Quantifying cost-effectiveness of systematic Leak Detection and Repair Programs using Infrared cameras

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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 gas sector. Emissions are partly *leaks* and partly engineered *vents*. According to data presented by the US Environmental Protection Agency (EPA), 16% of the methane emissions in the onshore production sector are leaks (2), which here means fugitive leaks past static seals such as 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 for oil and gas sector leaks. LDAR programs at oil and gas facilities, in this case using infrared cameras, 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 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 has been populated 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.

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: leaks amounting to more than 97% of gas emissions (assuming a value of gas of 3 US dollars (USD) per Mcf) are worth repairing. In addition, over 90% of the gas emissions are from leaks which 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.

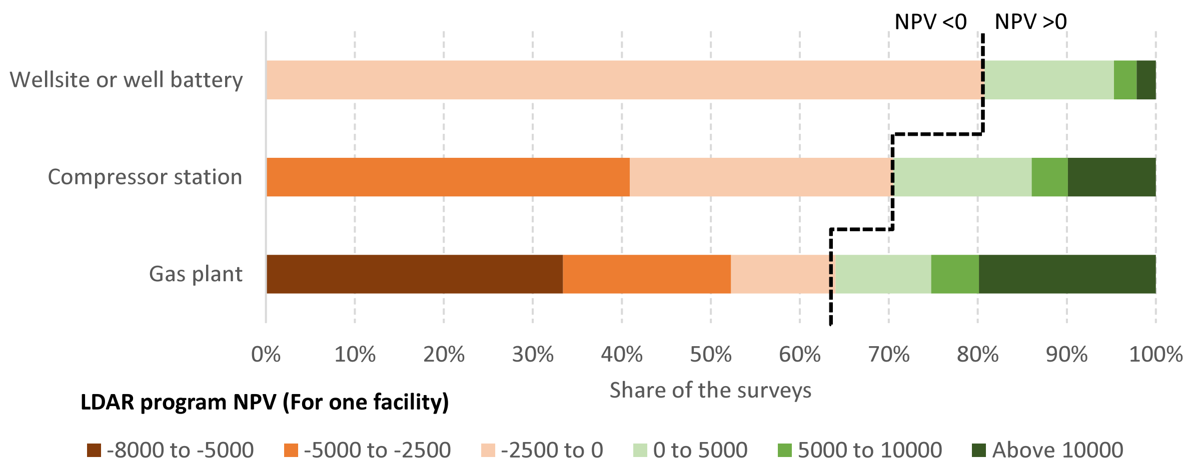
The costs and benefits of LDAR programs were analysed from (a) the perspective of individual facilities, where the distribution of net present values (NPV) for facilities of each category is examined, and (b) from a public perspective, where the aggregate cost-effectiveness of conducting LDAR programs 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) the *total* cost of conducting a leak-detection survey at a facility, including both the cost of the hiring the external service provider to survey the facility *and* internal costs that a facility owner bears to administer contracts, etc., is 150% of the cost of hiring the external service provider; and (iii) facility owners fix all leaks that the survey identifies. Base case results show results based on surveys as they were performed – with variable frequency. Finally, changes in cost-effectiveness when altering key assumptions, including the assumption that all leaks are fixed and the frequency of detection surveys, were examined.

Economic assessments – Individual facilities

We first calculated the distribution of NPVs of LDAR programs conducted at individual facilities. Although the detection surveys result in identification of gas emissions from vented sources, such as compressor seals or pneumatic devices, this analysis considers the entire survey cost but only the benefits of leak repairs. Surveys found more vented emissions than leaks at all facility types. This report does not include the benefits that can be realized through cost-effective reductions of vented emissions identified by the surveys, and therefore underestimates the value of LDAR programs. Future work will examine the economics of mitigation of those vented emissions and will present calculations of program costs and cost-effectiveness including both leaks and vented emissions.

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. 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 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 -1,160 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. The mean NPV for the 393 gas plant surveys having a negative NPV (64%) was -4,660 USD, while the mean NPV for the 221 gas plant surveys having a positive NPV was 34,412 USD. For the 1,915 compressor stations surveyed, 1,350 surveys had a negative NPV (with mean -2,401 USD) and 565 surveys had a positive NPV (with mean 17,182 USD).

