the cost effectiveness of conducting frequent surveys depends on the facility type, maintenance, and size; the optimal frequency may best be determined by analyzing the results of past surveys. This study focused only on LDAR using IR cameras, which appears to be the dominant method at present and a significant improvement over previous detection methods. Alternative technologies in the future may reduce cost and improve effectiveness.

Figure 3: Aggregate abatement costs at various survey frequencies

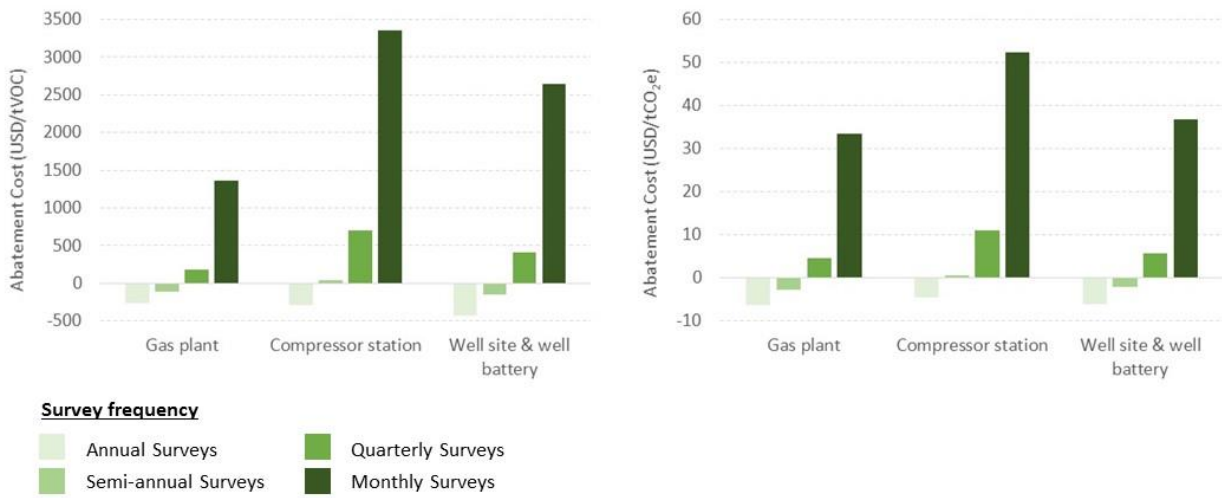
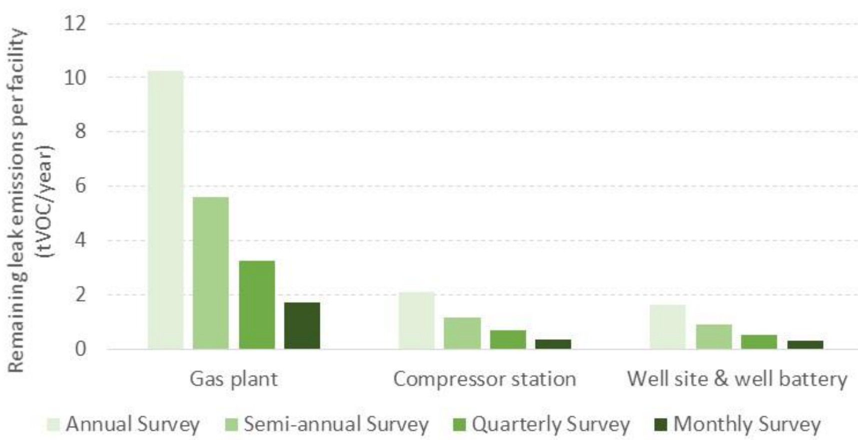


Figure 4: Remaining average leak emissions per facility for various survey frequencies



In general the analysis performed here is based on conservative assumptions, and will produce *overestimates* of the cost per ton of emissions abatement. Most importantly, the data used in this analysis is from facilities where LDAR programs have been in place for some time. Therefore, the observed emissions from leaks in this dataset are lower than the current level of leaks from a typical facility in the US, where, outside of new gas processing plants, LDAR programs are not generally required. Since the leaks (and therefore potential leak abatement) from the facilities in this database are *lower* than from the typical US facility, the cost per ton of emissions abatement is *higher* in this analysis than the real abatement cost in the US.

The economics of reducing excess emissions from reciprocating compressors by replacing rod packing rings were also examined. The rings can be cost-effectively replaced (i.e. NPV>0) for 13% of the compressors at gas plants and 19% of the compressors at compressor stations. These compressors account for 70% and 73% of the total emissions from all compressor rod packing at gas plants and compressor stations, respectively. Including these cost-effective measures to reduce compressor emissions increases the overall mitigation potential of the LDAR survey program significantly compared to the base case, in which only static leak repairs were considered (+21% CO_2e and +14% VOC). Including abatement of excess emissions from rod packing does not significantly affect the overall cost-effectiveness of the LDAR programs for any facility type.

To conclude, this report provides empirical calculations of cost-effectiveness of leak detection and repair programs based on data from a very large number of facility inspections. It shows that leak detection and repair programs at oil and gas production and processing facilities using IR cameras can reduce emissions of methane and VOC at low cost.

1. INTRODUCTION

Methane is a potent greenhouse gas with a relatively short lifetime in the atmosphere. For this reason, measures to reduce emissions of methane can quickly lower its atmospheric concentration, yielding a relatively rapid climate response. In the United States, 30% of anthropogenic methane emissions are from oil and gas sector activities, and these represent about 3% of total US greenhouse gas emissions (2). There is increased attention given to methane emission reduction measures in general and to actions in the oil and gas sector in particular.

This report presents results from an empirical analysis of costs and benefits of emission reduction measures in the oil and gas sector. The analysis is based on data collected during surveys carried out by two private sector 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. In total, data from 4,293 surveys were included in the database[1], covering all potential sources of emissions (both leaks and vents) and 58,421 sources with quantified emission rates. Some 90% of the surveys were performed in Canada, with the balance in the US This report primarily focuses on **leaks** from static components, which comprise 39,505 of the individual emission sources in the 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 (in general with a high-volume sampler[2]) or estimated[3]. 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.

The database contains information on the emitting component, the type of emission (i.e. leak or vent), the failure mode, 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[4]. Facility specific information such as age, size, operating mode and the technology used are not available.

[1] Data from oil sands and oil bitumen emission sources were excluded from the database and the analysis.

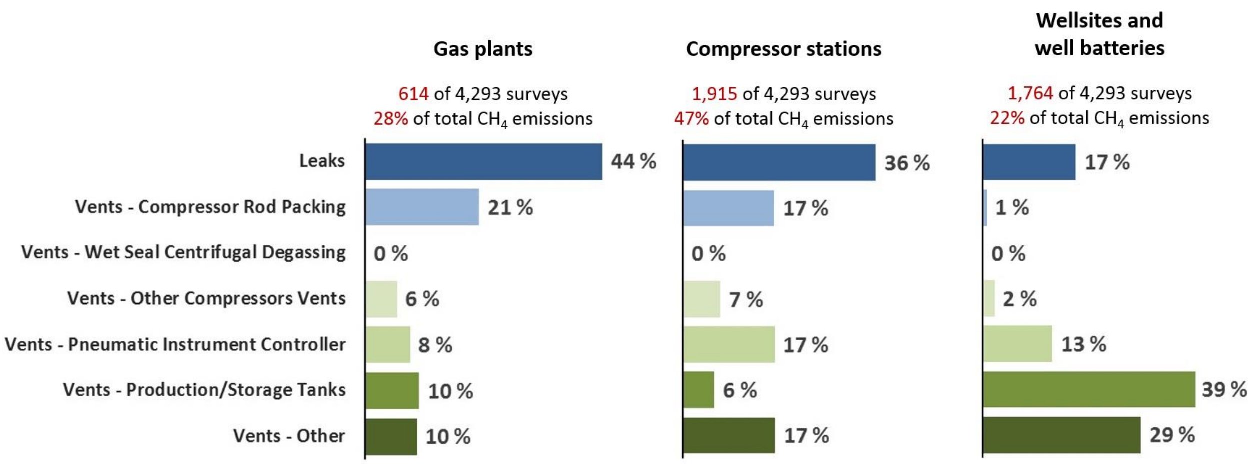
[2] See definition on page 15 in http://cdm.unfccc.int/filestorage/L/V/8/LV8NU1GYWTK06COJPDIXQ35FR2MA47/EB63_repan14_AM0023_ver04.0.0.pdf?t=cVB8bjE4bGdsfDBJlWuvjbA3gB2ASv_9VJMC

[3] In a number of cases, the facility owners do not need a precise volume measure; an estimate (evaluated visually using the IR camera based on the extensive experience of the operators) would be sufficient to make the decision to repair. In a few cases, the component leaking is also difficult to access for measurement. 51% of the leaks are estimated, representing 53% of the quantified leak emissions.

