Cap-Op Energy British Columbia Oil and Gas Methane Emissions Field Study

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Executive Summary

The British Columbia Methane Emissions Field Study was undertaken in order to inform the modeling parameters used in time-series methane emission modeling. An advisory team comprising the British Columbia Ministry of Environment and Climate Change Strategy – Climate Action Secretariat (BC CAS), the British Columbia Oil and Gas Commission (BC OGC), Environment and Climate Change Canada (ECCC), and the Ministry of Energy, Mines and Petroleum Resources (MEMPR) was established in order to engage directly with the project team comprising Cap-Op Energy, Greenpath Energy, DXD Consulting and Dr. Arvind Ravikumar. BC OGC inspectors also contributed to the data collection.

Scope of Field Survey

Total Sites Visited	266
Production/Facility Types Represented	12
Total Quantifiable Methane Emission Sources (#, volume)[1]	1,000 sources, 366 m^3/hour

The study gathered a broad spectrum of methane emissions data at 266 locations (wells and batteries) across British Columbia, encompassing fugitive emissions, equipment venting emissions, pneumatic inventory and emissions estimates, as well as episodic and other sources of methane emissions. The data were compiled and analyzed to characterize British Columbia's oil and gas operations from a methane emissions perspective. In order to align with current and projected production centres, coverage of tight wells and batteries in the Montney was prioritized. The collection of sites sampled was determined to be

[1] Some sources were quantified using visual estimation (e.g. inaccessible fugitives), or factors (e.g. pneumatic control instruments). Methane content of sources was not determined.

representative of the available population, based on recent production rates – both within each production/facility type category as well as overall.

Analysis of field survey results identified key similarities as well as key differences between British Columbia and other jurisdictions.

The findings from the field survey aligned with other similar studies where a small number of sources were found to be responsible for a large portion of the methane releases.[3] Specifically, 51% of emissions resulted from the top 8.7% of equipment fugitives. The vast majority of sites (186 of 266 sites visited) had no vents or leaks detected (excluding pneumatics).

Methane emissions from natural gas-driven pneumatic devices (66% of total) represent significant sources methane emissions at BC wells and batteries. Non-emitting control instruments and chemical injection pumps (e.g. solar electric or air-driven) were observed to be very common in BC. Of all pneumatic or pneumatic-equivalent devices observed in the study, 65% were non-emitting; a recent pneumatic inventory in Alberta found <5% non-emitting.

Summary of Field Survey Findings	
Total Leak-free and Vent-free Sites[2] Surveyed	186 (70%)
Total Natural Gas-Driven Pneumatic Devices	725 (34%) (242 m^3/hour est.)
Venting Emissions	101 (63 m^3/hour)
Equipment Fugitive Emissions	284 (61 m^3/hour)

Tanks contributed a significant proportion of total emissions (12% including vents and leaks). Tanks were responsible for 65% of total non-pneumatic venting emissions (2 other equipment types, Reciprocating Compressor and Surface Casing Vents, combined with tanks represent 94% of overall non-pneumatic venting emissions). This includes hydrocarbon venting from Produced Water Tanks (25% of total tank venting).[4] Thief Hatches, a tank-specific component, also have the highest average, median, and site level leak rates which suggests that Thief Hatches are currently responsible for a significant portion of methane leak emissions (3% of overall leak sources, 17% of overall leak emissions).

While compressor stations were not a specific focus of the study, 69 compressors units were observed at batteries. These were catalogued and found to exhibit average emission rates consistent with population-wide figures from the US Greenhouse Gas Inventory (see Sections 2.1.3 and 1.2.5.2).

In addition to the field survey, a Corporate Data Request was distributed in order to solicit additional insight into data that are not possible to observe with a one-time site visit, including fugitive survey and repair history, and episodic or other sources of methane emissions. These data were used to develop time series modeling parameters such as the Leak Occurrence Rate. These parameters are derived by combining historical data with direct observations from the field survey in order to better characterize the temporal aspect of methane emissions.

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[2] Excluding pneumatic venting

[3] Brandt, A.R., G.A. Heath, D. Cooley (2016). Methane leaks from natural gas systems follow extreme distributions. Environmental Science & Technology. DOI: 10.1021/acs.est.6b04303

[4] Compositional data was not obtained for any emission sources; venting from Produced Water Tanks may include significantly less methane than other vent sources and are distinguished within the scope of this report.

In January 2019, following the presentation of the draft study results, a workshop led by DXD Consulting Inc. (DXD) was conducted to consider the experience of oil and gas industry experts on factors that could influence certain parameters of interest. Input was solicited from these representatives for the purposes of adding context to numerical results of forecasting and backcasting time-series methane modeling. Three temporal states – distant past, recent past, and future – were interrogated across six specific focus areas in terms of the direction and relative magnitude of change from the “present” observed in the field study. The workshop sought to bring context and industry experience to the forefront to guide changes to modeling parameters over different time periods. The principal objective of the industry workshop was to solicit expert feedback on operator practices and historical and future design considerations that may impact methane emissions from upstream facilities. This uniquely collaborative session between industry and regulators was intended as an opportunity to extract technical feedback from industry experts on how their operations have evolved over time. Insights into key drivers that might influence parameters of interest for time-series modelling was determined through focused small-group discussions. It is expected that others can benefit from these insights when completing emissions modelling assessments over various time periods.

The data generated by the BC Methane Emissions Field Study encompass varied geographic, facility, production, and temporal coverage and were analyzed using transparent methodologies. The insights and results are presented herein with additional commentary and context, along with the anonymized raw data.

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Glossary

- **Advisory Team:** Project representatives from BC CAS, BC OGC, MEMPR, ECCC
- **BC CAS:** British Columbia Ministry of Environment and Climate Change Strategy – Climate Action Secretariat
- **BC OGC:** British Columbia Oil and Gas Commission
- **CAPP:** Canadian Association of Petroleum Producers
- **Components:** Relevant to the classification and attribution of methane emission sources; in order to enable application of component-to-equipment ratios from previous research, definitions and component types match those employed by Clearstone et al (2018):[5]
    - Compressor Seals:
        - Reciprocating: Packing systems (seals) are used on reciprocating compressors to control leakage around the piston rod on each cylinder. A reciprocating compressor is deemed to have one seal associated with each compressor cylinder regardless of whether it is a single or tandem seal.
        - Centrifugal: Centrifugal compressors generally require shaft-end seals between the compressor and bearing housings. Either face-contact oil-lubricated mechanical seals or oil-ring shaft seals, or dry-gas shaft seals are used. A centrifugal compressor has two seals, one on each side of the housing where the shaft penetration occurs.
    - Connector: Each threaded, flanged, mating surface (cover) or mechanical connection is counted as a single connector. Welded or backwelded connections are not counted.
    - Control Valve: A valve equipped with an actuator for automated operation to control flow, pressure, liquid level or other process parameter.
    - Meter: A flow measurement device is counted as a single component. The connections on the upstream and downstream sides of the device are counted as separate components.
    - Open-Ended Line: Each valve in hydrocarbon service that has process fluid on one side and is open to the atmosphere on the other (either directly or through a line) is counted as an open-ended line. If the open side of the valve is fitted with a properly installed cap, plug, blind flange or second closed block valve, or is connected to a control device, then it is no longer considered to be open-ended.
    - Pressure Relief Valves and Pressure Safety Valves (PRV/PSV): Each pressure-relief valve that discharges directly to the atmosphere or through a vent system is counted as a single component.
    - Pump Seal: Each pump in hydrocarbon service may leak from around the pump shaft and is typically controlled by a packing material, with or without a sealant. It may be used on both the rotating and reciprocating pumps (and includes pneumatic injection pumps). Specially designed packing materials are available for different types of service. The selected material is placed in a stuffing box and the packing gland is tightened to compress the packing around the shaft.