Figure 1: Distribution of Project NPV per LDAR program for different types of facilities

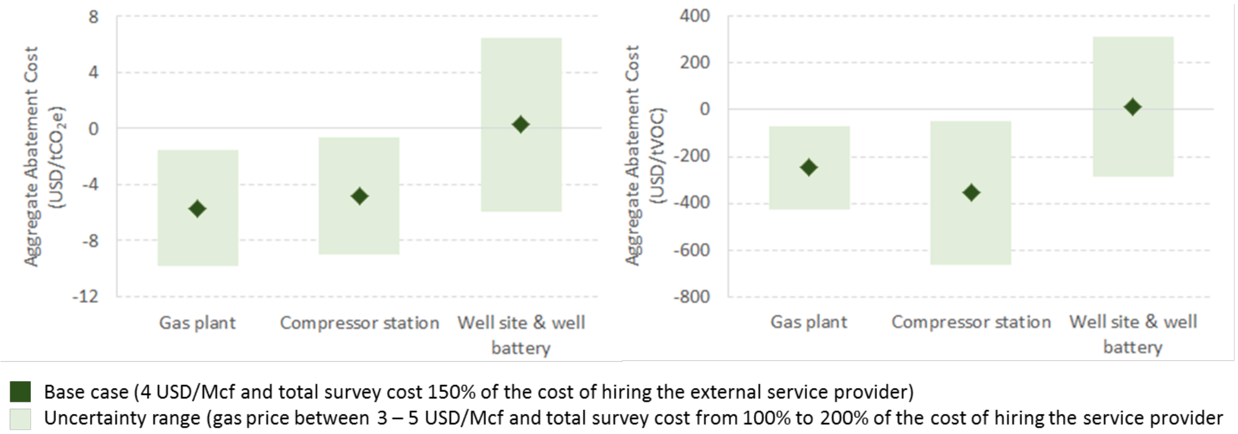


Economic assessments – Aggregate cost effectiveness of LDAR programs

To evaluate the overall benefit of systematic implementation of LDAR programs for a group of facilities of a similar type (e.g. over a jurisdiction or within a large company with a number of facilities), aggregate NPVs were calculated. Although less than 50% of all facilities surveyed have a positive NPV, the aggregate NPV for all facilities is positive in the base case, or close to zero in the case of well sites and batteries. We find that the *net cost* associated with facilities with negative NPV is less than the *net gain* associated with those having positive NPV. While the *net cost* for facilities with negative NPV is quite limited due to the low cost of conducting detection surveys, the *net gain* from facilities with positive NPV can be quite high.

The aggregate economic result of conducting LDAR programs can also be presented in terms of abatement costs (e.g. per metric ton of CO_2e or VOC reduced). A negative abatement cost means that the aggregate NPV is positive. 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 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 total cost of obtaining a survey is 200% of the cost of hiring the external service provider). 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 applying different repair strategies would reduce the abatement costs of systematic LDAR programs (e.g. (a) repair only the leaks that are economic to repair, or (b) repair leaks with an emissions rate over a certain threshold). 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.

The cost-effectiveness of survey at different frequencies is 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%, but increases the abatement costs. The aggregate abatement costs for quarterly surveys remain, however, below 15 USD/tCO_2e and 800 USD/tVOC. Monthly surveys increases the 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, and 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. Alternative technologies in the future may reduce cost and improve effectiveness.