[4] Repair lifetime in the database range from 1 to 5 years, with 30% of the repairs having a lifetime of 2 years or less and 97% of the repairs having a lifetime of 4 years or less.

While venting sources, such as tanks, instrument controllers, etc. constitute the majority of emissions at the surveyed facilities (see **Figure 5**), this report focuses primarily on leaks from static sources, such as connectors, valves, and regulators. We focus on emissions from leaks in this study due to the lack of empirical data on the cost-effectiveness of leak detection and repair (LDAR) programs using IR cameras as a means of reducing methane and VOC emissions from oil and natural gas facilities.

Figure 5: Distribution of emissions in the database by source and facility type



Almost 30% of methane emissions from the onshore oil and natural gas facilities are from leaks (1). In the database used for analysis, leaks account for 35% of total emissions. As shown in **Figure 5**, emissions from compressor rod packing represent about 14% of additional emissions, predominantly at gas plants and compressor stations. The potential value added to programs to detect and repair leaks by also identifying cost-effective opportunities for replacement of **compressor rod packing** is briefly discussed. However, due to limited data availability, we do not examine the economics of abatement of reducing emissions from venting sources such as tanks, pneumatic instrument controllers, dehydrators, or well completions in this reports.

2. ANALYTICAL APPROACH

2.1 Database coverage

Data from LDAR surveys of three main types of facilities were included in the database used for analysis, as shown in **Table 2**.

Table 2: Types of facilities and number of surveys[5]

Facility type:	No of surveys:	Description
Compressor station	1,915	This category includes mainly gathering and boosting compressors (upstream of processing plants) and compressor stations in the transmission and storage sector. Compressor stations in this category in general range from one[6] to three compressors and from 200 to 1,000 horsepower each. The majority of these compressor stations are more than five years old.
Gas plant	614	Gas plants in this category generally range from 10 MMcf/day to 500 MMcf/day. On average gas plants tends to be larger in USA than in Canada[7]. The vast majority of plants are more than five years old.
Well sites and well batteries	1,764	This category includes the following[8]: • Well sites are sites with only one well head • Well batteries include some equipment on site in addition to the well head (e.g. an oil/liquids storage tank, and/or separator, etc.). Multi-well batteries include in general five to fifteen well heads.

39,505 of the 58,421 individual emission sources in the database are classified as "leaks", i.e. unintended emissions from connectors, valves, regulators, etc.[9].

As seen in **Table 3**, while there is variability from site to site and between facility types, some trends in emissions are observed. Gas plants leak the most, whereas well sites and well batteries leak more

[5] Information based on discussion with the data providers. However, this information is not documented in the database. As a result, it is generally not possible to quantify the distribution of facility sizes or sub-categories within the three categories of facility types, nor to analyse how leak rates or net program costs vary between sub-categories.

[6] A large share of the compressor stations have only one compressor.

[7] Natural Gas Annual Respondent Query System (EIA-757 Data through 2012) and presentation by BlueLine at EBRD/GGFR workshop on gas utilization in Moscow 19th June 2013 (for info see http://www.aebrus.ru/en/member-notice-board/index.php?ELEMENT_ID=259927).

[8] These three subcategories are used separately in the database, but due to inconsistent terminology and practices between the two data providers, the results may not be robust for sub-categories. Therefore, we present results for the category as a whole.

[9] The database also includes 255 instances of improper venting from damaged pneumatic controllers and open thief hatches. Because these are inexpensive and simple to repair, in a manner similar to many leaks, they are included in the analysis of cost-effectiveness of LDAR, unlike other vented emissions recorded in the surveys. Due to the small number of these instances (less than 1% of leaks in the database), inclusion of these instances does not have a significant effect on the results of this work.

modestly, with about one-third having no detected leaks[10] and only 7% having leaks above 500,000 cubic feet per year (Mcf/year). Compressor stations leak more than well sites and well batteries, but less than gas plants.

Table 3: Distribution of facilities within each category by leak rate (in Mcf per facility per year)

Category:	No leaks	≤99	100-499	500-1499	≥ 1500
Gas processing plants	3%	17%	32%	25%	23%
Compressor stations	11%	30%	36%	15%	9%
Well sites and well batteries	36%	38%	18%	5%	2%

It is important to highlight that the distributions presented in **Table 3** are *not* representative of distributions of current gas emissions in the US, where systematic leak detection and repair programs are less common. The database largely consists of identified leaks at Canadian facilities that have been subject to regular leak detection and repair for some time. At present, such systematic requirements are generally not in place for most natural gas facilities in the US, outside of gas processing plants built after 1984. As a result, current emissions from most US facilities are expected to be higher than the emissions typical in these surveys (see **Section 4.2**; US versus Canadian Facilities).

Using the information in the database, in addition to average survey costs for facility types provided by the two leak detection firms, we have calculated the costs and benefits of leak detection programs of various design. For many analyses, we present data on cost-effectiveness using an abatement cost defined as cost per metric ton of avoided pollution, where the avoided pollution is calculated from the observed leaks. However, leak emissions at the facilities in the database are lower than typical of US facilities, since the facilities in the database were subject to ongoing LDAR surveys. **Therefore, we consider the abatement costs presented in this report to be an *overestimate* of the real abatement cost for reducing emissions from US facilities, relative to the current (no–LDAR) baseline.**

2.2 Assumptions, base case scenario, and sensitivity analysis

A set of assumptions and realistic variations of key parameter values have been used in the analysis of cost-effectiveness of abatement options presented in this report, and are summarized below:

- **Gas price**: The value of recovered gas has been assumed to be similar for all emission sources, independent of the composition of the gas. Gas values from 3 to 5 USD/Mcf have been assessed in sensitivity analyses, with a base case scenario of 4 USD/Mcf.
- **Discount rate:** A 7% per year real term discount rate has been assumed.
- **Gas compositions and emission factors:** Based on the qualitative description of the type of gas emitted from each source, a gas composition was assumed for each emission source in the database and a CO_2e and a VOC emission factor have been calculated (see Appendix 3). Per US

[10] This is very similar to the result from reference (7) where no leaks were detected at 34% of the well sites.

regulatory definitions, neither methane nor ethane are included in the calculations of VOC emissions.

- **Global warming potential** (GWP) of methane has been set at 25, for the purpose of calculating CO_2e tonnage.
- **Survey costs:** The total survey costs in the database are based on the current average market prices for purchasing such services[11] and an estimated mark-up to reflect the facility owner's internal cost. These internal costs include not only procurement costs to contract a service provider, but also staff time that may be required during the field survey. The total survey costs can vary between operators[12]. The base case scenario assumes that this mark-up for internal costs is 50% of the cost of hiring the external survey providers (*i.e.*, the total survey cost to operators is equivalent to 150% of the cost of hiring an external service provider to survey the facility). Sensitivity analyses have been conducted for mark-ups of 0-100% of external survey costs (*i.e.*, total survey costs to operators varying from 100% – 200% of the market prices for hiring an external service provider.
- **Repair costs and lifetime:** The estimated repair costs and repair lifetime per leak are provided by the two data providers for the majority of components. For the remaining components, repair costs and lifetimes are estimated based on information provided by the survey companies on (a) the type of repair suggested for the component, or (b) the type, sub-type, and size of the leaking component. See Appendix 1 for minimum, maximum, average, and median repair costs for various component types.
- **Repair efficiency**: 95% repair efficiency has been assumed for leaks, 80% for other emissions due to improper conditions[13].

In the base case, it is assumed that facility owners fix all leaks that the LDAR survey identifies. Variations in this assumption are examined in **Section 3.3.1**.

2.3 Methodology

The primary sources of information used for analysis, i.e. data from 4,293 LDAR surveys from two service providers, were subject to initial quality control prior to being compiled into a database. The manual coding done by the survey firms were checked (e.g. facility type, type of emissions, failure mode) and inconsistencies were rectified. Cost data provided for leak repairs were also carefully reviewed and changes made in cases of obvious errors.

The costs and benefits of implementing LDAR programs at oil and gas facilities have been assessed and used to determine the economic attractiveness of leak detection and repair programs at two levels:

[11] Service here includes gas emission detection and quantification survey and the delivery of a monitoring report to the operator. An average survey cost (see Appendix 1) has been assumed per type of facility category.

