CARBON LIMITS

Statistical Analysis of Leak Detection And Repair Programs in Europe

Final Report

This report was prepared by Carbon Limits AS.

Project title:

Statistical Analysis of Leak Detection And Repair Programs in Europe

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Finalized: 30/11/2017

Special thanks to the three companies who provided the survey data used for this study - for their continuous support and precious information provided during the course of the study.

The project team would also like to thank Daniel Zavala-Azaira from EDF for his insights on the analysis presented in this report

Finally, we would like to thank Ellen Baum from CHERN for her constant support.

The analysis and the report has been financed by Climate Works foundation (http://www.climateworks.org/)

The report has been prepared by Carbon Limits and does not necessary reflect the opinion of "EHS techniques", "LDAR Envolve" and "The Sniffers".

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

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Acronyms and definitions

Acronyms

cfm	cubic feet per minute
FID	flame ionization detector
IR	Infra-red
kg/h	kilograms per hour
LDAR	Leak Detection and Repair
LNG	Liquified Natural Gas
P&ID	Piping and Instrumentation Diagram
ppm	Parts Per Million
PID	photoionization detector
UK	United Kingdom
US EPA	United States Environmental Protection Agency

Definitions

Venting versus leak:

Typically, methane emissions from the oil and gas industry are separated into two categories: (i) vented methane (i.e. “intended” or “engineered” emissions) and (ii) leaks (i.e. “unintended” emissions)[1]. Venting can occur during routine maintenance of equipment or normal operational practices. Leaks can occur in the gas or oil infrastructure, for example, from the flanges, valves, and compressors.

Emission point:

In this report, the term “emission point” is used to designate both intentional (vent) and unintentional (leak) emission sources to the atmosphere.

Hydrocarbons:

In this report, the term “hydrocarbons” refers to organic compounds consisting of hydrogen and carbon, typically methane, ethane, propane and butane.

Leak detection and repair (LDAR):

In this report, “leak detection and repair” (LDAR) is a generic term covering a range of technologies and methodologies to identify, quantify and then mitigate hydrocarbon emissions.

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[1] The word «fugitive» is used in various contexts, with different meanings and is therefore not used in this report.

Executive summary

Compared to North America, fewer public studies have focused on measurement of methane emissions from oil and gas systems in Europe. This report provides insights on emissions patterns in Europe, focusing particularly on midstream emissions and sheds new light on a few critical issues related to the mitigation of methane emissions. In particular, this report addresses the following questions:

- What is the distribution of emission rates, and how do rates vary based on the type of components?
- When operators detect a leak, they typically perform a repair. How effective are these repairs at reducing the emissions?
- How frequently are new leaks detected after repair, and how often does repaired equipment leak again?

The analysis presented in this report is based on data collected during surveys carried out by three private sector firms that provide gas emission detection and measurement services to the industry. To perform the gas emission detection and measurement services, measurement companies typically first screen the facilities using infrared (IR) cameras to locate hydrocarbon gas emissions. Emission concentration is then measured with PID/FID equipment, or estimated (e.g. in case of non-accessible points) for all the identified emission points. Emission rates are calculated based on the emission concentrations, typically applying the US EPA “Method 21”. An emission register is then produced and delivered to the facility owner, which includes all the information gathered during the survey. These emission registers were made available to Carbon Limits in an anonymised format, and combined into one large database. The resulting database includes about 800 000 data points from four different countries, spanning over 11 years and nine different types of facilities in Europe.

Emissions distribution by equipment type: Similarly to North America studies, the analysis demonstrates that emissions distribution per component is skewed. A large share (i.e. 85%) of the components emit less than 0.07 kg/hr, while a minority of the components represent the majority of the emissions. This type of distribution has, of course, an important impact on emission mitigation: identifying and mitigating the largest emitters as early as possible can have a significant effect on the overall magnitude of emissions.

Effectiveness of repairs: Regular and systematic LDAR is currently considered best practice to identify emission points and guide the maintenance team in repairs. A statistical evaluation demonstrates that almost 40% of the repairs were only partially effective or not effective at all. Conversely, in 60% of the cases the repair led to more than 90% emission reduction, and were considered effective. Although the effectiveness of the repairs is likely to depend on the type of repair performed (e.g. tightening of the bolts versus replacement of a component), the available data did not allow for a comparison between different types of repair.

Effectiveness of LDAR over time: By following the same facilities over time (i.e. in some cases, up to 11 years for the same facility), the project team evaluated the long-term effectiveness of LDAR programs. The analysis demonstrates two main conclusions:

- At a given facility, new emission points are still detected after more than ten surveys, meaning that new emission points continuously appear during the lifetime of the equipment.
- The effectiveness of the repairs declines over time, with an increasing number of components developing another leak. This raises questions about the sustainability of the initial repair effort: a “quick fix” such as tightening the bolts may be successful in the short term, but a leak at that site may reappear in the next survey or later. On the other hand, a thorough root cause analysis and component replacement might produce longer-lasting results.