[5] Clearstone Update of Equipment Component and Fugitive Emission Factors for Alberta Upstream Oil and Gas Study (https://www.aer.ca/documents/UpdateofEquipmentComponentandFugitiveEmissionFactorsforAlber-1.pdf). See Section 8.3 for additional detail on components.

- Regulator: Most regulators are equipped with a vent where gas is released in the event the diaphragm inside becomes damaged.
- Thief Hatch: Storage tanks connected to a VRU or flare do not emit gas unless the internal tank pressure exceeds the PRV or thief hatch set pressures (and intermittent venting occurs). When the tank pressure drops, the PRVs return to a closed position and typically don't leak. However, once opened, thief hatches remain partially open until an operator closes the hatch. Gas loss from partially open thief hatches is unintentional and therefore classified as a leak. Gas losses from storage tanks open to the atmosphere (i.e., not connected to a VRU or flare) are classified as a process vent (not a leak).
- Valve: A valve that is **not** a control valve.

- **Control Instrument:** Any device used for process control (measurement and control of process variables) such as switches and controllers; predominantly includes the classifications:
  - Pressure controller: a device which continuously monitors pressure and outputs a corrective signal to the final control element based on the deviation from set point pressure
  - Pressure switch: a sub-type of pressure controller, capable of on/off output at preset pressure
  - Level controller: a device which continuously monitors fluid level and outputs a corrective signal to the final control element based on the deviation from set point level
  - Level switch: a sub-type of level controller, capable of on/off output at preset level
  - Positioner: a device which modulates the supply pressure to the control valve actuator to maintain a position based on the control signal
  - Temperature controller: a device which continuously monitors temperature and outputs a corrective signal to the final control element based on the deviation from desired temperature
  - Transducer: a combination of a sensor and a transmitter; converts physical signal (e.g. pressure) into electric signal (e.g. millivolts)
- **Crude Oil Single-Well Battery:** A production facility for a single oil well.[6]
- **Crude Oil Multiwell Group Battery:** A production facility consisting of two or more flow-lined oil wells having individual separation and measuring equipment but with all equipment sharing a common surface location.[6]
- **Crude Oil Multiwell Proration Battery:** A production facility consisting of two or more flow-lined oil wells having common separation and measuring equipment. Total production is prorated to each well based on individual well tests. Individual well production tests can occur at the central site or at remote satellite facilities. [6]
- **ECCC:** Environment and Climate Change Canada
- **Excessive Pneumatic Venting:** includes any gas release from pneumatic equipment that does not reflect normal operation, such as a release from the seal on the device casing. These types of releases were isolated during analysis as a separate category since they are treated differently under different regulations.
- **Facility:** Any site/location may be considered a facility within this report, including wellsites, but for analytical purposes facilities are batteries.
- **Fuel Gas:** See natural gas as the same definition was used for the purpose of this study.

[6] Facility definitions excerpted from the Petrinex British Columbia Inclusion Project – Industry Readiness Handbook available at https://www.petrinex.ca/Initiatives/Documents/PBCIP_Industry_Readiness_Handbook.pdf

- **Fugitive Emissions (Equipment Fugitives):** The field collection team employed the following definition for distinguishing equipment fugitives (leaks) from vents: "A leak is the unintentional loss of process fluid past a seal, mechanical connection or minor flaw at a rate that is in excess of normal tolerances allowed by the manufacturer or applicable health, safety and environmental standards. An equipment component in hydrocarbon service is commonly deemed to be leaking when the emitted gas can be visualized with an infrared (IR) leak imaging camera or detected by other techniques with similar or better detection capabilities."[5] OGI was the only detection technology used in this study. Equipment fugitives were attributed to component types listed above including connectors, valves, control valves, PRV/PSV, meters, regulators, pump seals, thief hatches. During analysis some equipment fugitives were further sub-classified (e.g. Excessive Pneumatic Venting).
- **Gas Multiwell Effluent Measurement Battery:** A production reporting entity consisting of two or more gas wells where estimated production from gas wells in the battery is determined by the continuous measurement of multiphase fluid from each well (effluent measurement). Commingled production is separated and measured then prorated back to wells based on the estimated production. [6]
- **Gas Multiwell Group Battery:** A production reporting entity consisting of two or more gas wells where production components are separated and measured at each wellhead. Production from all wells in the group is combined after measurement and then delivered to a gas gathering system or other disposition. [6]
- **Gas Single Well Battery:** A production facility for a single gas well where production is measured at the wellhead. Production is delivered directly and is not combined with production from other wells prior to delivery to a gas gathering system or other disposition. [6]
- **Heavy Liquid:** Process fluid that is a hydrocarbon liquid at the operating conditions and has a vapour pressure of less than 0.3 kPa at 15°C.[5] No heavy liquid service was encountered in the study.
- **Large Facility:** Refers to Compressor Stations and Gas Plants. [6]
- **LDAR:** Leak Detection and Repair
- **Leak Occurrence Rate:** An important parameter used in time-series modeling to establish the fugitive emission factor magnitude, which considers the number of detected leaking components by type, the number of leaks detected but not repaired from the previous survey, the number of months since the last survey, and the number of components and facilities of each type. See Section 3.2 for calculation details.
- **Light Liquid:** Process fluid that is a hydrocarbon liquid at the operating conditions and has a vapour pressure of 0.3 kPa or greater at 15°C. Light/medium crude oil, condensate and natural gas liquids (NGLs) fall into this category. [5]
- **MEMPR:** British Columbia Ministry of Energy, Mines, and Petroleum Resources
- **Natural Gas:** The Petroleum and Natural Gas Act (PNG) defines as all fluid hydrocarbons, before and after processing, that are not defined as petroleum, and includes hydrogen sulfide, carbon dioxide, and helium produced from a well.[7] In the scope of this study, typically refers to fuel gas or instrument gas that is (or was assumed to be) predominantly methane.
- **Pneumatics (Pneumatic Devices):** Refers to control instruments and pumps, including non-pneumatic (e.g. electric drive) equipment according to the classifications above.