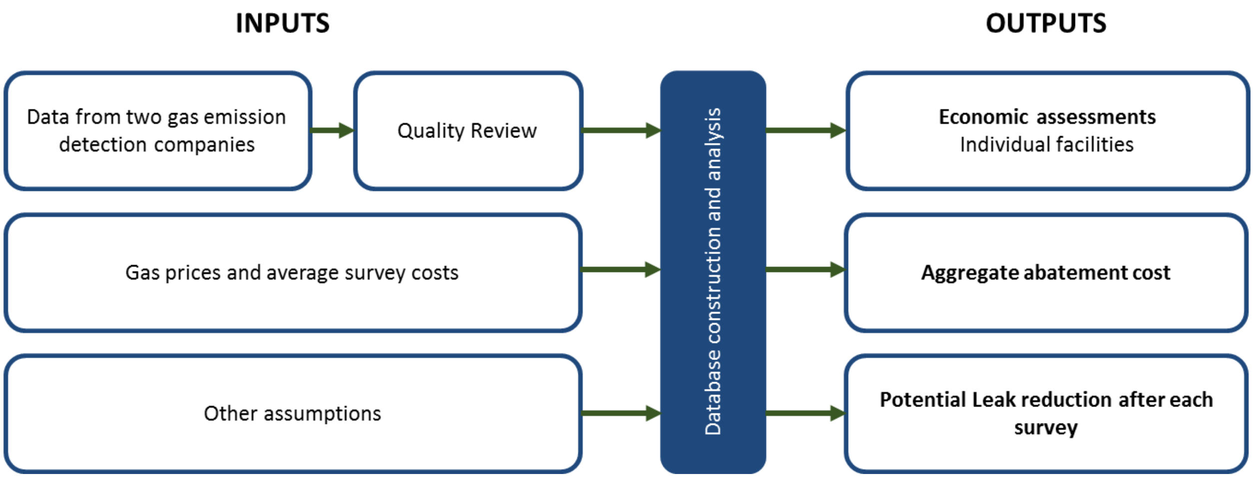
[12] Depending on the number and size of the facilities, distance between the facilities, internal organization, etc.

[13] Estimates based on discussion with the two service providers who have provided data for this study.

(i) The economic value of implementing LDAR programs at individual facilities.
(ii) The cost-effectiveness of implementing LDAR programs at a group of facilities of a similar type (aggregate abatement costs).

Results of the analysis at these two levels are presented in **Section 3.1** and **Section 3.2** respectively. In addition, **Section 3.3** presents a comparison of different strategies for LDAR programs.

Figure 6: Overview of the methodology for assessment of cost-effectiveness of LDAR programs



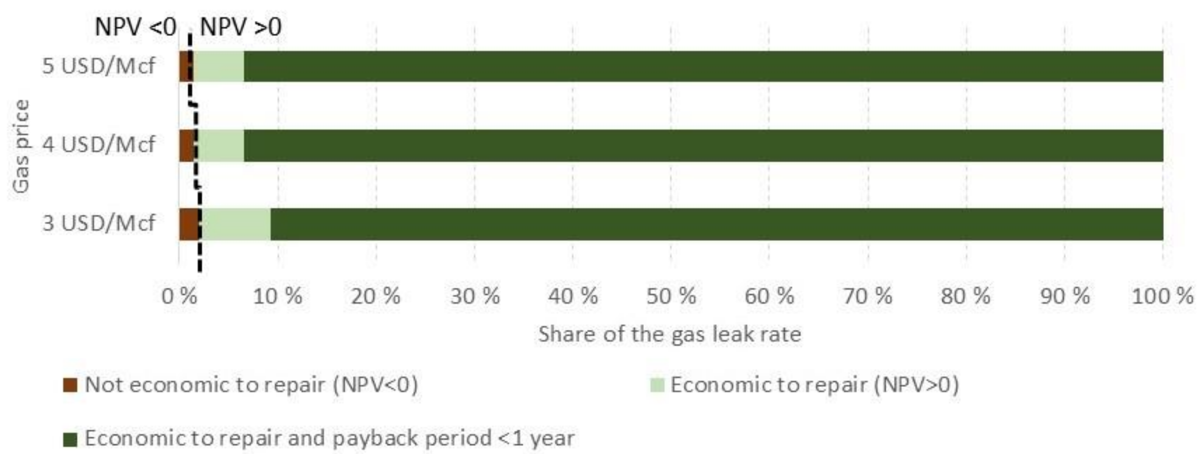
The assessment of the cost-effectiveness of implementing LDAR programs presented in **Sections 3.1** to **3.3** does not include potential benefits associated with cost-effective mitigation of venting emissions identified by the surveys. As LDAR programs could be expected to lead to identification and implementation of some of these cost-effective abatement measures targeted at vent sources, the overall value of LDAR programmes presented is conservatively estimated (the costs associated with quantifying the vent rate are included in the LDAR program costs, while potential benefits are excluded). **Section 3.4** presents the results of a sensitivity analysis where the net present value of implementing cost-effective replacements of reciprocating compressor packing rings has been taken into account when assessing the overall cost-effectiveness of the LDAR surveys.

3. LEAK DETECTION AND REPAIR (LDAR)

3.1 Economic assessment - Individual facilities

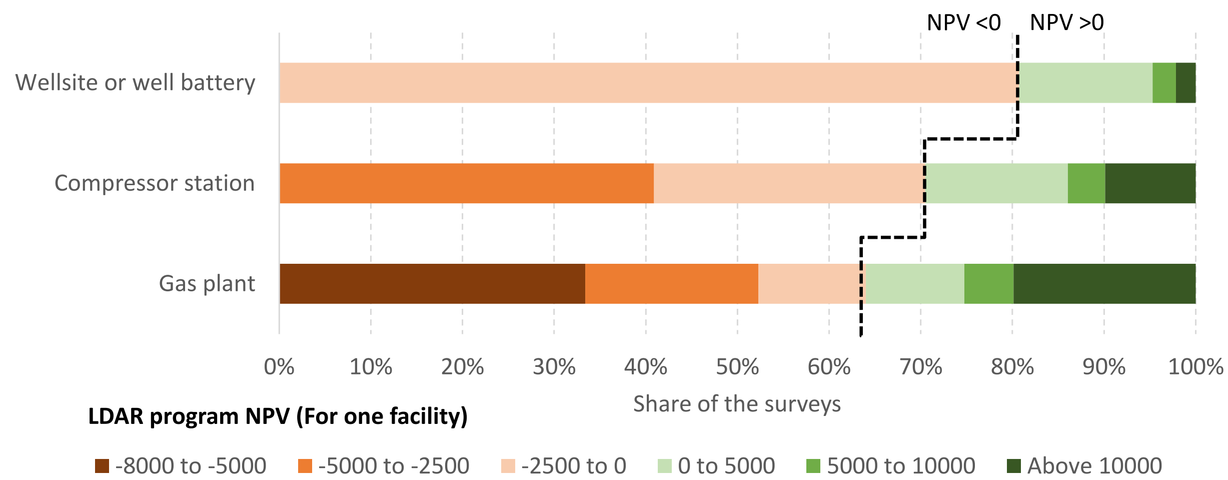
The net present values (NPVs) of repairing individual leaks identified in surveys have been calculated based on estimated repair costs and the value of gas conserved (for sale) by the repair. This analysis shows that the economic value of the conserved gas exceeds the repair cost in almost all cases. Once they are identified, the vast majority of the leaks, and the vast majority of emissions from leaks (more than 97% of the total leak rate), are economic to repair (NPV>0), even when the value of gas is 3 USD/Mcf. In addition, over 90% of gas emissions are from leaks which can be repaired with a payback period of less than one year (see **Figure 7**). There is almost no difference in these results across the three categories of facilities.

Figure 7: Economic attractiveness of the individual repair for all types of facilities – only repair costs included.



We now consider the full program cost, including both the total survey cost and repair costs. Calculated NPVs of the LDAR program per facility survey, assuming all identified leaks are fixed independent of the size of the leak and the economics of repairing it, are more variable. The resultant distributions of facility level NPVs for each of the three categories of facilities are shown in **Figure 8**. For all three categories, the majority of facilities have negative NPVs (i.e. net costs), with the well sites & batteries having the lowest share of facilities with positive NPVs (i.e. net gains).