Key implications

This analysis confirms the need for regular and systematic LDAR, because new leaks appear despite numerous surveys or equipment repair. In the context of discussions concerning the optimal frequency of LDAR surveys[2], these results highlight the importance of the quality and sustained effort of LDAR:

- Assessing the success of the repair performed would maximise the impact of a LDAR campaign and could significantly improve the emissions reduction achieved.
- Also, developing "best practice leak repair" guidelines for the operator could improve the impacts of LDAR campaigns significantly. Such guidance should cover issues such as how to deal with specific characteristics of individual components, implement optimal maintenance practices, and decide whether to overhaul equipment.

[2] For example, refer to: https://carbonlimits.no/project/quantifying-cost-effectiveness-of-systematic-leak-detection-ldar-using-infrared-cameras/

1. Background and objective

Methane is one of the “short-lived climate pollutants” that has received increased attention from the research community and policymakers in recent years. Oil and gas systems - including oil and gas production, oil transport and refining, gas processing, gas transmission and gas distribution - are among the largest anthropogenic sources of methane. According to the US Environmental Protection Agency (US EPA), they represent almost 25% of global anthropogenic methane emissions[3]. These emissions are distributed across more than a hundred thousand sites globally, including millions of individual emission sources. Each oil or gas well site, compressor station, gas plant and pipeline segment, for example, may include up to several hundred of point sources of emissions[4].

Over the last couple of years, important research to understand emission patterns, particularly in North America, has developed and refined emission factors and evaluated the cost-effectiveness of mitigation options. Despite some remaining uncertainty, this body of work has demonstrated that: (i) actual emissions are typically higher than originally expected, (ii) emissions vary significantly among sites, with a few sites and components representing a large share of the emissions[5], and (iii) mitigating these emissions is often very cost-effective[6] (i.e. the cost per unit of methane abated is relatively small).

Compared to North America, fewer public studies have focused on measurement of methane emissions from oil and gas systems in Europe. This report provides insights on emission patterns in Europe, focusing particularly on midstream emissions and sheds new light on a few critical issues related to methane emissions mitigation. This report focuses mostly on leaks, defined as unintended emissions. In particular, this report addresses the following questions:

- What is the distribution of emission rates, and how do rates vary based on the type of components?
- When operators detect a leak, they typically perform a repair. How effective are these repairs at reducing the emissions?
- How frequently are new leaks detected after repair, and how often does repaired equipment leak again?

This report does not seek to evaluate or compare different LDAR methodologies.

This document is structured in two main sections: section 2 describes the methodology and the data used, section 3 then presents and explains the results of the analysis. Finally, the annex provides information on the limitations of the study.

2. Data and methodology

2.1 Sources of data

This analysis is based on data collected during surveys carried out by three 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 anonymised format and combined into one large database.

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[3] Data for 2015, based on https://www.epa.gov/global-mitigation-non-co2-greenhouse-gases/non-co2-greenhouse-gases-international-emissions-and

[4] Compressor stations in Canada are e.g. estimated to have more than 10 emission points in average (and a number of gas vents), while gas plants include tens of thousands of components of which a few percent are typically emitting methane. http://carbonlimits.no/project/statistical-analysis-leak-detection-and-repair-canada/

[5] https://www.nature.com/articles/ncomms14012

[6] E.g. https://www.edf.org/energy/icf-methane-cost-curve-report , IEA WEO 2017,

To perform the gas emission detection and measurement services, measurement companies typically first screen the facilities using infrared (IR) cameras to locate hydrocarbon gas emissions. Emission concentrations are then measured with PID/FID equipment, or estimated (e.g. in case of a non-accessible point) for all the identified emission points, in PPM. Emission rates are calculated by the measurement companies, based on the emission concentrations (see also annex), using the US EPA “Method 21”[7]. This method has been applied for the vast majority of the data in the database, so the data are considered comparable across datasets. An emissions register is then produced and delivered to the facility owner, which includes all the information gathered during the survey.

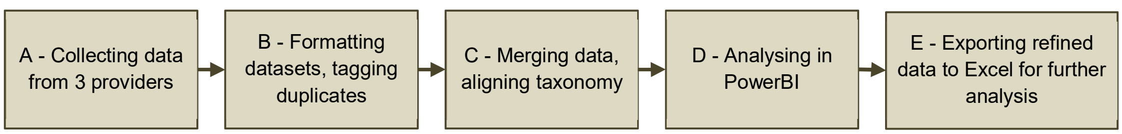
The leak repairs are performed immediately (or soon after the survey) or at a later date if a partial or full shutdown is required. In some cases, the measurement team performs a second measurement after the repair to evaluate the effectiveness of the repair (see also section 3.2).

The database includes data from facilities located in the Netherlands, the UK, Spain and Belgium.

2.2 Construction and content of the database

Due to the large volume of available data, Microsoft PowerBI was used to build the database and conduct the analysis. The main steps of the process are presented below (Figure 1).

Figure 1: Main steps of database construction and analysis



Carbon Limits first collected the data from three providers in various formats (Step A). Each dataset was then formatted consistently to facilitate merging the datasets (e.g. common field names, filtering the useful information). Duplicates were also tagged to remove them from the later analysis (Step B). The datasets were then merged into a common database in Microsoft PowerBI (Step C).