Figure 3: Aggregate abatement costs depending on the survey frequency

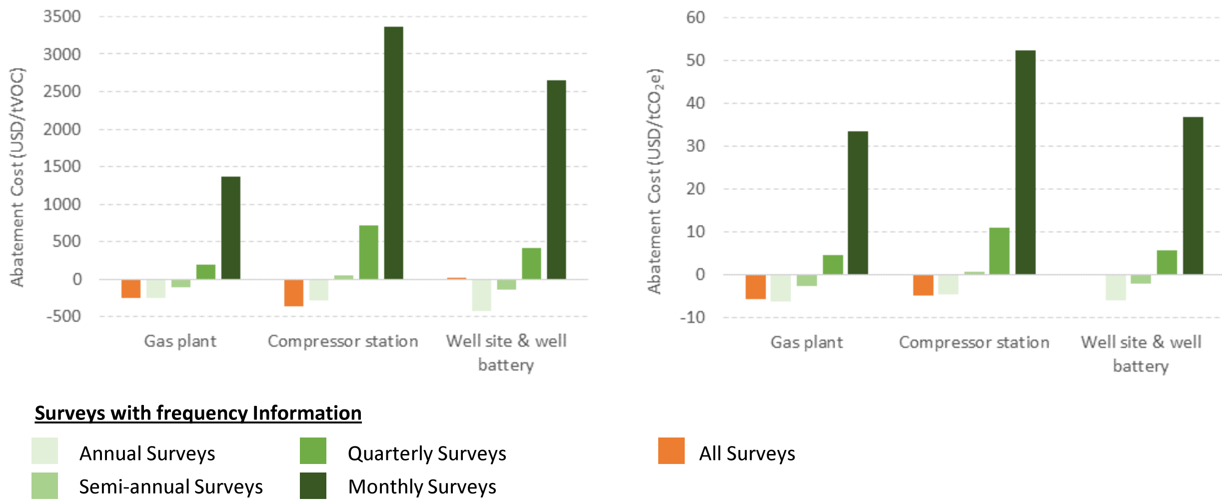
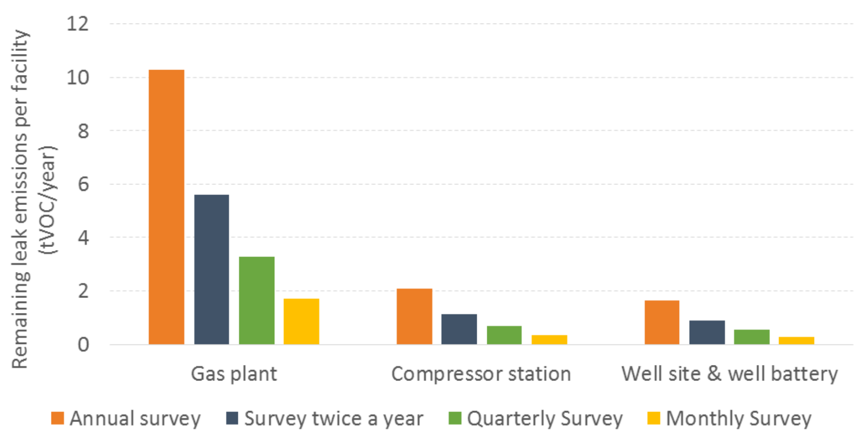


Figure 4: Remaining leak emission per facility in average depending on the survey frequency



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 have low abatement costs.

1. INTRODUCTION

Methane is a greenhouse gas with short lifetime in the atmosphere. For this reason, measures to reduce emissions of methane can quickly lower 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 U.S. greenhouse gas emissions (1). 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 focus is on programs to detect and repair leaks from Canadian and U.S. oil and gas sector facilities. Gas leaks (unintended emissions) can occur from oil and gas sector equipment such as connectors, valves and flanges. According to inventories published by the US EPA, leaks from these types of components account for 16% of the methane emissions in the onshore production sector (2). Other sources of methane emissions from oil and gas, such as venting from tanks and other equipment[1], compressor seal leaks, and incomplete combustion of methane in gas-fired engines, are not covered in this report.

2. DATA SOURCES AND ANALYTICAL APPROACH

2.1 Data sources and leak rates

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 sample[2], covering all potential sources of emissions (both leaks and vents). The surveys detected 58,421 emission sources, including 39,505 leaks from connectors, valves, regulators, etc.[3]. Some 90% of the surveys were performed in Canada, with the balance in the U.S.

As part of the LDAR 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-

[1] Vents here include those from pneumatic controllers, well completion and workover venting, dehydrators, and unlit flares.

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

[3] 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 this analysis, 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.

volume sampler) or estimated[4]. 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 repair lifetime for each individual emission source detected in the surveys[5]. Facility specific information such as age, size, operating mode and the technology used are not available.

Three types of facilities were surveyed, as shown in **Table 2**.

Table 2: Types of facilities and number of surveys[6]

Facility type:	No of surveys:	Description
Compressor station	1,915	This category includes mainly compressors upstream (gathering compressors) and compressor stations in the transmission and storage sector. Compressor stations in this category in general range from one[7] to three compressors and from 200 to 1000 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[8]. The vast majority of plants are more than five years old.
Well sites and well batteries	1,764	This category includes the following[9]: • 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.

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

[4] 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.

[5] 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.

[6] 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 type, nor to analyse how leak rates or net program costs vary between sub-categories.

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

[8] 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).

[9] These three subcategories are used separately in the database, but due to inconsistent terminology and practices between the two data providers, the category "well sites & well batteries" is used in this study.

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

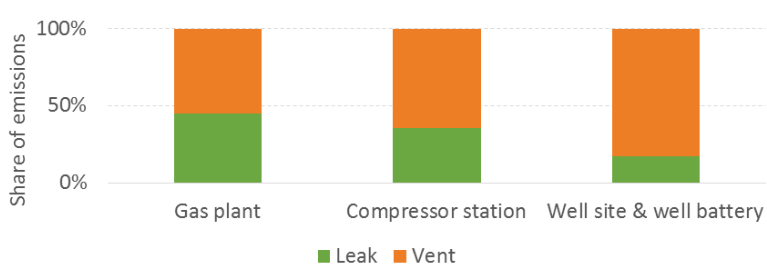
Table 3: Distribution of facilities within each category by leak rate (in Mcf per facility per year)

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 & 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 baseline gas emissions in the U.S., 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. Currently, there are no such systematic requirements for most natural gas facilities in the U.S., outside of gas processing plants built after 1984. As a result, current emissions from most U.S. facilities are expected to be higher than the emissions typical in these surveys.