Figure 8 : Distribution of NPV per LDAR program for different types of facilities – survey and repair costs included.[14]



The low leak rates, which are typical for well sites & well batteries (see **Table 1**), explain the large share of negative NPVs found for this category. While the individual leaks are economic to repair, for many facilities the economic benefit from repairing the leaks is less than the total cost of the survey so the NPV of the LDAR program at those facilities is negative. However, the relatively low survey costs (600 to 1,800 USD per facility in total survey costs in the base case) limit the magnitude of net costs. For the well sites and batteries surveyed, the lowest NPV was -3,000 USD. The mean NPV for the 1,424 well surveys having a negative NPV (81%) was -1,167 USD, while the mean NPV for the 340 well surveys having a positive NPV was 4,704 USD. As a result, the average NPV at well facilities was -35 USD.

For compressor stations, about 30% of the surveys have positive NPV, and as many as 10% have NPVs exceeding 10,000 USD. For the 565 compressor station surveys having a positive NPV, the mean NPV was 17,182 USD. In contrast, none of the surveys have a NPV of less than -5,000 USD. The average survey NPV at compressor stations was 3,376 USD.

Gas plants typically have survey costs exceeding 5,000 USD [15]. Almost a third of the 600 gas plant surveys have a positive NPV, with about 120 gas plant surveys having a NPV above 10,000 USD. The mean NPV for the 221 gas plant surveys having a positive NPV was 34,412 USD. This category also has the lowest proportion of surveys with negative NPVs, and none with a negative NPV of less than -8,000 USD. The average survey NPV at gas plants was 9,403 USD.

The economic attractiveness assessed at the survey/facility level shows considerable variability, particularly for gas plant and compressor station surveys, but the net cost per facility survey, when there is a net cost, is always relatively low. However, it is important to consider that the NPVs illustrated in **Figure 8** are calculated per facility and most companies own several facilities. As a result, the aggregated

[14] Under base case assumptions, including 50% mark-up for internal costs to administer surveys (total survey cost to operators is 150% of the cost of hiring an external service provider to survey the facility).

[15] External costs only (mark-up for internal costs not included).

NPV for companies is likely to be higher than that of the median facility as displayed in Figure 4 and may be positive (see below).

3.2 Aggregate abatement cost

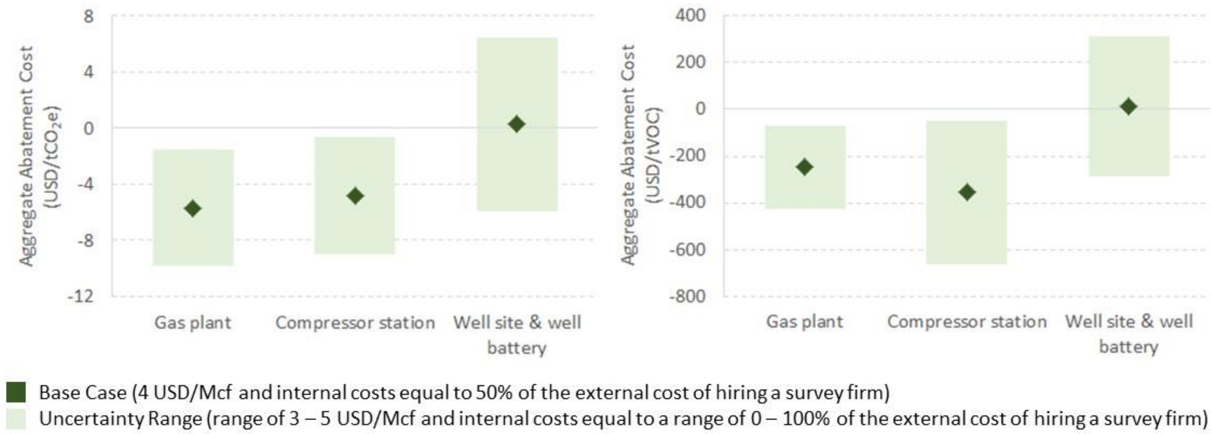
To evaluate the overall cost-efficiency of systematic implementation of regular LDAR programs for a group of facilities of a similar type (over a jurisdiction or over a large company), aggregate NPVs were estimated. Although the majority of the 4,293 facility surveys have negative NPVs when evaluated individually, the aggregated NPV for all facilities is positive, meaning that those facilities with surveys with negative NPVs (net cost) are outweighed by those having surveys with positive NPV (net gain). This is due to the asymmetry in NPV distributions for individual facility surveys (see **Figure 8**). The aggregate economic results of the LDAR programs can also be presented in terms of abatement costs (e.g. per metric ton of CO_{2e} or VOC emissions avoided), which is common when environmental policies are considered. The aggregate abatement costs have been calculated as:

$$Aggregate\ Abatement\ Cost = \frac{Discounted\ sum\ of\ cash\ flows\ for\ all\ the\ facilities}{Discounted\ emission\ reductions\ for\ all\ the\ facilities}$$

The discount rate applied is 7% in the base case both for cash flow elements and emission reductions. Other approaches, such as applying a lower (even zero) discount rate for future emission reductions, or amortizing costs of repair over its lifetime and then calculating annual net costs for emissions avoided in a given reference year, can also be used to evaluate and compare cost-efficiency of mitigation options. As shown in Section 4.2, the results are not very sensitive to variations in discount rate (due to limited repair lifetimes).

Figure 9 shows that gas processing plants and compressor stations have negative abatement costs (i.e. positive NPV) in the base case scenario. This conclusion also holds when assuming a lower gas price of 3 USD/Mcf and higher total survey costs (mark-up for internal costs up to 100% of the external cost of hiring an external service provider). With the base case assumptions, well sites & well batteries have abatement costs around zero, increasing to 6 USD/tCO_2e or 300 USD/tVOC applying the less favourable assumptions for gas price and total survey costs.

Figure 9: Aggregate VOC and CO_2e abatement cost for different types of facilities



3.3 Comparison of different approaches for LDAR programs

The results presented in the previous sections are based on the base case assumption that the operator would repair all the leaks that have been identified during a survey. In **Section 3.3.1**, we consider ways to potentially increase the value of routine LDAR by using economic or emissions thresholds to allow certain leaks not to be repaired. **Section 3.3.2** then examines costs and benefits of LDAR programs with different survey frequencies.

3.3.1 Impact of different repair strategies

Two alternative strategies to the base case strategy of repairing all identified leaks are analysed:

- **Strategy 2:** Perform a leak detection and quantification survey, and only repair the leaks which are economic to repair – i.e. those components that can be repaired with a net gain (NPV>0).
- **Strategy 3:** Perform a leak detection and quantification survey, and only repair leaking components with an emissions rate exceeding a certain threshold, e.g. 20 Mcf per year.

For each strategy, the potential leak reduction and aggregate abatement costs per metric ton of CO_2e and VOC are calculated for different types of facilities[16]. **Table 3** summarizes how the two alternative strategies compare to the base case strategy (i.e. "repair all leaks") for two (sub-)categories of facilities; compressor stations and multi well batteries. Other types of facilities show similar patterns.

[16] Only corrective maintenance program approaches are reviewed here. Preventive maintenance programs have not been evaluated as part of this project.

Table 4: Comparison of three hypothetical repair strategies for compressor stations and multi-well batteries (examples)[17]

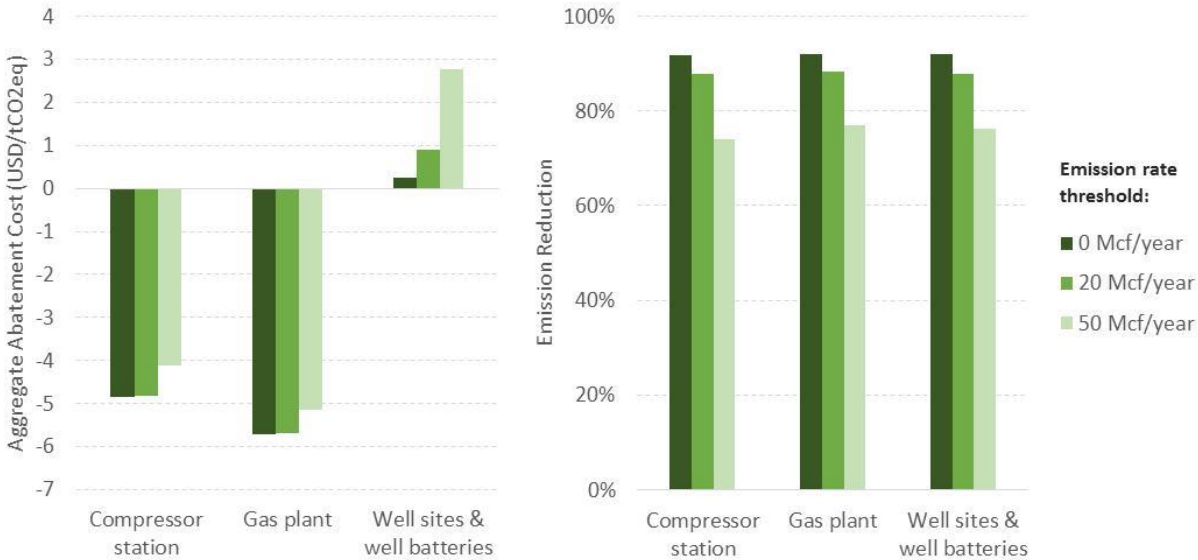
Compressor Station	**Base Case** (all identified leaks)	**Strategy 2** (leaks with NPV>0)	**Strategy 3** (leaks > 20 Mcf/yr)
Potential leak reduction after each survey	94.7%	93.0%	87.7%
Methane abatement cost (in USD/tCO_{2e})	-4.9	-5.0	-4.8
VOC abatement costs (in USD/tVOC)	-355	-368	-357
Average number of leaks to repair per facility	11.3	10.2	6.9
Multi well Battery	**Base Case**	**Strategy 2**	**Strategy 3**
Potential leak reduction after each survey	94.5%	92.6%	88.1%
Methane abatement cost (in USD/tCO_{2e})	1	0.8	1.7
VOC abatement cost (in USD/tVOC)	46	41	79
Average number of leaks to repair per facility	3.8	3.5	2.9