The combined and cleaned database includes a total of 791 696 measurement points: both active emission points and points within background concentration level. Each point includes the following elements:

- Date of the measurement;
- Survey ID;
- Country, facility ID and facility type;
- Component ID (P&ID tag), type and sub-type of component;
- Location of the emissions on the component (for dataset 1);
- Emissions concentration in parts per million (for datasets 1 and 2);
- Emissions flowrate in kg/h (for datasets 1 and 3); and
- Description of the repairs (for dataset 2).

Given the anonymous format of the data, no information was available on the facility size, throughput, age or the operator of the facility.

As presented in Table 1, more than half of the measurement points are related to compressor stations. The database also contains a significant number of data points for transfer stations[8], gas storage units, LNG plants[9], mixing/blending units and metering units.

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[7] https://www.epa.gov/emc/method-21-volatile-organic-compound-leaks

[8] Stations where the gas is further compressed and injected into the transmission network.

[9] The sub-category of LNG facilities (i.e. liquefaction or regazification) was not available in the dataset.

Table 1 Unit types and measurement points in the database

Unit type	Number of measurement points	Share (%)
Compressor station	494 133	62.4
Transfer station	98 186	12.4
Gas storage	84 319	10.7
LNG	54 741	6.9
Mixing / blending	26 985	3.4
Metering	19 893	2.5
Metallurgy	8 651	1.1
Valve station	4 041	0.5
Storage & Distribution	559	0.1

The three datasets used different categories for components and component types. A common taxonomy was applied (Step C) and a subset of ten component types and eight sub-types was defined (Table 2). About half of the measurements relate to valves and a third to connectors. Ball valves were the most common component sub-type in the database (22%), followed by raccords (16%, sub-type of connectors), and needle valves (13%).

Table 2 Component types, sub-types and measurement points in the database

Component type	Component sub-type	Number of measurement points	Share (%)
Compressor		1 082	0.1
Connector	Elbow	38 467	4.9
	Raccord	129 150	16.3
	Reduction	12 551	1.6
	T-Connector	60 161	7.6
	Others	13 811	1.7
Control Valve		41 067	5.2
Flange		10 161	1.3
Instrument		52 574	6.6
Line		260	0.0
Others		36 043	4.6
Pump		215	0.0
Relief Valve		10 241	1.3
Valve	Ball	171 802	21.7
	Block	57 463	7.3
	Needle	103 161	13.0
	Others	53 760	6.8

The database was analysed using PowerBI to identify trends between sites, component types, and to derive data on repair efficiency (Step D). The results of the analysis were then exported to Microsoft Excel to produce the tables and charts presented in this report (Step E). For some categories of equipment, small sample size could not provide statistically reliable results. These results were not included in the presentation of the analysis[10].

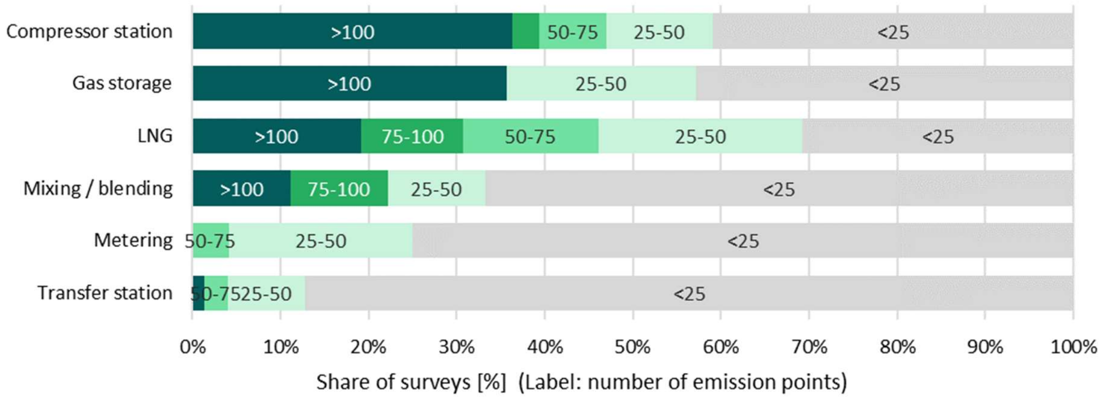
The database covers 415 separate surveys. A survey consists of several measurements carried out by a single team at a defined facility (i.e. one or several units), for a limited period, typically several consecutive days. Emission points (i.e. points where the measured concentration or flow indicates leaking emissions) were detected in 88% of the surveys. For those surveys, 56 emission points were detected on average per survey. A breakdown of the amount of emission points detected per survey is presented in Figure 2.

Compressor stations were the facilities where most emission points were detected, with an average of 223 points per survey. For those facilities, 36% of the surveys detected 100 emission points or more. On the other hand, 41% of the surveys detected less than 25 emission points at compressor stations. Gas storage units were the second type of facilities where most emission points were detected at each survey, with an average of 118 points per survey. 35% of the surveys detected more than 100

[10] Typically, samples of 100 or less data points were not presented.

emission points in this equipment type, while 43% of the surveys detected less than 25 emission points.

Figure 2 Number of emission points detected per survey



3. Analysis and key results

3.1 Distribution of emissions by equipment type

Similar studies in North America[11] have demonstrated that the distribution of emission rates across different sites is highly skewed, so that a minority of the components represent the vast majority of emissions. This analysis documents similar distributions for European installations.