[7] Oil and gas Glossary and Definitions Version 1.11: February 2019, BC OGC (Available at https://www.bcogc.ca/node/11467/download)

- **Pneumatic Pump:** Any device used for chemical injection at wellsites, compressor stations, batteries or gas plants; no sub-classification was employed in this report although the observed pump types include diaphragm positive displacement pumps and electric drive positive displacement pumps.
- **Process Gas:** Process fluid that is a hydrocarbon gas at the subject operating condition.[5] For the purpose of the analysis process gas was defined as natural gas.
- **Project Team:** Cap-Op Energy, including its subcontractors Greenpath Energy, DXD Consulting, and Dr. Arvind Ravikumar
- **OGI:** optical gas imaging using infrared (IR) leak imaging camera
- **Reporting Facility:** Refers to a facility with a Reporting Facility ID from the BC OGC.
- **Site Classification (or Facility Types):** Sites, or facilities, were classified according to existing BC OGC classification schemes including gas wells, oil wells, single well batteries, and others as further delineated in Facility Types
- **Venting Emissions:** An intentional release of hydrocarbon gas directly to the atmosphere. Venting does not include partial products of combustion that might occur during flaring or other combustion activities. Vents were attributed to component types including open-ended line, compressor seal, and thief hatch.

Background and Context

British Columbia (BC) launched its Climate Action Plan in 2008 as one of the first jurisdictions in North America to formally address anthropogenic climate change with GHG emission reduction targets and a suite of programs to achieve them.[8] In 2016, BC's Climate Action Plan included programs launched to specifically target methane emissions from upstream natural gas production, including a reduction target of 45% by 2025 and a commitment to investing in infrastructure to power natural gas projects with clean electricity.[9] In December 2018, BC confirmed their methane emissions reduction target in the CleanBC Plan.[10] At a high level, BC's upstream methane emission reduction target is aligned with sub-national policies in neighbouring Alberta,[11] states including Colorado, California,[12] Ohio, Pennsylvania, and Wyoming as well as federally in Canada, the US, and Mexico.[13]

Methodologies have been established to model methane emission sources, including certain defined parameters (e.g. facility types, and equipment types). Inputs for these modelling methodologies should represent local operating configurations and production types, however they are often generic historical factors, developed in different jurisdictions. This study aimed to develop modelling parameters specific to BC operations.

The Province of British Columbia along with Environment and Climate Change Canada proposed and supported the field study and subsequent analysis to translate observations from the field to the defined time-series modeling parameters.

Following a description of the scope and approach, reporting of results is structured as follows:

CHAPTER	TITLE	SOURCE OF INFORMATION
CHAPTER 1	Field Observations	Field Survey Data
CHAPTER 2	Comparison to Contemporary Studies	Field Survey Data, Other Studies
CHAPTER 3	Fugitive and Episodic Emission Management Practices	Field Survey Data, Corporate Data Request
CHAPTER 4	Long Term Methane Emission Drivers	Expert Workshop

[8] British Columbia Climate Action Plan, 2008 (Available at https://www2.gov.bc.ca/assets/gov/environment/climate-change/action/cap/climateaction_plan_web.pdf)
[9] British Columbia Climate Leadership Plan, August 2018 (Available at https://www2.gov.bc.ca/assets/gov/environment/climate-change/action/clp/clp_booklet_web.pdf)
[10] CleanBC, March 2019 (Available at https://blog.gov.bc.ca/app/uploads/sites/436/2019/02/CleanBC_Full_Report_Updated_Mar2019.pdf)
[11] Alberta Climate Leadership Plan, Implementation Plan 2018-2019 (Available at https://open.alberta.ca/dataset/da6433da-69b7-4d15-9123-01f76004f574/resource/b42b1f43-7b9d-483d-aa2a-6f9b4290d81e/download/clp_implementation_plan-jun07.pdf)
[12] Proposed Short-Lived Climate Pollutant Reduction Strategy, California Air Resources Board, April 2016 (Available at https://www.arb.ca.gov/cc/shortlived/meetings/04112016/proposedstrategy.pdf)
[13] Joint Statement on North American Climate Leadership, Environment and Climate Change Canada, September 2018 (Available at https://www.canada.ca/en/environment-climate-change/news/2018/09/joint-statement-on-north-american-climate-leadership1.html)

Scope

Facility Types

Upstream oil and gas production is generally comprised of wells, batteries, gathering and transportation systems, and upstream processing facilities. Since facility sizes tend to increase further down the supply chain, the upstream sector is characterized by large numbers of small facilities (9,191 active wells and 327 active batteries)[14] which can be highly diverse in their operating practices and the type of equipment found on site. Diversity at upstream sites is also a result of diverse operators, design and operating practices, facility ages, and product characteristics. For example, the presence of liquids can alter the equipment and operating practices of upstream sites.

Characterizing the upstream sector accurately is challenging because large sample sizes are required for statistical significance but field data collection costs scale with both sample size and facility size/complexity. In order to ensure sufficient sample sizes, Compressor Stations and Gas Plants (Large Facilities) were excluded in order to focus on wells and batteries, however some compressors were observed at smaller facilities. Specifically, the study considered the following facility types (consistent with Petrinex definitions):

- Wells (W)
- Single-Well Batteries (SWB)
- Multiwell Group Batteries (MGB)
- Multiwell Proration Batteries (MPB)
- Multiwell Effluent Measurement Batteries (MEM)

Production Types

British Columbia produces oil and gas from the northwest end of the Western Canadian Sedimentary Basin. Oil production, comprising light crude oil and natural gas condensates, is secondary to gas production in most areas, and both are produced from a mix of older legacy wells ("Conventional") as well as newer Shale and Tight wells. Based on the BC OGC records, very few facilities are classified as producing "Shale Gas" as distinct from "Tight Gas" and so these were combined to form a single production category (Tight Gas (T)). Tight Gas was distinguished from Conventional Gas (C), and a single Oil (O) category was considered to include sites classified as either Tight Oil or Conventional Oil.

Specifically, the study considered the following categories of facility and production types:

- Well Site
- Gas Single Well Battery
- Gas Multiwell Group Battery
- Gas Multiwell Effluent Measurement Battery
- Crude Oil Single-Well Battery
- Crude Oil Multiwell Proration Battery
- Crude Oil Multiwell Group Battery

[14] "Active" was defined based on May 2018 production reporting.

Source Types

Upstream methane sources result from intentional or unintentional releases to atmosphere, or from combustion. Combustion emission sources such as flares were considered outside the scope of the study. Intentional (venting) sources of emissions were attributed to pneumatic devices and other specific pieces of equipment wherever possible (see Sections 1.2.5.2 and 1.2.4.2, respectively). Unintentional (equipment fugitive) emissions were attributed to specific components (see Section 1.2.3.2 for examples).