Comparing the alternative repair strategies and the “repair all leaks” base case shows:

- Strategy 2 results in lower aggregate abatement costs, since repairs that are uneconomic are not performed. However, the difference is minimal (<0.2 USD/tCO_{2e}). It is also important to consider that this strategy would be more complex to implement in practice. For each leak identified, at a minimum some evaluation (based on measurements or estimates of leak volume, etc.) would need to be carried out, and for those leaks not repaired, documentation of leak magnitude, repair cost, etc., might be required (and possibly verified). The additional administrative costs this entails are not accounted for in this analysis.
- Strategy 3 does not represent cost savings of any significance, and there are markedly less emission reductions. For multi well batteries, the aggregate abatement costs actually increase (this is due to the fact that small leaks can be economic to repair). As a result, abatement cost per ton *rises* as the threshold rises under Strategy 3. **Figure 6** explores further the emission reductions and aggregate abatement costs for different emissions rate thresholds for this strategy. The sensitivity analysis shows that, statistically, it is both more environmentally efficient and more economical to repair all the leaks detected.

[17] The trend is similar for other types of facilities. The results of Strategy 3 depend on the volume threshold set (see Figure 11). Gas emission reductions are calculated for the year following the survey.

Figure 10: Strategy 3 - Sensitivity to the emissions rate threshold with base case assumptions[18]



To conclude, as the vast majority of leaks are economic to repair once the survey has been performed, it is most economic and environmentally effective to repair almost all the leaks. Adding an economic constraint on the repair program only marginally improves the economics of the overall program.[19]

3.3.2 Impact of the frequency of surveys

Increasing the frequency of surveys and subsequent repairs further reduces emissions, but will increase abatement costs. This section examines the effect of survey frequency.

The database used in this report includes surveys performed at a variety of facilities and in several jurisdictions in both Canada and the US. 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 on the survey frequency for 12% of the total surveys in the database (i.e. 542 surveys)[20]. Almost 80% of these repeated surveys were performed on a yearly basis and 17% were performed every two years. For the analysis of the impact of survey frequency presented below, only data for surveys with a known frequency of one year (427 surveys in the database) have been used.

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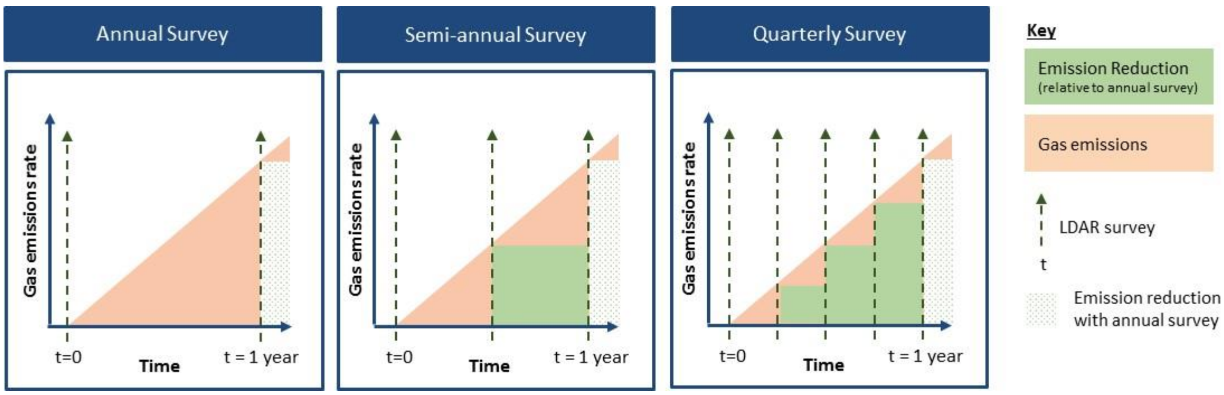
[18] The abatement costs for VOC emission reductions (now shown) show the same trend as for CO_2e (illustrated in the figure).

[19] The current study does not review the administrative cost of implementing and enforcing the regulation. However, we can highlight that Strategy 2 (and to some extent Strategy 3) are more complex to implement and to enforce than the base case strategy of repairing all identified leaks.

[20] While definitive frequency information is only available for 12% of the surveys, it is clear, based on interviews and reference (8), that the facilities in our database are typically surveyed every one or two years.

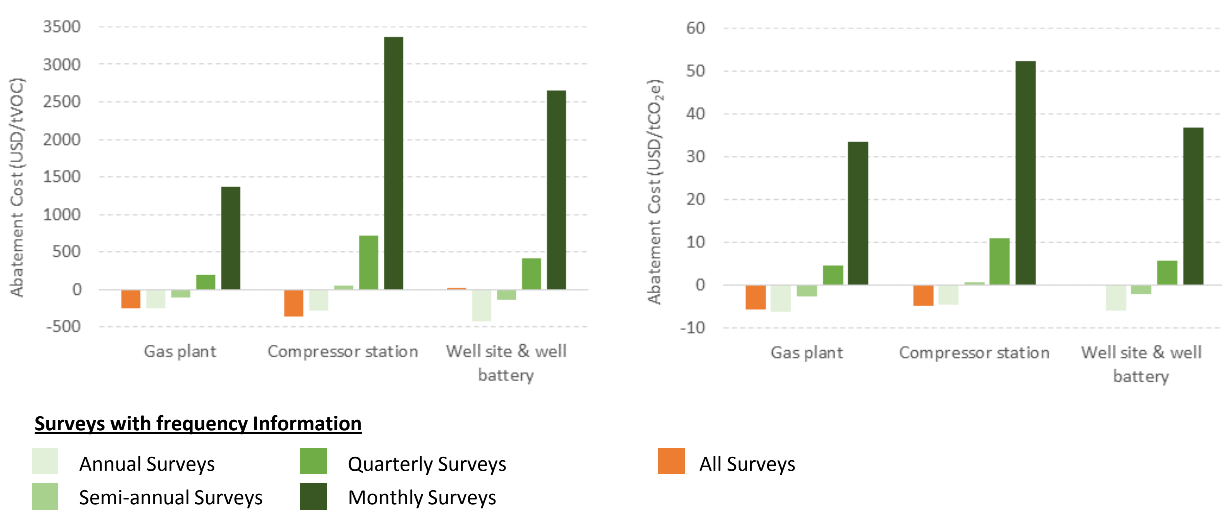
Increasing the frequency of the leak detection and repair survey will have a positive impact on the emission reductions that can be achieved, as the leaks are detected and can be repaired earlier (see Figure 11).

Figure 11: Schematic overview of emission reductions within a year depending on the frequency of the surveys



However, more frequent surveys increase program costs. **Figure 12** shows the increase in abatement costs for VOC and CO_2e as a function of increased survey frequency. However, even with these increased costs, in all the cases evaluated, the abatement costs remain below 55 USD/tCO_2e and 3,500 USD/tVOC.