Description of the analysis and key results

Out of the entire sample of measurement points, 22 386 points were identified as emission points (i.e. they had an emission concentration above the detection threshold[12]). The distribution of emission rates per component was analysed by sorting all points by their calculated emission flowrate and plotting this against the cumulative number of points (Figure 3). Note that the x-axis for the figure was truncated at 0.10 kg/h (0.09 cfm) because this corresponds to the highest measurable concentration of methane[13] (see also limitations in Annex).

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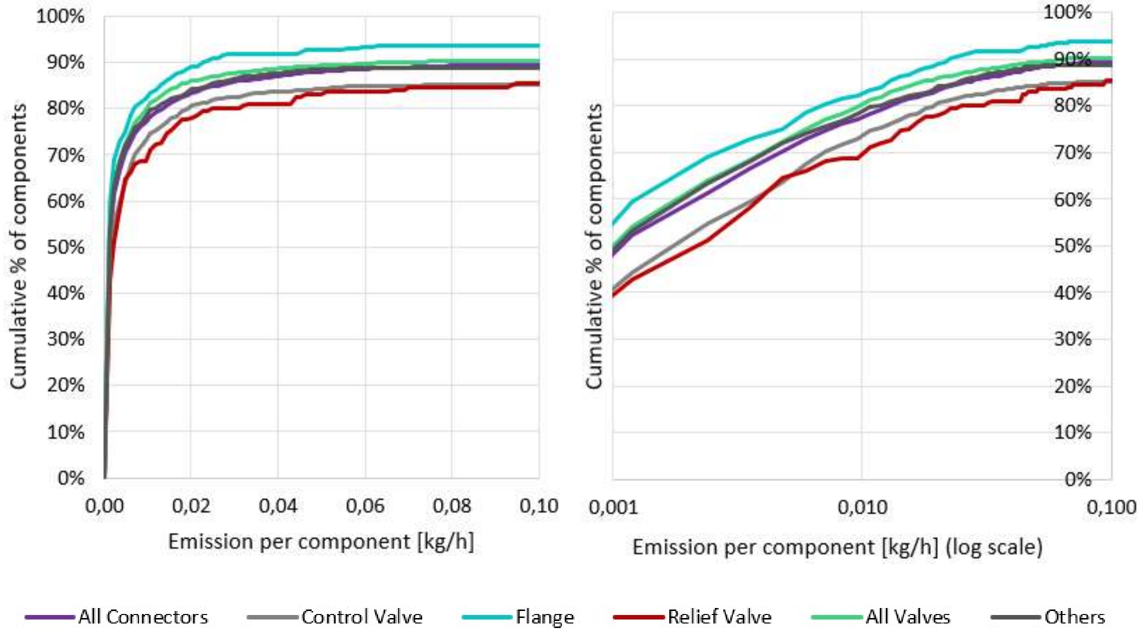
[11] Zavala-Araiza D, Alvarez RA, Lyon DR, Allen DT, Marchese AJ, Zimmerle DJ, Hamburg SP. Super-emitters in natural gas infrastructure are caused by abnormal process conditions. Nature Communications. 2017

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

[12] The detection threshold is set at 10ppm.

[13] Given the equipment used by the measurement companies

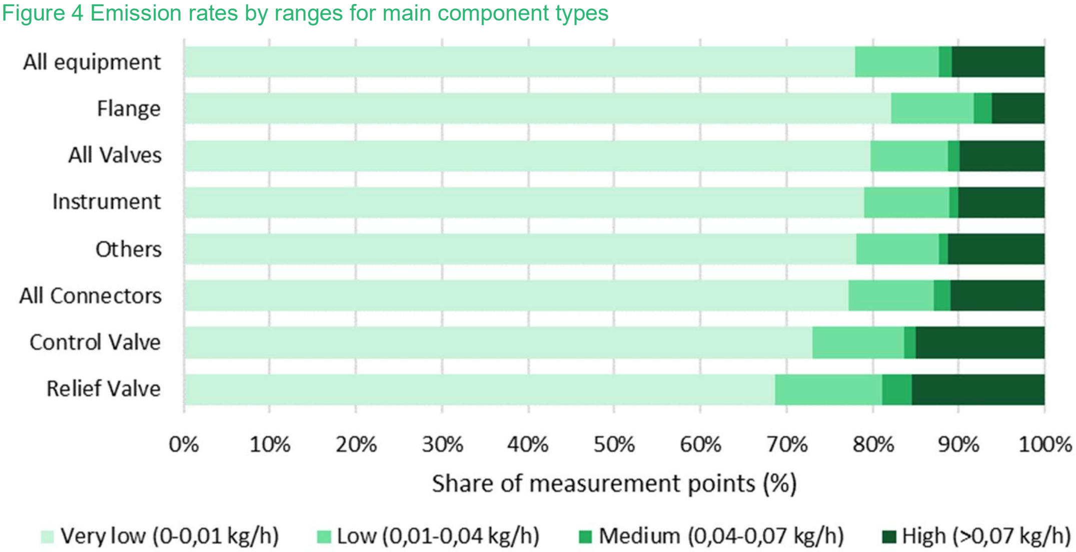
Figure 3 Emission rates versus cumulative number of components, for the main component types



The results show that most components are small emitters, with 78% of the components emitting less than 0.01 kg/h (0.008 cfm). On the other hand, 11% of the components have an emission flowrate above 0.07 kg/h (0.06 cfm), and this minority of components is responsible for most of the emissions.