Time Period

Field data collection occurred during the month of September 2018, with a single inspection at each location (snapshot survey). Between October 2018 and February 2019, historical site-level data was acquired concerning emissions and activities that occurred between 2016 and February 2019. In January 2019, expert opinion was solicited regarding past, present, and future time trends and their impacts on emissions (see Chapter 4).

Approach

A field protocol and sampling plan were developed to facilitate the development of numerical results on a per-facility basis (emitting and non-emitting equipment counts), per-component basis (fugitives, where possible) and including the quantification of emitting equipment.

Greenpath lead the development of the field protocol for on-site data collection methodologies, in consultation with Cap-Op and the advisory team, with particular focus on:

1) Methodology employed to estimate equipment and component counts/inventories where applicable
2) Methodology employed to quantify emissions from fugitives and emitting equipment

The protocol that was selected balanced time and resource constraints with the granularity and accuracy of data collected. The protocol required a two-person team, including contractors and BC OGC Inspectors, who were tasked with the following:

- Inventory of pneumatic devices, process equipment and other potential vent sources and fate of vent sources (compressor packing, tank controls)
- Inspection via OGI Camera and quantification of leaks and vents via High Flow Sampler
- Collection of supplemental information to aid in quantification

Concurrently, Cap-Op lead the development of the sampling plan, in consultation with Greenpath and the advisory team, with particular focus on:

3) Types of facilities to be considered for study (e.g. Wells, Batteries)
4) Production types to be considered for study (e.g. Tight Gas, Conventional Oil)
5) Representation of the population using randomly selected sample sets of sites

Site Selection

Participation in the study was voluntary, but was structured as “opt-out” instead of opt-in. This allowed the project team to select sites randomly in order to form a robust sample. The sites visited were selected through the process detailed below before any contact with producers. All but one producer selected allowed the field survey to take place which prevented or minimized a "coalition of the willing" effect that may introduce bias to studies relying only on voluntary participation.

Site selection was done using a quasi-random process, seeking to balance the statistical benefits of random selection with logistical challenges presented by visiting a large number of geographically dispersed locations, and the limited amount of time available for both site selection and field data collection. Filtered data were provided by BC OGC which contained records of the most recent available month of production reporting, the facility type categories and production type categories as well as other identifying information.

The approach involved filtering the population of wells and batteries in BC before applying random selection procedures. The populations in each facility-production type category were filtered according to the principles outlined in Table 1:

Table 1: Well and battery population filters

Filter Applied	Rationale
Active (or recently active) operations only	Inactive (shut-in) locations are out of scope.
Exclude extremely remote locations (e.g. Horn River)	Focused on Montney due to provincial production and forecasts.
Battery not co-located with another battery in the same LSD	Co-located facilities, or those with multiple permits at the same location, require manual review of metering schematics in order to correctly attribute emissions and equipment. This level of manual review was out of scope of the study.
Wells geographically proximate to batteries (3 km)	Improve efficiency of transportation logistics.

While it is acknowledged that each of the filters applied to the population introduces bias to the results, the filtering also increased the sample size by allowing the field team to visit more locations. This trade-off was considered in the context of the advisory team's objective of focusing on most sensitive parameters for time-series modeling. The focus was to characterize smaller sites in BC which were believed to differ from Alberta sites covered by most other research. In this context, observing a significant cross-section of well and battery facility/production categories was prioritized.

A randomized selection process was then applied to the filtered list of facilities and wells resulting in a set of sites that could be tested for whether it was representative of the overall population. The process is summarized in Figure 1:

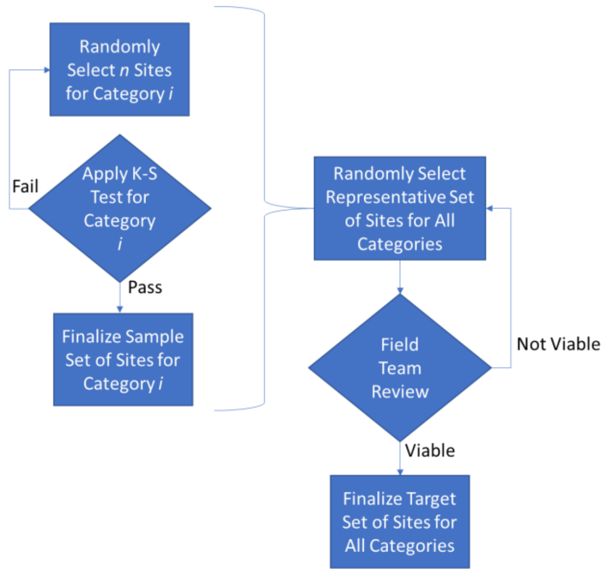

Figure 1: Site selection iterative review process

The number of sites visited in a given category was driven by the facility type (size considerations), the relative focus (Tight Gas prioritized over Conventional) and the available population size. The following table summarized sample sizes as % coverage of the available population:

Table 2: Coverage ratios - sample size as percent of available population[15]

	Oil	Conventional	Tight	Average
Wells	38%	47%	52%	46%
SWB	19%	24%	100%	48%
MGB	100%	21%	45%	55%
MPB	19%			19%
MEM		16%	22%	19%
Avg	46%	20%	56%	35%

Representativeness

Representativeness was quantitatively assessed using the Kolmogorov-Smirnoff goodness-of-fit test (K-S test). The basis that was used for the K-S testing was the distribution of normalized energy production rates, which was characterized for both the sample sites and the available population of sites (two-sample K-S test). The test is designed to assess whether the two samples represent the same underlying population and was run using a significance level of alpha = 0.05.[16] Regardless of the alpha selected, small sample sizes due to time and resource constraints may have an effect on the utility of the K-S test since the threshold for pass/fail increases with fewer samples to compare.

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[15] Available population refers to the set of wells and batteries that passed the filtering criteria described in Table 1. Note that coverage of wells only refers to wells within 3km of selected batteries as per Table 1.

[16] Alpha level is the probability of rejecting the null hypothesis when the null hypothesis is true.

The K-S test was applied at the level of each individual combination of facility type and production type, as well as on the entire selection. The entire selection was then assessed against the "available population" of wells and batteries after application of the filtering criteria above. All assessments passed the K-S test.