Using the information in the database, in addition to average survey costs for facility types provided by the two leak detection firms, costs and benefits of leak detection programs of various design can be calculated. Although the focus of this analysis is on leaks, it should be noted that vents are the dominant source of emissions (see Figure 5), and some portion of these venting emissions can be cost-effectively mitigated. Vents from instrument controllers and compressor rod packing represent about 40% of the vent emissions and will be covered in a separate report. Other significant sources of venting are production/storage tanks, lube oil vents, compressors, pumps and engines. Since this report does not include the benefits of the cost-effective venting emissions reductions identified by the surveys, it underestimates the overall value of LDAR programs.

Figure 5: Share of the detected emissions (both measured and estimated) as leaks and vents, for various facility types



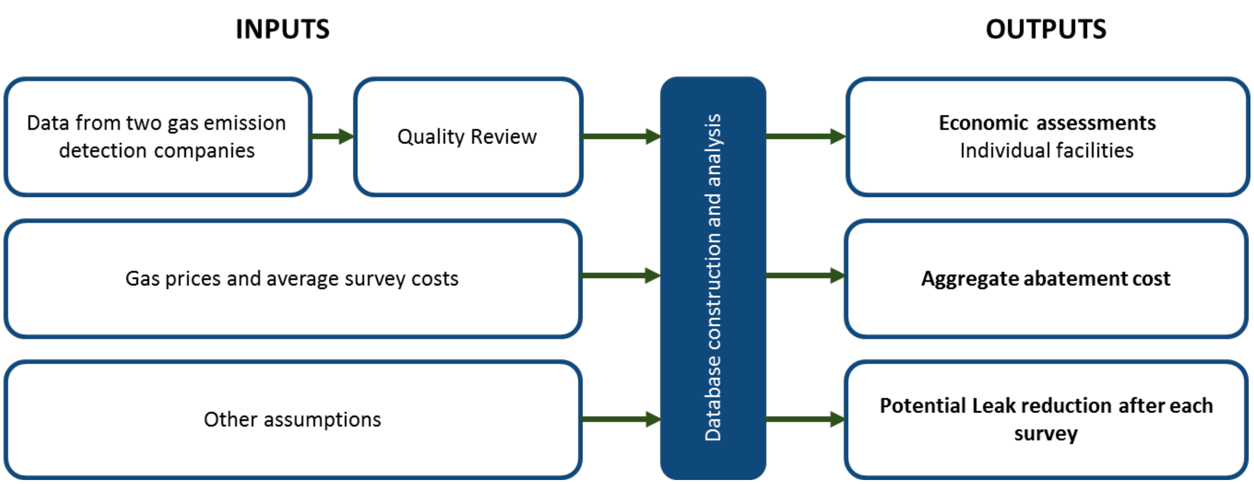
[10] This is very similar to the result from reference (7) where no leaks were detected at 34% of the well sites.

2.2 Methodology and assumptions

2.2.1 Analytical approach

The primary source of information used for the analysis, i.e. data from 4,293 LDAR surveys from two service providers, was subject to an 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. The cost data were also carefully reviewed and changes made in cases of obvious errors.

Figure 6: Overview of the project's methodology



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:

(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.

2.2.2 Assumptions, base case approach, and sensitivity analyses

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

- **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]. Sensitivity analyses have been conducted for total survey costs to operators varying from 100% – 200% of the current market prices for hiring an external service provider (*i.e.,* an estimated mark-up of 0-100% of the external cost).
- **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.
- **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.
- **Repair efficiency**: 95% repair efficiency has been assumed for leaks, 80% for other emissions due to improper conditions[13].
- **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 leak in the database and a CO_{2e} and a VOC emission factor have been calculated (see Appendix 3). Per US 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.

The base case scenario includes the following assumptions: (i) the value of recovered gas is 4 USD/Mcf; (ii) the total cost to facility owners of conducting a leak-detection survey at a facility is equivalent to 150% of the cost of hiring the external service provider to survey the facility; and (iii) facility owners fix all leaks that the survey identifies.