The profile is relatively similar across all component types (Figure 4). Relief valves and control valves have a larger share of large emitters (i.e. 15% above 0.07 kg/h). Flanges have the smallest share of large emitters (i.e. 6% above 0.07 kg/h).

Figure 4 Emission rates by ranges for main component types



Interpretation of results

Like the North America studies[14], the analysis shows that the distribution of emissions across sites and components is highly skewed. A large share (i.e. 85%) of the components emit less than 0.07 kg/hr, while a minority of the components represent the vast majority of emissions. Given the existing

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[14] For example: http://carbonlimits.no/project/statistical-analysis-leak-detection-and-repair-canada/

concentration measurement threshold, however, it is not possible to calculate emissions above 0.10 kg/h (0.09 cfm). It was therefore not possible to measure the statistical dispersion (e.g., using the GINI coefficient as presented in Zavala-Araiza et al.[15]) or to estimate the exact share of the emissions represented by the largest emitters (see further discussion in Annex).

This type of distribution has, of course, an important impact on efforts to mitigate emissions: identifying and mitigating the largest emitters as early as possible can have a significant effect on the overall magnitude of emissions.

It is important to highlight that frequent LDAR surveys and repair campaigns were performed at the facilities covered by the analysis. This means that that “large-emitters” would have less time to develop in the facilities presented in this report than in facilities without LDAR programs. Facilities not covered by regular LDAR schemes may, therefore, have many more “large-emitters”.

3.2 Effectiveness of repairs

Regular and systematic LDAR is currently considered best practice to identify emission points and guide maintenance teams in repairing leaks. Repairs are expected to reduce emission rates significantly. This part of the analysis evaluates the effectiveness of the repairs within this dataset.

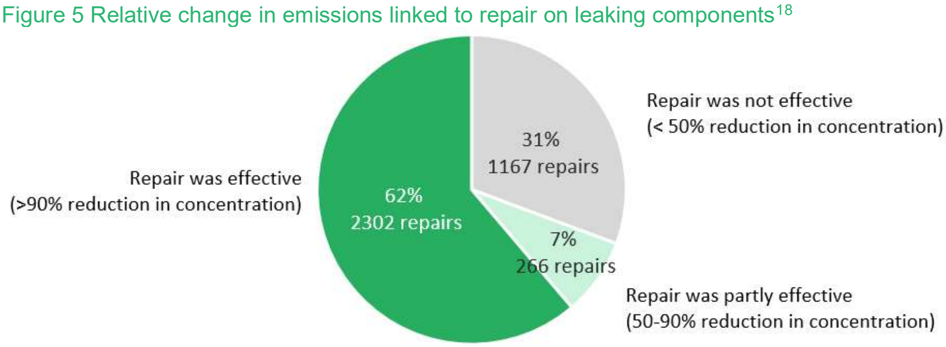
Description of the analysis and key results

The database contains about 2000 data points where a company measured emissions both before and after the repair. This makes it possible to analyse the effectiveness of the repairs[16].

The effectiveness of a repair was calculated as the difference in emission concentrations (hereafter called the “emission reduction”) between the measurements pre- and post-repair. When the emission reduction is less than 50% or when emissions actually increased, the repair is considered to be ineffective. An effective repair has an emission reduction closer to 100%. The “effective” threshold is set at 90% for this study.

Figure 5 presents the repair effectiveness for different components. In a majority of cases (61%), the repair leads to a decrease of more than 90% of the emissions concentration. However, in 31% of the cases, the emission concentration either stayed within the same range or increased after the repair[17].

Figure 5 Relative change in emissions linked to repair on leaking components[18]



[15] Zavala-Araiza D, Alvarez RA, Lyon DR, Allen DT, Marchese AJ, Zimmerle DJ, Hamburg SP. Super-emitters in natural gas infrastructure are caused by abnormal process conditions. Nature Communications. 2017;8

[16] The company indicated that all repairs are marked as such in the database, so it is possible to avoid bias where repairs would have been carried out without subsequent repeated measurement.

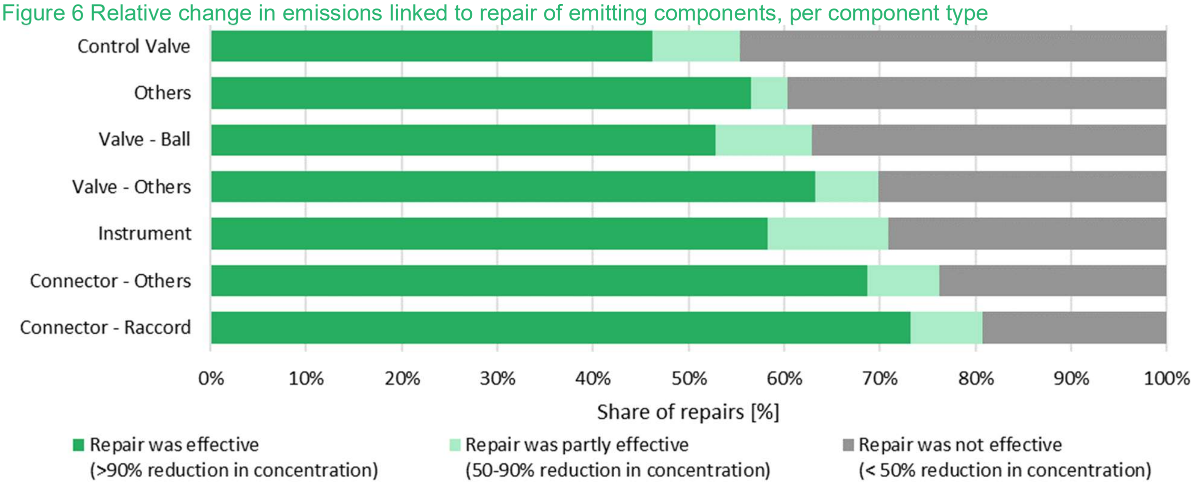
[17] Uncertainties in the concentration measurements have been taken into account in the figure