The available population was also assessed against the overall population of all active wells and batteries in BC. Figure 2 illustrates the effect of the filtering process:

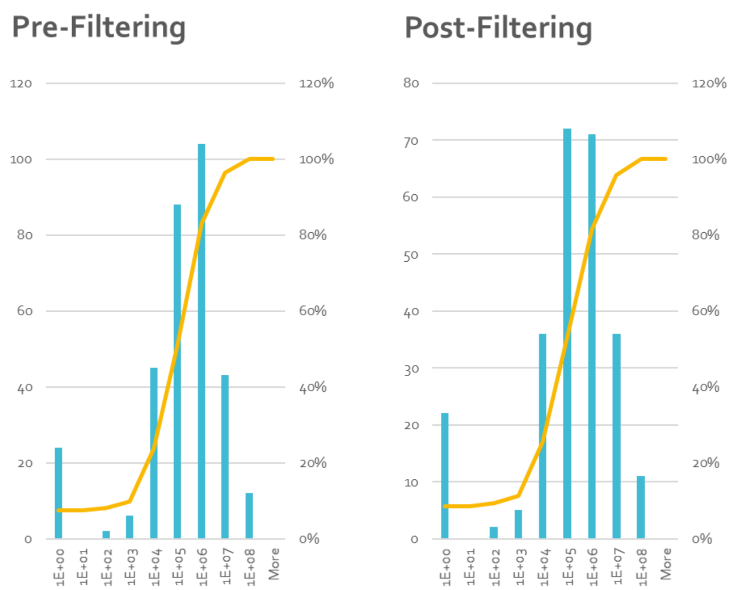

Figure 2: Distribution of normalized energy production rates before and after application of site selection filters

Energy production rates are accessible and present as a reasonable characteristic with which to assess representativeness, although emissions are not necessarily robustly correlated with energy production rates, and so additional considerations for diversity were included qualitatively on the entire selection:

- Age, represented by date of first production
- Operator mix

The date of first production was determined using BC OGC records. For facilities, the available population included first production dates covering 30 years, from 1989-2018 and the target sample included facilities representing 22 (73%) of these first production years spanning 1989-2017. For wells, 37 distinct years were represented from 1958 to 2017. Figure 3 shows the distribution of first production years among the visited wells:

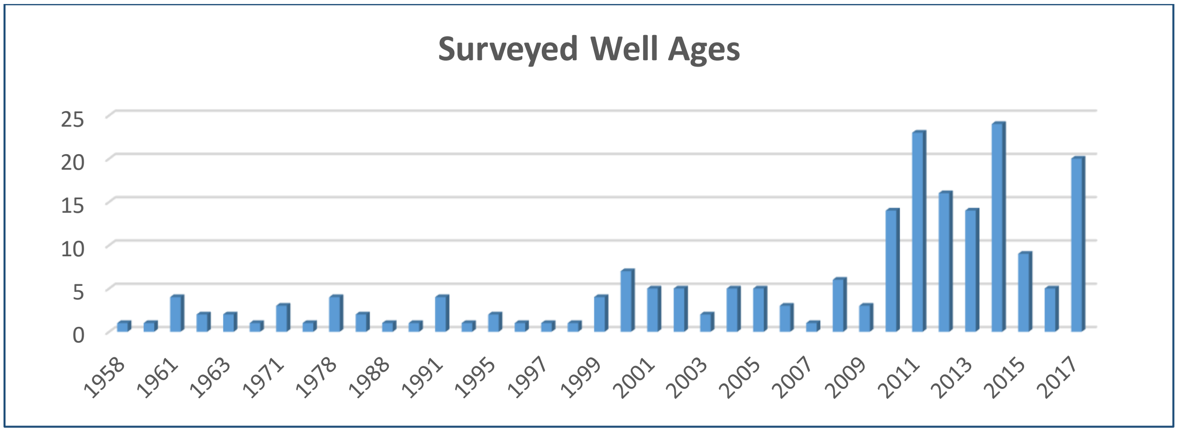

Figure 3: Year of first production - visited wells

A total of 47 operator names were represented in the available population of facilities, of which 21 operated facilities that were visited (45%). The participation rate of each operator varied between 1 and 47 sites with approximately half of the operators having 10 or more sites each.

Site Classification (Study Code):
[Facility/Site Type] + [Production Category]
e.g. MGBT: Multiwell Group Battery – Tight Gas
SWBO: Single-Well Battery – Oil

Figure 4: Site classification used for selection and results analysis includes facility type and production type

BC OGC records include redundant information within the facility type classifications that also indicates production type (e.g. Gas Single Well Battery and Crude Oil Single Well Battery are different Facility Types). These were grouped logically where possible (e.g. all Single Well Batteries) and then re-stratified using the more detailed production characterization that is available within each facility's record (e.g. Tight Gas, Non-Associated (Conventional) Gas, etc.). A classification scheme for site selection (and analysis/reporting) was developed which combines the facility type and production type as explained in Figure 4.

Target and Actual Sample Sets

The site selection process resulted in the selection of 254 locations within the study areas outlined in Figure 5 (266 were ultimately surveyed). The field team, comprising Greenpath Energy staff and OGC inspectors, was provided with the list of selected sites and site information and instructed to visit as many as possible.

With exceptions noted below in Table 3, the actual sites visited matched the target sites and priority focus points for the study. The representativeness tests were re-run to compare the actual sample set of sites to the available population and representativeness was maintained both quantitatively and qualitatively in all facility type and production type categories.

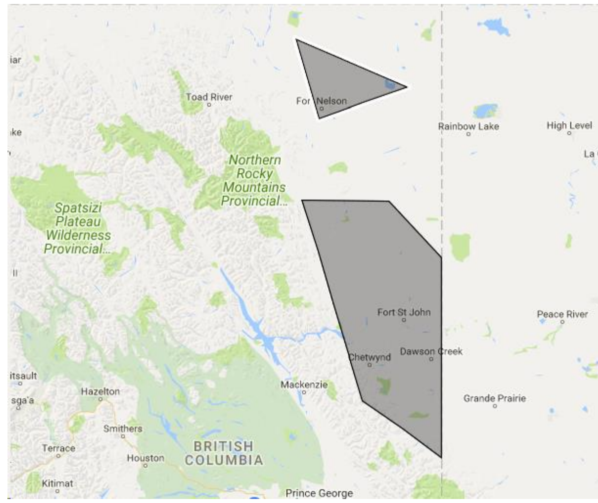

Figure 5: Target study areas

Table 3: Actual locations sampled as percent of planned by facility and production type

	Oil	Conventional	Tight	Total
W	124%	128%	145%	137%
SWB	100%	80%	60%	82%
MGB	100%	29%	150%	100%
MPB	100%			100%
MEM		88%	120%	106%
Facility Total	100%	65%	120%	97%

All sub-categories in Table 3 with less than 100% represent categories with very small sample sizes to begin with, for example for SWBT sub-category 3 of 5 planned facilities were visited.

Field Data Collection

Equipment counts and classifications require working knowledge of oil and gas operations. Qualified personnel are also required to properly operate specialized emissions detection and measurement equipment and to accurately identify equipment and component types. The field team was responsible for source identification and quantification according to the following study design elements:

- Equipment Fugitive emissions
  - OGI Camera, trained technician
  - Hi-Flow Sampler
  - Some visual estimation required
    - For inaccessible methane releases detected[17]

[17] For example, sources at height. Visual estimation employed at discretion of field team.