[11] Service here includes gas emission detection and quantification survey and the delivery of a monitoring report to the operator. An average survey cost 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.

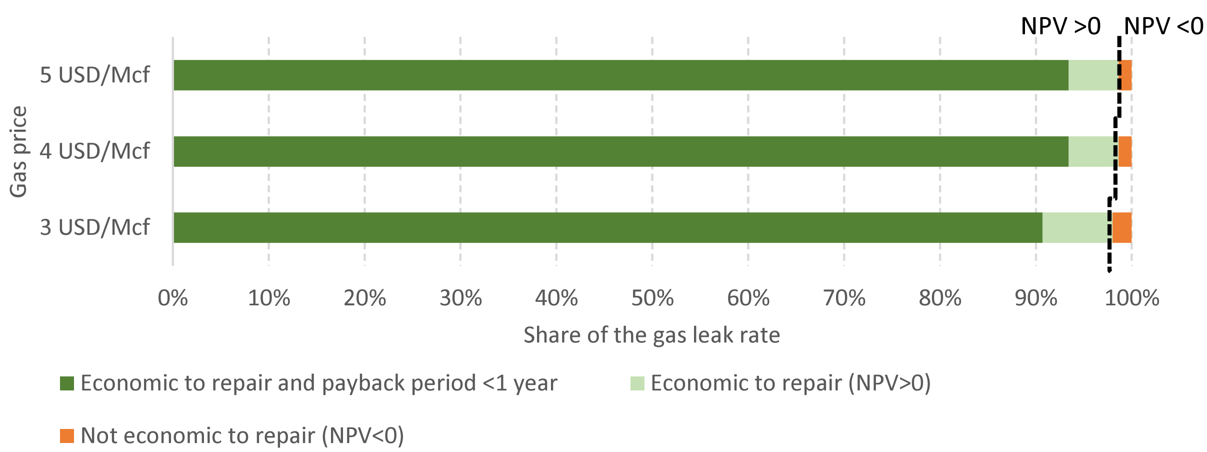
[13] Estimates based on discussion with technology providers.

3. SUMMARY OF THE ANALYSIS

3.1 Economic assessment - Individual facilities

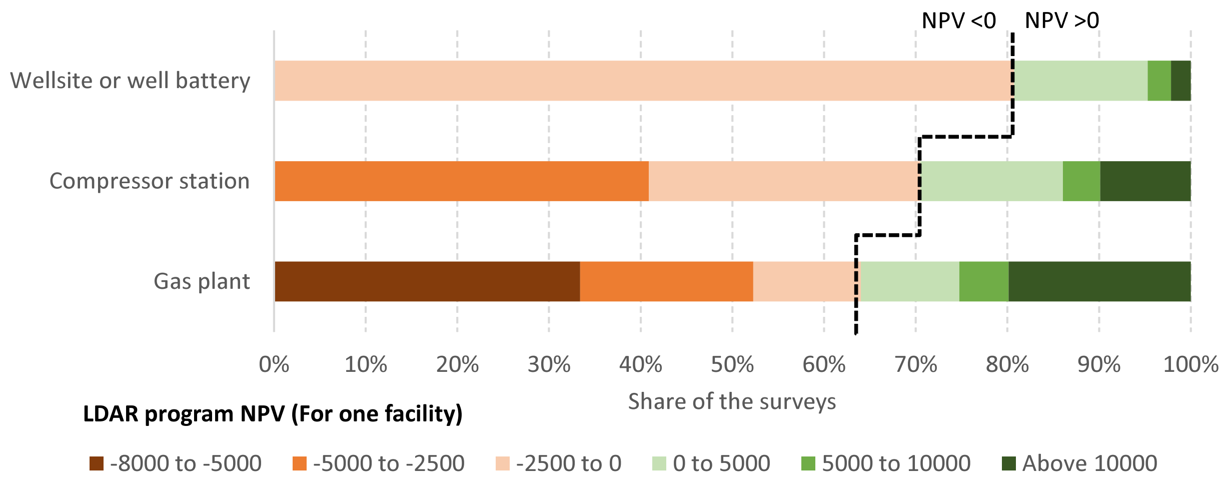
The net present values (NPVs) of repairing individual leaks identified in surveys have been calculated based on estimated repair costs and the value of the recovered gas. This analysis shows that the economic value of the recovered gas exceeds the repair cost in almost all cases. Once they are identified, 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 is 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 the total survey cost. 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 -1,160 USD, while the mean NPV for the 340 well surveys having a positive NPV was 4,704 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.

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 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 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 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).

[14] Taxes have been excluded from the analysis.
[15] 5,000 USD represents the typical cost of hiring an external service provider.