[18] The concentration reduction categories above have been selected to take into account uncertainties in the concentration measurements (i.e.±25%).

Figure 6 below shows the same results for each component type. Connectors have the highest success rate for repairs, with up to 73% of the repairs being effective. On the other end of the range, repairs on control valves are only effective at 46% of the leaks.

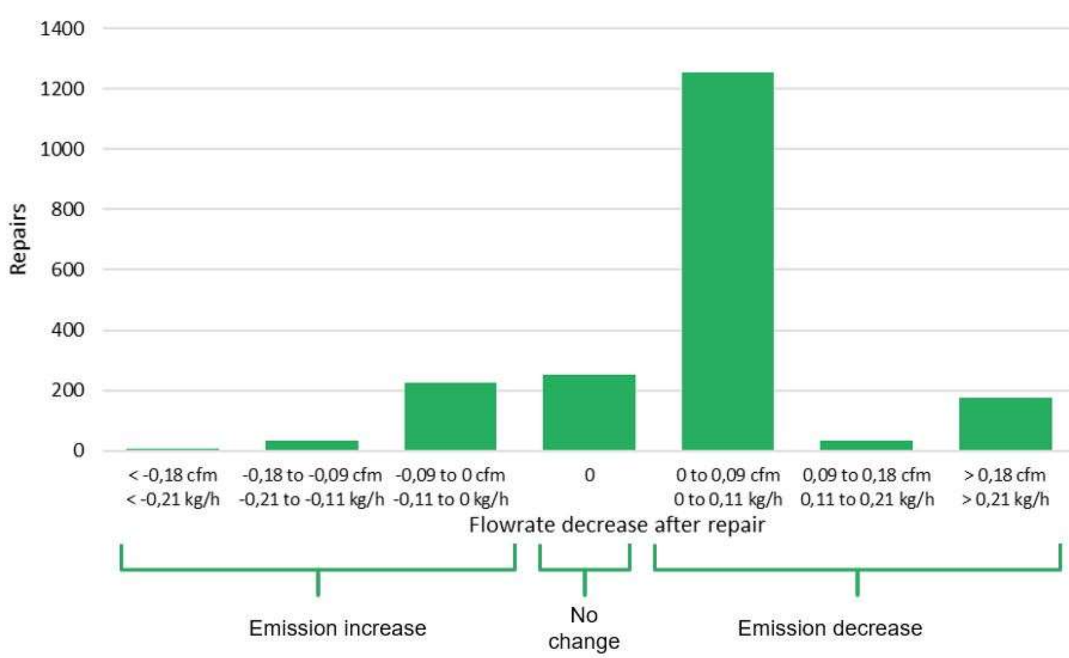
The authors could not find a correlation between the emission rate and the repair effectiveness, which means that the effectiveness of the repair seems independent of the emission rates (i.e. repairs work as well on high emission rate leaks as on low ones).

Figure 6 Relative change in emissions linked to repair of emitting components, per component type



Change in absolute emissions, expressed as the difference in emission rates pre- and post-repair, are presented in Figure 7. Most repairs decrease emissions up to 0.11 kg/h (0.09 cfm), although there is a smaller group with a decrease of more than 0.21 kg/h (0.18 cfm).[19]

Figure 7 Absolute changes in emission rates[20]



[19] These results contain significant uncertainties, however, because of the conversion from concentration to emission flowrate and the maximum threshold on the concentration measurements (see discussion in Annex).

[20] The emission reduction categories above have been selected to take into account uncertainties in the concentration measurements (i.e. ± 25%).

Interpretation of results

The analysis demonstrates that repairs were not effective – an emission reduction below 90% – in almost 40% of the cases. And in some of these cases emissions even increased. The effectiveness of the repairs depends on the type of component, with repairs on connectors generally most effective and repairs on control valves least effective. Although the effectiveness of the repairs is likely to depend on the type of repair performed (e.g. tightening of the bolts versus replacement of a component), the available data available did not allow a comparison of the effectiveness of different repair types.

The analysis shows that assessing the success of the repair performed through use of an IR camera or PID/FID measurement equipment for example would maximise the impact of a LDAR campaign and could significantly improve the emissions reduction achieved. Evaluating the success of certain repair types (e.g. so-called “quick fixes”) is an important area for future analysis.