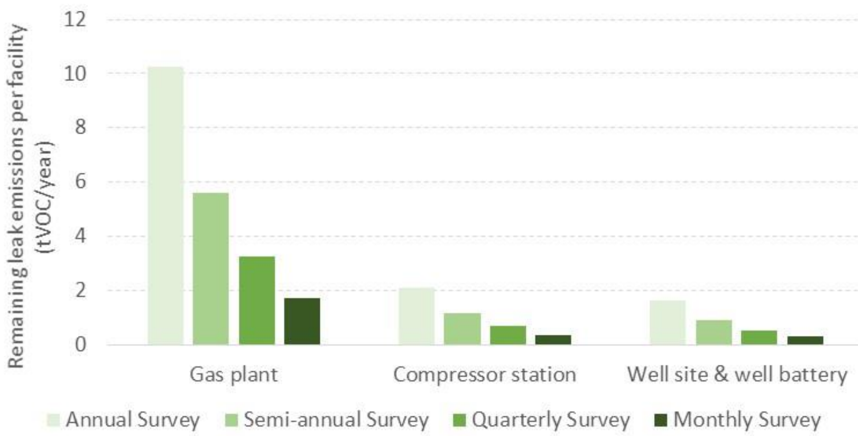
Figure 12: Aggregate abatement costs depending on the survey frequency[21]



[21] Base case assumptions are applied, and repair lifetimes are maintained for all components. It is assumed that leaks arise over time - more frequent detection will lead to quicker repairs of identified leaks, but fewer leaks will be detected per survey. The repair cost for a component found to be leaking is independent of the survey frequency.

Figure 13 presents the remaining average VOC emissions per facility depending on the survey frequency.

Figure 13: Average remaining leak emissions per facility depending on the survey frequency[22]



We note that the leak rates shown in **Figure 13** values are not, in general, representative of US facilities, where leak detection surveys are not generally routine.

To conclude, by increasing the survey frequency, remaining emissions are reduced, but abatement costs increase. Still, the abatement costs for quarterly surveys remain below 15 USD/tCO_2e and 800 USD/tVOC.

We note that the cost efficiency of conducting frequent surveys depends on the facility type, maintenance, and size, and therefore the optimal frequency may best be determined by analysis of the results of past surveys. This study focused only on LDAR using IR cameras, which appears to be the dominant method at present. Alternative technologies in the future may reduce cost and improve effectiveness.

[22] It is important to highlight that we assumed 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), or for repair of some other leaks, such as those that are difficult to access . As a result, emissions reduction overestimated, and abatement cost (per ton) is underestimated in regards to this aspect. The share of repairs which will be delayed is not available in the database.

3.4 Impact of including compressor rod packing replacements

This section assesses how the results of the analysis presented above are affected when the net present value of economic replacements[23] of compressor rod packing rings are included in the analysis.

As shown in **Figure 5**, compressor rod packing emissions represents 21.2% of total observed gas emissions for gas plants, 17.0% for compressor stations, and less than 1% for well sites and well batteries. There are various parameters that affect the packing vent rate, e.g.:

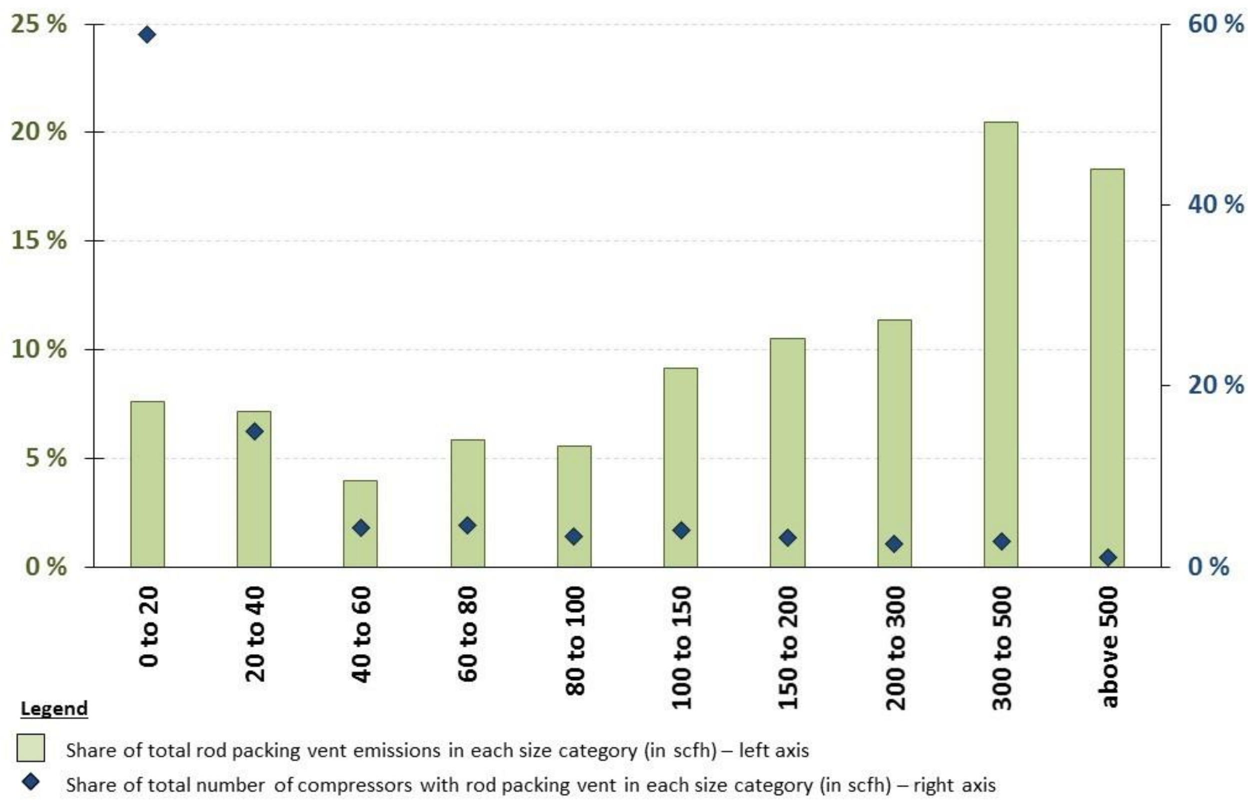
- The number of operating hours (packing rings become worn over time)
- The packing technology (various designs and materials with different initial performance and wear resistance are available)
- The deterioration of the piston rod (a worn or not properly aligned piston rod can affect the fit of rod packing against the shaft and increase leakage; piston rods can become worn because of friction, scratches, or when the compressor is operated intermittent or unused for a long period)

The emission database comprises 2,160 individual emission sources for compressor rod packing emissions, all with measured emission rates[24]. The database used for this study does not contain sufficient context information to relate variations in rod packing emissions rates to variations in parameters that are expected to affect these rates. The mean rod packing emissions rate in the database is 56.7 scfh. **Figure 14** shows the distribution of measured rod packing vent rates in the database. A large portion of emissions originate from a relatively small fraction of compressors; 50% of gas emissions is from less than 7% of compressors emitting more than 200 scfh.

[23] Economic replacements are defined as those with a positive expected net present value (NPV>0).

[24] Emissions were measured using a hi-flow sampler, predominantly in Canada, during the period 2007-2013. 58% of total emissions of this nature are related to compressors in gas plants, 41% are related to compressors in compressor stations, while the remaining 1% are related to compressors in other types of facilities.

Figure 14: Distribution of measured rod packing vent rates per size category (in scfh)



In order to reduce excessive compressor packing emissions, it is necessary to replace the rod packing. It might also be necessary to re-align or replace the rod. Here we estimate the quantity of additional emissions reductions that could be achieved by using LDAR programs to identify compressors with excess emissions and replacing rod packing when economic to do so. We also estimate the effects of including rod packing replacements on the overall cost-effectiveness of LDAR programs. Because many of the parameters that affect the cost-effectiveness of rod-packing replacement are not available in our database, this estimate is less precise than our calculations of abatement costs, etc., for leaks from static components. We include this analysis to illustrate the additional benefits that may be realized by expanding LDAR programs to include other emissions sources at oil and gas facilities, beyond leaks from static components.

The following assumptions have been used to calculate the cost-effectiveness of replacing packing rings[25]:

[25] Assumptions regarding the number of hours in pressurized mode and the average number of shafts per compressor in gas plants and in compressor stations are based on estimates provided in Table 6-2 in a TSD from EPA (9). Costs for equipment and installation are based on discussions with Ceco and John Crane and represent costs for rod packing replacement for larger compressors and are similar to those in (9).

- Economic lifetime of new packing rings: Three years
- Average number of cylinders per compressor: 2.5 for gas plants, 3.3 for compressor stations.
- Total purchase and installation cost for new rod packing: 1,800 USD per cylinder (*i.e*. total cost per compressor of 4,500 USD for gas plants, 5,940 for compressor stations).
- Annual hours in pressurization mode: for compressors in gas plants, 7,800; for compressor stations: 7,000.
- It is assumed that vent rates initially can be reduced to 11.5 scf/hr/cylinder after replacement of packing rings, and that the emission rate would grow over time in the same manner both if packing was not replaced and, if replaced, after replacement (from the lower, post-replacement value).