3.2 Aggregate abatement cost

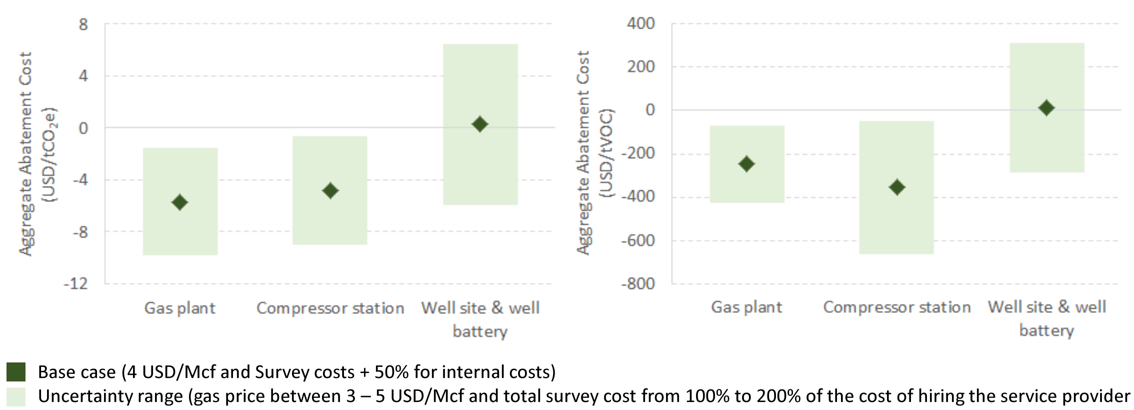
To evaluate the overall cost-efficiency of systematic implementation of regular LDAR programs for a group of facilities of a similar type (over a jurisdiction or over a large company), aggregate NPVs were estimated. Although the majority of the 4,293 facility surveys have negative NPVs when evaluated 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 (equivalent to 200% of the 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 which 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.

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

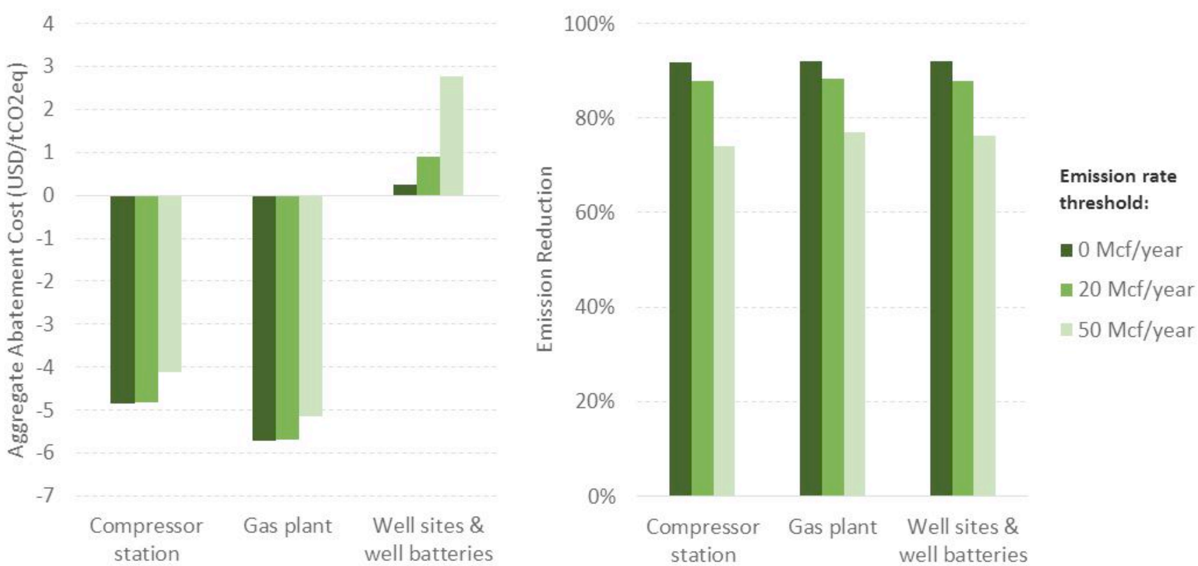
16 Only corrective maintenance program approaches are reviewed here. Preventive maintenance programs have not been evaluated as part of this project.

17 The trend is similar for other types of facilities. The results of Strategy 3 depend on the volume threshold set (see Figure 6). Gas emission reductions are calculated for the year following the survey.

When comparing the results of the analysis of the two alternative repair strategies with the base case results, the main findings are:

- Strategy 2 results in lower aggregate abatement costs, since repairs which 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). **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.