The results also show that developing “best practice leak repair” guidelines for the operator could improve the impacts of LDAR campaigns significantly. Such guidance should cover issues such as repairing different types of components, with different characteristics, implementing optimal maintenance practices, knowing which components fail more, and deciding whether to overhaul equipment.

3.3 Effectiveness of LDAR over time

The facilities covered in the database were often surveyed repeatedly (e.g. up to over 11 years for one of the facilities), which represented a unique opportunity to assess the long-term effectiveness of LDAR programs. In particular, this section aims at answering the following questions:

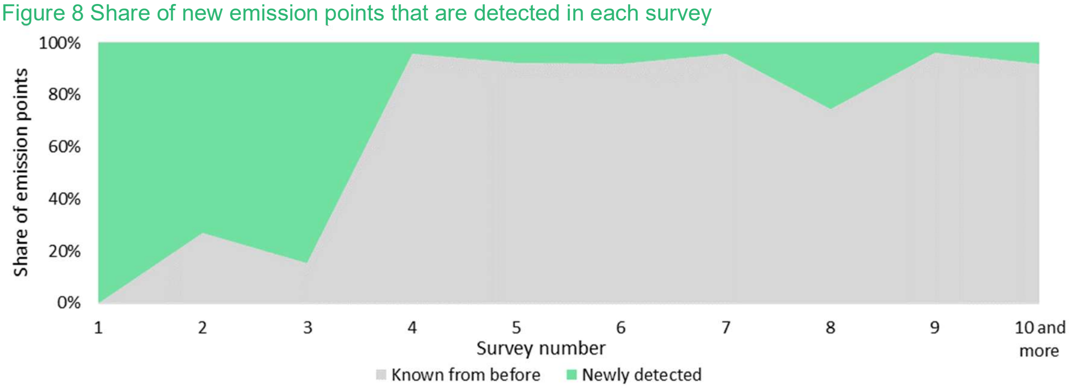
- How often are new emission points detected?
- How often does repaired equipment leak again?

Description of the analysis and key results

The surveys were sorted by date and could be organised sequentially for each facility (i.e. from first to last survey). Tracking the same emission points over multiple surveys made it possible to identify when each emission point was first detected and to follow that point over time. 298 surveys with active emission points were included in this portion of the analysis. Some facilities were surveyed only once, but others were surveyed multiple times, with up to 19 surveys per facility. The database contains an average of 2.6 surveys per facility.

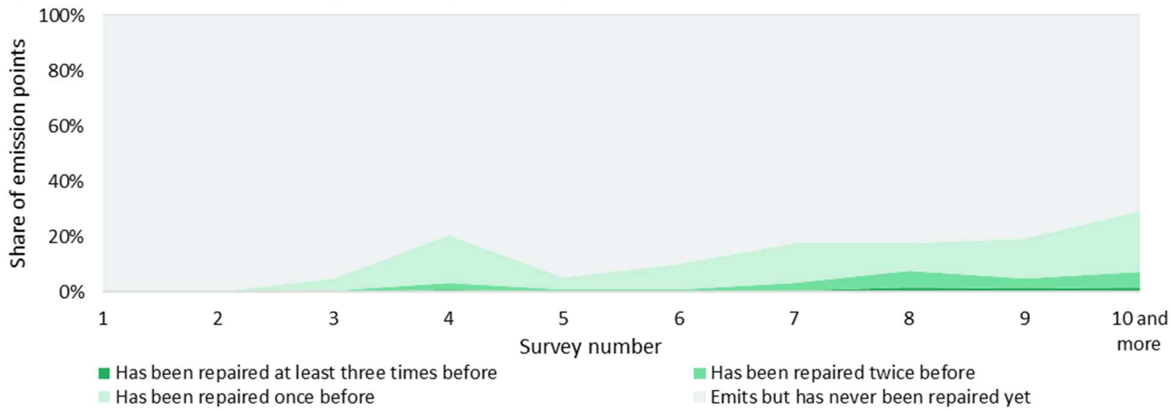
The chart below shows the average share of emission points (i.e. with a concentration above the background noise) over the timeline of surveys in the database. Surveys in category *Survey number 1* were the first surveys recorded for a given facility, *Survey number 2* the second, etc. As expected, most new emission points were detected over the first few surveys at a given site. However, new emission points continued to be identified after more than ten surveys at the same facility.

Figure 8 Share of new emission points that are detected in each survey



Since the database also contains information on repairs, it was possible to check if an active leak had been repaired at a previous survey. Figure 9 shows the share of leaks on components that were previously repaired during this set of surveys. Not only components that had been repaired at some point leak again, but even some components that were repaired more than once leaked again.

Figure 9 Share of active emission points with previous repairs



In addition to the analysis above, the project team evaluated other possible relationships:

- Frequency of surveys and number of emission points identified: Are there more emission points detected when surveys are less frequent?
- Number of past surveys and the number of emission points: Are less emission points detected (i.e. both known sources and newly-detected points) after several surveys?

The analysis of the data did not, however, reveal any specific correlations on these two questions. The lack of correlation could be due to the relatively poor repair effectiveness (see section above) and/or the fact that some leaks were identified but not repaired.