In addition, general (base case) assumptions presented in **Section 2.2** have been applied for the discount rate and the value of conserved gas. With these assumptions, packing rings can be replaced at zero or negative abatement cost when vent rates exceed ~85 scfh for gas plant compressors and ~120 scfh for compressors in compressor stations.

Including the potential emissions abatement from those compressors where rod packing can be replaced at zero or negative costs (i.e. 328 compressors with NPV>0 for packing replacement) increases the methane emissions mitigation in the first year after a survey achieved by the LDAR programs by 23% (**Table 5**). Over the lifetime of the mitigation measures (three years for new rod packing or lifetime of individual leak repairs), including rod packing increases LDAR program methane mitigation by 21% and VOC mitigation by 14%.

Table 5: Increase in mitigation potential and aggregate NPV from inclusion of economic Rod Packing Replacement (RPR) in LDAR programs

	Average mitigation potential per facility (tons CO_2e, 1st year)			**Average NPV** (USD per facility)		
Facility type:	Base case (leaks only)	With RPR included in LDAR Program	Relative abatement increase from including RPR	Base case (leaks only)	With RPR included in LDAR Program	Relative NPV increase from including RPR
Gas plant	566	721	27%	9,403	12,394	32%
Compressor station	250	313	25%	3,376	4,616	37%
Wellsite and well battery	61	61	0%	-35	-35	0%
All facilities in database	**217**	**267**	**23%**	**2,837**	**981**	**35%**

It should be noted that little context information is available about the compressors in the emission database (*e.g.,* neither cylinder size nor the number of operating hours of the compressor since the last packing replacement are available). To be conservative we assumed replacement costs for all rod packing were representative of larger compressors. On the other hand, some operators would have replaced rod packing within the three-year period after the survey (as part of fixed maintenance schedules, for example). As a result of the latter effect, our calculated NPVs for rod packing replacement may be too high.

While replacing rod packing when economic to do so would significantly increase emissions abatement from LDAR programs, it only has small effects on the overall abatement cost of an LDAR survey program (< ±1 USD/tCO_2e and < ±65 USD/tVOC compared to the base case presented in **Figure 9**).

To conclude, packing rings can be replaced at zero or negative abatement costs for 13% of the compressors at gas plants, and 19% of the compressors at compressor stations. These compressors account for 70% and 73% of the total emissions from reciprocal compressor rod packing vent volume at gas plants and compressor stations, respectively. While inclusion of these economic measures to reduce emissions from rod packing increases the mitigation potential significantly compared to the base case when only leaks from static components are considered (+21% for CO_2e and +14% for VOC), the overall cost-effectiveness of the LDAR programs is not significantly affected for any facility type.

4. Concluding remarks

4.1 Main findings

The analysis presented in this report provides new insight into leak detection and quantification survey costs and benefits, as it is based on data collected from over four thousand facility surveys and data on almost forty thousand leaks. This robust dataset allows calculation of the economic value of LDAR programs under a range of program designs and frequencies.

The evaluation of available survey data shows that most leaks, once identified, are economic to repair with a payback period less than one year. As a result, once the survey has been performed, it is economic to repair almost all the leaks.

Overall, LDAR programs at oil and gas production and processing facilities using IR cameras have low abatement costs on an aggregate basis. Program costs and emission reduction potentials are not very sensitive to program design, although aggregate abatement costs are sensitive to the survey frequency. However, abatement costs for quarterly surveys remain below 15 USD/tCO2e and 800 USD/tVOC. For monthly surveys, abatement costs are below 55 USD/tCO2e and 3,400 USD/tVOC.

The abatement costs reported here are calculated from the observed leaks at the surveyed facilities, where LDAR programs had been in place for some time. At US facilities, LDAR programs are not generally in place, and thus current leaks are expected to be larger than at the facilities in our database. Since emissions abatement from the current baseline due to LDAR programs would be higher at US facilities than the emissions abatement from *ongoing* LDAR documented in our database, the abatement costs presented here are an *overestimate* of the true emissions abatement cost from LDAR for most natural gas facilities in the US.

From a facility owner's perspective, implementing a routine LDAR program may represent a net cost (NPV < 0) for many facilities. However, even in those cases, the overall cost is always relatively low due to the low survey costs.

As described in the following section, the results presented here were calculated with conservative assumptions – with the exception of one assumption (prompt repair), all assumptions are set to overestimate abatement cost. Considering these assumptions and the overestimate of abatement cost described above in this section, we are confident that this analysis calculates a conservative estimate of the cost of mitigating methane and VOC emissions from oil and natural gas facilities.

4.2 How robust are the results?

Some sensitivity analyses were presented in **Section 3.1 to 3.3** with variations in survey costs and gas prices. However, there are other assumptions being made (see **Section 2.2**) that potentially impact the results. These assumptions are considered below, either quantitatively or qualitatively.

Discount rate: A discount rate of 7% (real terms) has been applied in all of the analyses presented in this Chapter. With an increase in the discount rate to 12%, aggregate abatement costs increase by less than 0.5 USD/tCO_2e or 30 USD/tVOC.

Measured versus estimated emissions: Leak rates are to some extent uncertain since a number of them were estimated and not measured. A sensitivity analysis was performed to evaluate if the inclusion of estimated leak rates impact the results of the analysis. Abatement costs were calculated for the subset of surveys for which more than 80% of total emissions was measured, as opposed to estimated. For all categories of facilities, the abatement costs calculated for this subset of surveys is very similar (within 1 USD/tCO_2e) to the results obtained using data from the entire database.

Value of recovered gas: The value of the recovered gas has been assumed to be similar for all emissions sources, independent of the composition of the gas. This is a conservative assumption when calculating the abatement costs of LDAR programs, as richer gas (propane, butane, etc.) leaks are detected in many cases, and the value of this gas would typically be higher.

GWP of methane: A GWP of 25 was used for methane (see **Section 2.2**), based upon the recommended 100-year GWP from IPCC's Fourth Assessment Report (10). The recently released Fifth Assessment Report recommends a 100-year GWP of 30 or 36 for methane from fossil sources, depending on the inclusion of certain climate feedbacks in the calculation[27]. Using these more recent calculations of the GWP of methane would reduce the abatement costs per ton of CO_2e by 17 – 30%.

Survey costs: Operators may consider it economic to perform the survey internally instead of outsourcing the services, as was the case for the surveys analyzed in this work. In these cases, the total survey costs presented above might be on the high side.

Exclusion of benefits from reductions in venting: The exclusion of benefits from cost-effective repairs of venting sources identified in the surveys, while including the full cost of the survey identifying those vents in addition to leaks, underestimates the value of the LDAR programs and the emissions reductions resulting from such programs. As shown in **Figure 5**, most of the

[27] See Fifth Assessment Report, Working Group I Contribution, page 714.
Available at: http://www.climatechange2013.org/images/report/WG1AR5_Chapter08_FINAL.pdf.

identified emission sources at facilities are venting, so this effect may be significant. As illustrated in **Section 3.4**, the mitigation potential is significantly higher (+21% for CO2e and +14% for VOC) when including economic (NPV>0) replacements of compressor rod packings in the analysis, while the overall cost-effectiveness of the LDAR programs is not significantly affected for any facility type.

No specific shutdown required: Repairs are assumed to be performed rapidly after surveys, during the normal (ongoing) operations of the facilities. Hence repair activities do not cause production losses, and no potential revenue losses are accounted for in the analysis. When the facility needs to be shut down to perform the repair, the repair is assumed to be postponed to the next planned maintenance. The potential delay in realizing emission reductions from repairs requiring shutdown, or other repairs which are not carried out rapidly (such as for components which are difficult to access), has not been accounted for in the analysis. The abatement costs per ton are underestimated, to some degree, since this approximation overestimates emissions abatement.

Gathering compressor stations versus transmission compressor stations: As described in **Section 2**, the database includes compressor stations in the production segment (e.g. gathering stations) and compression stations in the transmission segment. It was possible to extract definitive information on the location of the compressors for about half of the surveys of compressor stations. For these 1,032 surveys, the aggregate abatement cost for LDAR programs on compressor stations in the production segment is -1.7 USD/tCO_2e, while the aggregate abatement cost for LDAR programs in the transmission segment is -8.3 USD/tCO_2e in the base case scenario. For the latter category of compression stations, if the value of recovered gas is zero (i.e. no additional revenues from sale of gas), the abatement cost increase to 2.3 USD/tCO_2e.