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]

[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.

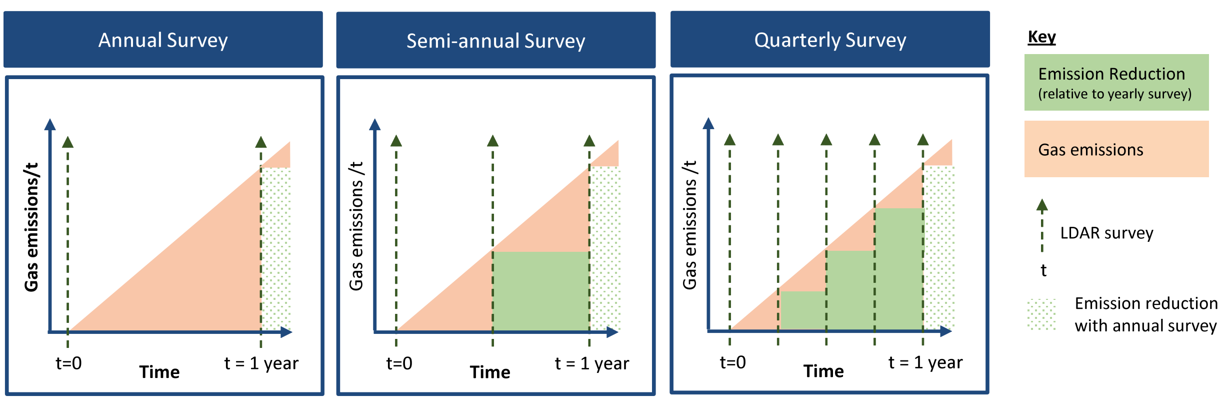
3.3.2 Impact of the frequency of surveys

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 in a variety of facilities and in several jurisdictions in both Canada and USA. 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.

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.

[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.

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

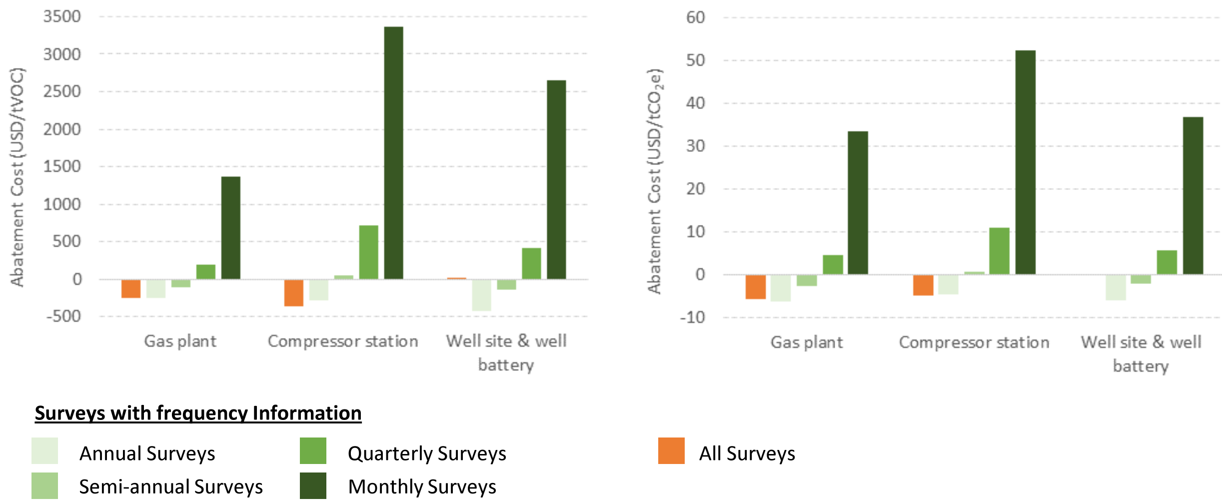
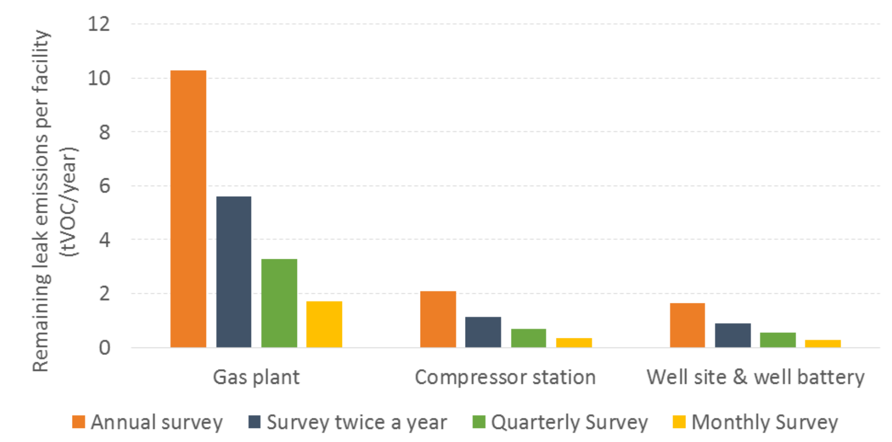