Interpretation of results

This analysis shows that a significant share of new emission points is still detected after two or three surveys, and new sources can still be found even after ten or more successive surveys for a given unit. Assuming that previous surveys had been reasonably thorough, this means that new emission points continuously appear and confirms the need for regular LDAR surveys for detecting and managing leaks.

The analysis also confirms the conclusions in section 3.2 about repair efficiency: even though emitting components are repaired, some repairs are only partly effective, and some fully repaired components will emit again after a few surveys. Therefore, the share of active leaks from previously repaired components increases over time. This raises questions about the sustainability of the initial repair effort: a “quick fix” such as tightening the bolts may be successful in the short term, but a leak at that site may reappear in the next survey or even later. On the other hand, a thorough root cause analysis and component replacement might produce longer lasting results. Unfortunately, the dataset was not sufficient confirm or reject this hypothesis. Nevertheless, the analysis demonstrates the need for regular and systematic LDAR campaigns.

Annex: Limitations of the analysis

This section provides an overview of the relevant limitations of the analysis and their impact on the interpretation of the results. Overall, the project team has followed the following principles: (i) excluding any analysis where there was insufficient data to produce statistically significant results (ii) using conservative assumptions where necessary.

Representativeness of the sample: As explained in section 2.2, the data sample is quite large, and includes data from four countries and nine different types of facilities in Europe. However, the sample is not representative of the entire European oil and gas industry. In particular, the sample does not include data from some important categories of installations (e.g. offshore platforms) and from many European countries (e.g. Eastern Europe). In addition, by design, the sample only includes facilities, which already perform regular LDAR.

Differences in measurement approaches: The database comprises three datasets provided by companies using different teams and surveying different type of sites with different measurement equipment. Differences include different component terminology[21], different information recorded during the survey, whether measurements are made after the repairs. That said, the project team worked to ensure that the data presented are as comparable as possible.

Relative size of the different datasets: One of the datasets used for this study has a significantly larger sample than the two other datasets. As a result, this specific dataset is over-represented in most of the results of the study, which could introduce bias. The datasets were also compared to one another during the analysis, however, to review their content and ensure they were of similar quality.

"Signal" versus "noise": Methane is typically present in the atmosphere at midstream facilities, so these measurements are attempting to detect a "signal" of leaks above this background "noise". A lower background noise threshold was applied to the measurements[22]. The application of a background noise threshold prevents mistakenly identifying background concentrations as an emission point. However, using this threshold means that some emission points with very low emission rates (e.g. equivalent to concentrations below 10 ppm) will be missed.

Measurement threshold: In some cases, the equipment used for the measurement performed could not measure emission concentrations above 100 000 ppm, even if the actual concentration at the source was higher. As a result, all emission concentrations above this point are recorded as 101 000 ppm[23]. Given the flat tail distribution[24] of the emission points, this required some additional considerations in the analysis:

- It was not possible to analyse the *total* emissions across one facility, one facility type or a region.
- The cumulative distributions (section 3.1) are only presented for the measurable intervals; the distributions of emissions beyond the emission threshold are unknown.

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[21] It should be noted that there may be variations in the categorisation of components, across data providers and potentially across teams for a given provider. Therefore, only a limited number of component types and sub-types has been used in the analysis, in order to avoid too precise categories and the associated risk for miscategorising components.

[22] All measurements below 10 ppm are considered to be part of background noise for dataset 1 and 2

[23] This leads to a peak in concentration values, at 101 000 ppm, and two peaks on the calculated flowrates (in kg/h).

[24] I.e. a small share of the emission points represents a large share of the emissions

- The concentration peak creates some uncertainties in repair effectiveness (section 3.2), although it is expected to lead to an underestimate of the repair effectiveness.

Concentration versus flow rate: The vast majority of the measurements are made in concentration (ppm) and not actual emission flowrate (e.g. kg/h). The emission flowrate is estimated using the methodology provided in US EPA Method 21. The results on absolute flowrates therefore present some uncertainties due to the methodology applied. The figures are, however, comparable within the boundary of this study.

Concentration measurement uncertainties: The uncertainty range for the concentration values is estimated at ±25%, which has been taken into account when categorising and interpreting the results, in particular in section 3.2 about repair effectiveness.

Multiple measurement points: There are a few data points where several concentration values are provided for a unique measurement timestamp (i.e. repeated measurements on the same point). According to the measurement companies, measurements may have been performed several times when the measurement operator experienced important variations in emissions. This reveals potentially large uncertainties for the measurement on those points. In order to avoid over-representing those measurements in the results, the mathematical average of the measurements was used in the calculations.

Maintenance performed outside the LDAR program: One of the datasets contains measurements before and after repairs, and repairs are marked as such in the database. There may have been times when components are repaired outside of an LDAR program (e.g. during routine maintenance), and thus the repair effectiveness therefore cannot be assessed in this study. This means that the data used as a basis for the repair analysis in section 3.2 does not necessarily represent all repairs done on the facilities, but only those that are part of the LDAR programs. This is not considered to be a major problem, however, because the analysis does not address changes in concentrations outside of repair events.

Small sample size for specific subcategories: For some component types or facility types the data available was limited to a few hundred data points (e.g. pumps, lines). The samples are even further reduced when analysing specific cases (e.g. repairs), and samples become too limited to be representative. Therefore, components and facility types with too few data points have been excluded from some of the results presented in this report.