- Venting emissions
  - OGI Camera, trained technician
  - Hi-Flow Sampler
  - Some visual estimation required
- Major equipment inventory
  - Direct observation (count)
  - Emitting or non-emitting determination
  - Emission control observation
- Pneumatic equipment inventory[18]
  - Direct observation (inventory)
  - Emitting or non-emitting determination
- Component counts
  - Derived from Clearstone 2018 where possible
  - Otherwise direct observation (count)

Data Schema

Figure 6 outlines the data elements that were captured by the field team at each site:

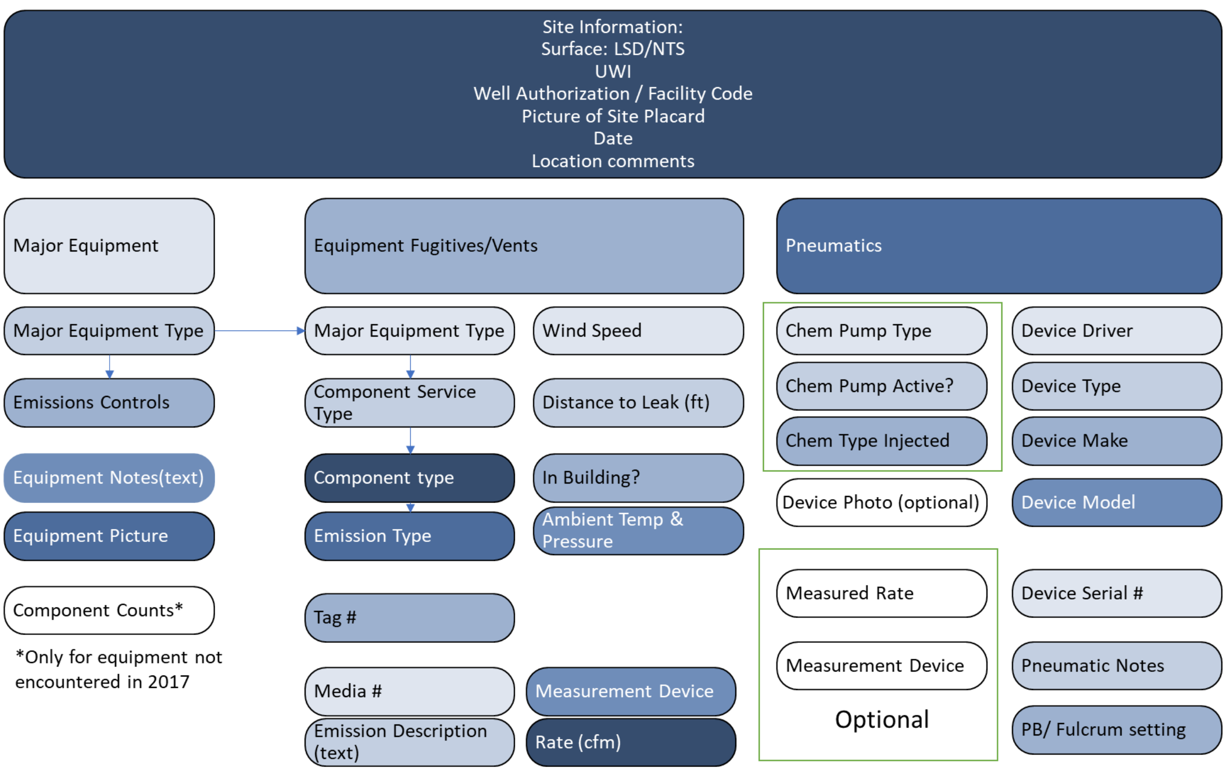

Figure 6: Data elements collected by field team

[18] Includes non-pneumatic control instruments and chemical injection pumps (e.g. electric devices)

Where possible, existing component-to-equipment ratios were leveraged for this study (see below). Some equipment was observed in BC that was not observed in Alberta during Clearstone 2018, and these equipment types were subject to component counts on an exception basis, as further delineated below and in Table 6 of Section 1.1. See Section 1.1 Analytical Approach for additional details.

Use of Existing Factors

The scope was determined to ensure representative results from the facility and production types visited. Existing factors were employed for two data points (where possible): component counts and pneumatic device vent rates.

It was determined that component-per-equipment ratios from existing literature could be combined with observed equipment counts in order to develop results that represent BC operations. This approach avoided the need to directly acquire component count information which is highly time consuming. The number of components per piece of major equipment is expected to be the same in Alberta and BC. As such, observed equipment counts were combined with published average components per major equipment / process block to determine the total number of components per facility type. These component counts are used in combination with the detected leaks to characterize fugitive emissions from the facilities visited during the survey. Clearstone 2018 was used as it developed representative component counts per major equipment type for AB.

Release rates from pneumatic control instruments and pumps were not measured during this study, but estimated based on the observed makes and models in order to facilitate comparisons between source release type (e.g. venting emissions and fugitive emissions) as well as comparisons to other studies. The pneumatic controller release rates from recent studies were used; including early work by Cap-Op and Greenpath (Prasino Study, 2014)[19] as well as more recent measurements campaigns by Spartan Controls and Greenpath Energy.[20] Other meta-analysis of existing fieldwork has also been done.[21]

Fugitive History and Repair Data Collection

A Corporate Data Request (CDR) was developed in order to obtain data needed for time-series modeling parameter development that could not be obtained from the site visit observations.

The CDR solicited historical information regarding the most recent fugitive survey and any associated leak repair information. Company logs were requested for the same set of sites as was visited by the field team.

Episodic and Other Sources of Methane Emissions Data Collection

The Corporate Data Request solicited historical information regarding episodic and other sources of methane emissions based in part on Cap-Op's 2017 report for Environment and Climate Change Canada (ECCC)[22]. Company logs were requested for the same set of sites as was visited by the field team.

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[19] Final Report For Determining Bleed Rates for Pneumatic Devices in British Columbia, The Prasino Group (now Cap-Op Energy), December 2013 (Available at http://www.bcogris.ca/sites/default/files/ei-2014-01-final-report20140131.pdf)

[20] Pneumatic Vent Gas Measurement, Brian Van Vliet and Spartan Controls, April 2018 (Available at https://auprf.ptac.org/wp-content/uploads/2018/05/Pneumatic-Vent-Gas-Measurement.pdf)

[21] Osman, A. (2016). Determining Pneumatic Controller and Pumps Release Rates, available by request from ECCC.