Figure 13 presents the remaining average VOC emissions per facility depending on the survey frequency.

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



We note that it is not straightforward to compare leak rates from U.S. facilities, where leak detection surveys are not generally routine, to the calculated leak rates shown in **Figure 13**, since these (like the

[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.

[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. Note: the share of repairs which will be delayed is not available in the database..

distribution of leak rates shown in **Table 3**) reflect leaks from facilities with routine LDAR programs in place (see **Section 2.1**).

To conclude, by increasing the survey frequency, remaining emissions are reduced, but at increased abatement costs. 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 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.

4. CONCLUDING REMARKS

4.1 Main findings

The study 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 allows calculation of the economic value of LDAR programs under a range of program designs and frequencies, with a robust dataset.

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.

From a facility's owner 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 (no LDAR program studied had a NPV of less than -8,000 USD per survey *and* facility).

4.2 How robust are the results?

Some sensitivity analyses were presented in **Section 3** with variations in survey costs and gas prices. However, there are other assumptions being made (see **Section 2.2.2**) 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 **Section 3**. 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.

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 **Figure 5** shows, most of the identified emission sources at facilities are venting, so this effect may be significant. Future work will attempt to include analysis of venting emissions to address this effect.

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, by this approximation, since the analysis 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 USA. The key relevant similarities and differences between the two countries are:

- Results from analysis of data contained in the database: 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 USA 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 USA are, on average, larger than Canadian ones[23]. 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.[24]

Finally it should be added that other analyses for US facilities generally show higher leak rates than presented in this analysis, see **Appendix 3**. This review suggests that the results of the analysis performed in this study may be conservative when considering US facilities. However, comparison with other studies as shown in **Appendix 3** should 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.

[23] 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).

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

Appendix 1: LDAR costs

Table 5: 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 6: 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 7: 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 8: 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: 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 9 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 9: Comparison of the current study with past 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)[25]	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[26]	12	NA	7	NA	5	60.2
	Average vent[27]		NA		NA		65.2
	Average emissions[28]		0.8		12.2		155.1
University of Texas 2013 (7)	Average emissions	146	0.23[29]	NA	NA	NA	NA

It is important to highlight that the studies compared in **Table 9** 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.

25 Annex 3A

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

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

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

29 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.

References

1. **EPA.** [Webpage]. 2012. http://epa.gov/climatechange/ghgemissions/gases/ch4.html.
2. **EPA.** Petroleum and Natural Gas Systems – 2012 Data Summary. Greenhouse gas reporting program. 2013. http://www.epa.gov/ghgreporting/documents/pdf/2013/documents/SubpartW-2012-Data-Summary.pdf
3. **Eastern Research Group.** Fort Worth Natural Gas Air Quality Study. 2011. http://fortworthtexas.gov/uploadedFiles/Gas_Wells/AirQualityStudy_final.pdf
4. **Natural Gas Star Program.** Directed Inspection and Maintenance at Processing Plants and Booster Stations. 2006. http://www.epa.gov/gasstar/documents/ll_dimgasproc.pdf
5. **Natural Gas Star Program.** Directed Inspection and Maintenance at Compressor Stations. 2006. http://epa.gov/gasstar/documents/ll_dimcompstat.pdf
6. **National Gas Machinery Laboratory, Clearstone Engineering Ltd. Innovative Environmental Solutions, Inc.** Cost-Effective Directed Inspection and Maintenance Control Opportunities at Five Gas Processing Plants and Upstream Gatllering Compressor Stations and Well Sites. 2006. http://www.epa.gov/gasstar/documents/clearstone_II_03_2006.pdf
7. **David T. Allen, & al.** Measurements of methane emissions at natural gas production sites in the United States. 2013. http://www.pnas.org/content/early/2013/09/10/1304880110.full.pdf+html
8. **CAPP.** Management of Fugitive Emissions at Upstream Oil and Gas Facilities. 2007. http://www.capp.ca/getdoc.aspx?DocId=116116&DT=PDF