US versus Canadian facilities:
The majority of the surveys included in the database have been performed in Canada, with about 500 surveys in the US. The key relevant similarities and differences between the two countries are:

- <u>Results from analysis of data contained in the database:</u> In general, the average leak emissions per facility is higher for the US facilities compared to the Canadian ones, which indicates that the abatement costs presented in this analysis are higher than they typically would be for the sample of US facilities. However, it is important to highlight that the surveys conducted in the US are not necessarily repeat surveys and thus may not be representative of *systematic repeat* LDAR programs examined in this report.

- Size of the facilities: Gas plants in the US are, on average, larger than Canadian ones[28]. A large number of the gas plants in the database are very small plants and thus the abatement costs presented above for this facility type may be conservative.
- Other similarities: According to interviews with technology providers, the practices are very similar in the two countries, with similar designs, equipment, and suppliers. Maintenance practices vary significantly from site to site, but there is not necessarily a significant difference between the two countries, with the exception of different regulations, such as the requirements to perform regular LDAR in Alberta.[29]

Finally it should be added that other analyses for US facilities generally show higher leak rates than presented in this analysis, see **Appendix 3**. For many analyses, we present data on cost-effectiveness using an abatement cost defined as cost per metric ton of avoided pollution, where the avoided pollution is calculated from the observed leaks. However, this review suggests that the results of the analysis performed in this study may be conservative when considering US facilities, since the facilities in the database were subject to ongoing LDAR surveys. Therefore, the abatement costs presented in this report are considered to be higher than the expected abatement cost for reducing emissions from US facilities where LDAR is not currently in place. Comparison with other studies as shown in **Appendix 3** should however be interpreted with great caution because of the great variation in statistical samples (this analysis having a far greater number of observations), type of facilities surveyed, and analytical approach.

The assumptions and considerations, with the exception of the assumption that all leaks can be repaired without waiting for shutdown, all tend to overestimate the cost of LDAR programs and/or underestimate of the mitigation potential associated with such programs. In summary, this indicates that our assessments of the value and cost-effectiveness of LDAR programs are in general conservative.

[28] Factor of about 3, calculated based on data from Natural Gas Annual Respondent Query System (EIA-757 Data through 2012) and a presentation by BlueLine at EBRD/GGFR workshop on gas utilization in Moscow 19th June 2013 (for info see http://www.aebrus.ru/en/member-notice-board/index.php?ELEMENT_ID=259927).

[29] See Alberta Energy Regulator Directive 060 at 8.7; http://www.aer.ca/documents/directives/Directive060.pdf

Appendix 1: LDAR costs

Table 6: Average cost of hiring an external service provider to conduct a survey, depending on the facility type (not including any internal administrative costs)

Facility type:	Cost of hiring an external service provider, USD:
Compressor station	2,300
Gas plant	5,000
Multi well batteries	1,200
Single well batteries	600
Well site	400

Table 7: Leak rate and repair costs depending on the component type (main component types only; rates are in cubic feet per minute (cfm))

		Rate (cfm)			Repair Cost (USD)			
	# in DB	Min	Average	Max	Min	Average	Median	Max
Valve	10,575	0.01	0.12	36	20	90	50	5,500
Connector/Connection	23,577	0.01	0.10	60	15	56	50	5,000
Regulator	1,081	0.01	0.12	5	20	189	125	1,000
Instrument Controller (Leak only)	1,106	0.01	0.14	5	20	129	50	2,000

Appendix 2: Leak rate per component type and per facility type

Table 8: Total average leak rate from facilities, only from specific component types (cfm)

	Compressor station	Gas plant	Well sites and well battery
Connector/Connection	0.58	1.69	0.11
Instrument Controller (Leak only)	0.04	0.05	0.03
Valve	0.41	0.77	0.04
Open Ended Line	0.10	0.11	0.02
Regulator	0.04	0.05	0.02

Appendix 3: Gas compositions

Based on the description of the type of gas emitted from each source, the following compositions were assumed for the leaks in the database, from which CO_2e and VOC emission factors have been calculated:

Table 9: Assumed gas compositions and emission factors for the main gas types used (these are used for > 99% of the gas leaks)

Type of gas (described in database)	**Methane** (Mol %)	**EF_{CO2e}** ($kgCO_2e/scf$)	**VOC** (Mol %)	**EF_{VOC}** (kgVOC/scf)
Methane	100%	0.48	0.0%	0.0000
Custom gas	83%	0.40	6.8%	0.0047
Sweet gas	79%	0.38	7.5%	0.0045
Sour gas	71%	0.35	3.6%	0.0023
Propane	0%	0.00	100%	0.0813
Ethane	0%	0.00	0.0%	0.0000

Appendix 4: LDAR - Comparisons with past work

A number of other published studies evaluate either the emissions rates of different facilities or the economics of performing leak detection and repair programs. This section briefly reviews key similarities and differences in the approach and results of this study and other existing publications. However, while use of IR cameras in leak-detection has been discussed in previous work, the project team is not aware of a study that fully quantifies costs and benefits of screening facilities for leak emissions with IR cameras using extensive field data.

Emission rates

Table 10 presents a comparison of emissions rates from a number of published studies (results from some studies were analyzed by Carbon Limits to categorize emissions as leak and vent emissions).

Table 10: Comparison of the current study with previously published work (results presented in cfm)

		Wellsite & well batteries		Compressor stations		Gas plants	
		# of assessments	results	# of assessments	Results	# of assessments	Results
This study	Average leak	1,764	0.4	1,915	1.4	614	3.3
	Average vent		1.2		2.4		3.9
	Average emissions		2.1		3.8		7.3
Fort Worth Natural Gas air quality study (3)[30]	Average leak	375	NA	7	6.4	1	13.5
	Average vent		NA		4.3		45.2
	Average emissions		3.1		10.7		59.1
Natural gas star program, lessons learned 2006 (4) (5)	Min emissions	NA	NA	13	0.7	4	85.4
	Max emissions		NA		380.5		244.4
Clearstone 2006 (6)	Average leak[31]	12	NA	7	NA	5	60.2
	Average vent[32]		NA		NA		65.2
	Average emissions[33]		0.8		12.2		155.1
University of Texas 2013 (7)	Average emissions	146	0.23[34]	NA	NA	NA	NA

It is important to highlight that the studies compared in **Table 10** have been performed using very different approaches and methodologies, and with very different sample sizes. As a result, any comparison should be interpreted carefully.

Overall, the results for well sites are in the same order of magnitude for all the studies presenting measured gas rates. A few hypotheses may explain the differences observed in emissions rates from gas plants and to some extent from compressor stations:

- Sizes of facilities:
    - Gas plants in USA are, on average, about three times larger than Canadian ones. A large number of the gas plants in the database are very small plants, which would have an impact on the average emissions presented.

[30] Annex 3A

[31] Includes: Pressure relief valves, regulators, block valves, connectors (unions, flanges, and plugs), and control valves

[32] Includes: Crank case vent, compressor seals, open-ended lines, orifice meter, glycol dehydrators, pneumatic controllers, equipment blowdowns and purging activities, tank vents, combustion equipment

[33] For well sites and compressor stations, glycol dehydrators, pneumatic controllers, equipment blowdowns and purging activities, tank vents, flares, and combustion equipment are not included

[34] Estimate per well site based on the average number of wells per wellsite.

- Compressor stations in the database include a large share of compressors situated in the production segment (i.e. gathering/boosting compressors), which are generally smaller than the stations in the transmission sector.

- Some of the past studies have focused on very limited samples of facilities per survey. It is not clear what the selection criteria have been and how representative the sampling has been relative to the overall distribution of facilities.
- According to the data providers for this study, many gas plants in the database have been engineered to high standards, and many have a number of personnel on-site to identify and correct emission related problems before they are detected by third party companies.
- In a number of the other studies reviewed, the leak detection and repair programs were performed for the first time (pilot study or baseline survey), and a large number of leaks were detected. When leak detection surveys are repeated regularly, repeat year surveys (which constitute the majority of the data used for this study) may identify decreased leak rates.

Economic attractiveness of leak detection and repair

An earlier study confirmed that the vast majority of fugitive natural gas losses (96.6%) were cost-effective to repair (6). However, several reports ((5), (6), and (4)) find that in most of the evaluated individual facility cases, the full LDAR program – survey + repairs – is economic to implement. In this report, we find that LDAR programs at most *individual* facilities will have negative NPV, although the aggregated NPV is positive. This difference can be explained by the smaller overall emission rates identified at each facility in this study (see above).

This review of past work shows that the results of the analysis performed in this study may be conservative when considering US facilities.

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