[22] Available from www.capopenergy.com

Episodic emissions are from non-continuous or highly variable emission sources, and include:

- Blowdown, purging, and other de-pressure events
- Liquids loading/unloading from tanks
- Compressor starts (gas starts)
- Flare operational issues (e.g. unlit flares)

Temporal Trends

A variety of elements confound the acquisition of objective, accurate, comprehensive and comparable datasets on temporal trends in methane emissions. Constraints include changes in reporting regulations over time (and differences between jurisdictions), inaccessible or nonexistent recordkeeping, asset acquisition/divestitures, and employee turnover. That said, for a time-series model to back-cast and forecast methane emissions accurately it is necessary to better understand the direction and magnitude of change.

Workshop Objectives

In January 2019, following the presentation of the draft study results, a workshop led by DXD Consulting Inc. (DXD) was conducted to consider the experience of oil and gas industry experts on factors that could influence certain parameters of interest. Input was solicited from these representatives for the purposes of adding context to numerical results of forecasting and backcasting time-series methane modeling. The incorporation of industry knowledge to the MEFS is intended to enhance stakeholder understanding of the study results and to offer guidance on temporal implications to BC's emissions performance for time-series modeling applications.

The principal objective of the industry workshop was to solicit expert feedback on operator practices and historical and future design considerations that may impact methane emissions from upstream facilities. A key outcome of the workshop was for BC OGC, ECCC and the government of British Columbia through BC CAS and MEMPR to gain a better understanding from industry representatives, of how British Columbia oil and gas facilities and operating practices (regarding methane release drivers and management practices) may have differed in the past and how they may change in the future due to various factors.

Workshop Methodology

The workshop was designed to build upon the presentation of current operational practices and emission profiles as observed during the BC Methane Emissions Field Study. The workshop participant list targeted oil and gas producers with operations in BC that were visited during the Study, as well as Federal and BC provincial regulators.

The workshop focused on gaining industry insights on six factors that could influence modeling parameters, or modeling drivers, that impact time-series methane emissions modeling. Specifically, industry experts were asked to comment on how their facilities and operating practices (as they could impact methane management) were different in the past and would be different in the future, with respect to these six drivers. Participants were asked to characterize these differences in terms of directionality (i.e., more or less than current practices) and magnitude as banded into 5 categories. Magnitude categories ranged from **not applicable** to **neutral** (0-15%) to high (>= 100%). Table 4 shows the six drivers considered, and Table 5 shows the scale for analysis of these drivers.

Table 4: Modeling Driver

1	Equipment to Facility Ratios
2	LDAR inspection frequencies
3	Prevalence of high bleed pneumatic devices
4	Level of implementation of mitigation technologies, (for example, flares, vapour recovery)
5	Level of preventative maintenance conducted
6	Prevalence of non-emitting pneumatic devices

Table 5: Scale for characterizing the directionality and magnitude of change for each driver

Directionality and Magnitude of Change	**Estimated Percent Change to Driver (or Equipment Ratios)**
↑↑↑ (3)	> 100%
↑↑ (2)	50% to 100%
↑ (1)	15% to 50%
---	Neutral - No Change (+/- 15%)
NA	Not Applicable (doesn't exist)
↓ (-1)	15% to 50%
↓↓ (-2)	50% to 85%
↓↓↓ (-3)	>85% (didn't exist in past or doesn't exist in future)

Notably, a neutral or no-change scenario was given a range of zero change to 15% change in either direction. A change of -3 indicates that a practice essentially did not exist in the past or will not exist in the future.

The workshop was designed to gain industry knowledge of how those drivers, with respect to operations and practices, have changed over the past several years, and how they are expected to change, relative to current day, in the future. To collect this information over time, the following periods were defined for the purposes of the workshop:

Distant Past: this period is defined as pre-2009 and pre-dates the requirements for GHG reporting in British Columbia.

Recent Past: this period is defined as 2010 to 2015 and reflects the growing influence of unconventional gas production and potential liquefied natural gas overseas sales channels.

Current: this period is defined as 2016 to 2019. This period pre-dates the implementation of federal methane regulations and British Columbia methane regulations.

Future: this period is defined as 2020 to 2030. This period begins after the implementation of federal and provincial methane regulations. It was not considered practical to characterize industry practices and operations beyond 2030.

Initially, two future states were considered:

Future – Compliance: this state assumes that industry is compliant with the currently proposed provincial and federal regulations and that market and regulatory conditions remains as they are currently.

Future – Best-In-Class Methane Emissions Reductions: this state assumes that industry is not only compliant but exceeding the regulations and leading the world in methane emissions reductions. During the facilitated workshop, this state was considered to be redundant, because federal and provincial regulations is expected to position BC-based oil and gas production as leading the global industry in methane emissions reductions.

Based on feedback during the workshop, these two future states were considered to be the same, and the single future state in which Producers were compliant with the federal and provincial regulations was evaluated during the workshop. Participants were asked to characterize projected operations and behaviours for the future state, including anticipating practices or changes in operations that have no defined certainty of occurring in the future.

The following guidance was provided:

- The magnitude and directionality of change are always in relation to the current state, and not the state before or after it.
- The future state assumes that BC is compliant with methane regulations.
- Only British Columbia oil and gas production was to be considered.

To conduct the workshop, the participants were put into three groups, with even representation of producers and regulators/government in each group. Groups were first asked to define the conditions and activities associated with each temporal state. This exercise ensured a common understanding of the temporal state prior to investigating each of the six modeling drivers. Subsequently, for each model driver noted above, the groups assigned directionality and magnitude of change relative to current operations for all six drivers across three temporal states: distant past, recent past and future. Commentary framing each rating was collected and results of each time period were presented and discussed as a group. Finally, for the future state, the three groups came together to integrate diverging points of view, resulting in workshop-wide general agreement on broad trends.

Chapter 1: Field Observations

1.1 Analytical Approach

1.1.1.1 Major Equipment Survey

Major equipment was counted during the field survey at all sites that were visited. The list of major equipment considered are listed in Table 7. Recent field work to determine component counts for various major equipment types has been undertaken in Alberta (Clearstone 2018). It is not expected that these component counts will differ between operations in BC and Alberta as the equipment shares common manufacturers and is often designed and installed by similar firms. If major equipment was found during the field survey which did not have associated component counts in Clearstone 2018, its components were counted. Site-level component count averages are determined by multiplying the total major equipment counts by their respective component count from either Clearstone 2018 or from the field survey. Further details on major equipment types are provided in Table 6 and below. Overall component count averages are a combination of the Clearstone 2018 study and the field survey (for unique equipment) shown in Table 6.

Table 6: Major Equipment Component Count from Survey and Clearstone 2018[23]

Major Equipment – Component Counts from Field Study	Major Equipment – Component Counts from Clearstone 2018
Dehydrator - Dessicant	Catalytic Heater
Gas Sweetening: Sulfinol	Dehydrator - Glycol
Heat Trace System	Flare KnockOut Drum
Sand Separator	Gas Boot
Stabilization Tower	Gas Metering Building
Thermal Electric Generator	Gas Pipeline Header
	Gas Sweetening: Amine
	Incinerator
	LACT Unit
	Line Heater
	Liquid Pipeline Header
	Liquid Pump
	Pig Trap - Gas Service
	Pig Trap - Liquid Service
	Pop Tank
	Power Generator (natural gas fired)
	Process Boiler
	Production Tank Fixed Roof - Light Liquid
	Reciprocating Compressor
	Reciprocating Compressor - Electric Driver
	Screw Compressor
	Screw Compressor - Electric Driver
	Separator
	Storage Bullet
	Treater
	Well Pump
	Wellhead (Gas Flow)
	Wellhead (Gas Pump)

[23] Equipment definitions available in Clearstone 2018 Section 8.4

	Wellhead (Oil Flow)
	Wellhead (Oil Pump)

Major equipment is categorized under each site classification to determine average major equipment per site classification for the surveyed sites. Some site classifications (e.g., WT) are extensively surveyed (WT had 123 sites surveyed), whereas some site classifications had very low sample sizes (e.g., 2 MGBC sites visited). This will affect the accuracy and reliability of the average major equipment per site calculations as smaller sample sizes may not accurately account the differences between sites with the same classification.

1.1.1.2 Leaks and Vents Quantification

Leaks and vents observed during the field surveyed were measured if possible and estimated if measurement was not possible, at the discretion of the field team based on safe operating practices. The ambient conditions during measurement or estimation were also recorded. Using the ambient conditions and measured/estimated volumetric rates, a corrected leaks/vent rate is calculated using the combined gas law below.

Equation 1,

$$\frac{P_i V_i}{T_i} = \frac{P_f V_f}{T_f}$$

Where,

P_i, V_i, and T_i, = the initial Pressure, Volumetric flow rate, and Temperature recorded in kPa, m^3/hr, and °C respectively (temperatures recorded in °C but converted to °K throughout)

P_f and T_f, = Pressure and Temperature at standard conditions (101.325 kPa and 15°C respectively)

V_f = Corrected volumetric flow rate in m^3/hr

Leaks and vents are classified and analyzed based on source component, major equipment, site classification, volumetric flow rate magnitude, and whether they were estimates or measurements.

Field staff classified excessive pneumatic venting as open-ended lines (OELs) during data collection. These releases have been re-classified as excessive pneumatic venting to better represent the source of the observed emissions. These sources may have been categorized as open ended lines in previous studies. Therefore, for purposes of multiple different jurisdictions and differences in regulations around treatment of these emissions, these 42 leaks have been re-assigned from open-ended lines to excessive pneumatic venting to allow parties to determine their own methods to treat these emissions. these excessive pneumatic venting instances could not be attributed to a specific make and model at the site for a variety of reasons (e.g., instrument vent header leaks associated with multiple devices). Emissions categorized by the field team as open-ended line *venting* was not observed to be related to the operation of pneumatics. Venting from OELs mostly resulted from wellheads (surface casing vent flows) at ~75% of OEL vent sources.

1.1.1.3 Pneumatic Count and Pneumatic Venting

Pneumatics were counted during the field survey with data on device type, drive type (e.g., electric, solar, fuel gas (natural gas), etc.), chemical injection type, and make and model. Some limited data were also gathered regarding flow rates and pressures, but pneumatic vents were not directly measured. Any devices that may be pneumatically actuated (e.g. lube oil pumps) that were not classified as control instruments or chemical injection pumps were included in the major equipment inventory and not in the pneumatic inventory, in the same way that gas starter units would not be inventoried separately from compressors.

Pneumatics that were not fuel gas driven were assumed not to vent methane as part of normal operation. These pneumatics drives include electric, instrument air, solar, and propane. Pneumatic counts were analyzed and classified based on drive type and pneumatic device type from the following list;

- Pump,
- Level Controller,
- Transducer,
- Level Switch,
- High Level Shut Down Switch,
- Positioner,
- High Pressure Shut Down Switch,
- Pressure Controller,
- Pressure Switch,
- Plunger Lift Controller,
- Temperature Switch, and
- Other

Fuel gas pneumatics makes and models were verified so that estimates for pneumatic venting could be calculated. Pneumatic vent rates were estimated using available data from Alberta Environment and Parks Quantification Protocol for GHG Emission Reductions from Pneumatic Devices – Table C2,[24] WCI 2013,[25] the Prasino Study,[19] Alberta Energy Regulator's Manual 15,[26] PTAC Level Controller Study,[27] and in some cases manufacturer's specifications. Pneumatic vent data was matched based on the make and model of the fuel gas pneumatics surveyed. This method to estimate pneumatic venting requires reliance on available public studies that typically have varying vent rate results for pneumatic makes and models. Other analyses can be done based on the make and models of the pneumatics determined from the field survey and analysis in this study to determine a possible range of vent rates.

[24] Quantification protocol for greenhouse gas emission reductions from pneumatic devices (version 2.0), Alberta Environment and Parks, January 2017 (Available at https://open.alberta.ca/publications/9781460131633)

[25] WCI Quantification Method 2013 Addendum to Canadian Harmonization Version, Western Climate Initiative, December 2013 (Available at https://www2.gov.bc.ca/assets/gov/environment/climate-change/ind/quantification/wci-2013.pdf)

[26] Estimating Methane Emissions, Alberta Energy Regulator, December 2018 (Available at https://www.aer.ca/documents/manuals/Manual015.pdf)

[27] Level Controller Emission Study Fisher L2 and Improved Relays, Norriseal 1001As and EVS, Greenpath Energy, October 2018 (Available at https://auprf.ptac.org/wp-content/uploads/2018/10/Final-Report-Level-Controller-V8-20181003.pdf)

Excessive pneumatic venting is not included in this section, as it is considered in the section on fugitive emissions. Current regulation surrounding excessive pneumatic venting varies across jurisdictions and excessive pneumatic venting is classified as either a vent or a leak in different regulations. This study adopts BC's requirements under the Drilling and Production Regulation by classifying this source as a fugitive emission.

1.2 Results

1.2.1 Major Equipment Counts

Major equipment in hydrocarbon service were counted for each location surveyed. The counts included both operating and pressurized non-operating equipment from the list in Table 7 and Table 8. The average (mean) process equipment count for a given facility subtype or well status is determined using the following relation:

Equation 2,

$$\bar{N}_{ME} = N_{ME} / N_{F/W}$$

Where,

$\bar{N}_{ME}$ = average (mean) major equipment count for a given site classification,

N_{ME} = total number of process equipment surveyed for a given site classification,

$N_{F/W}$ = total number of sites visited of the considered site classification (12 site classifications)

Average and total major equipment counts per facility subtype are presented in Table 7 and Table 8 respectively.

Table 7: Average Major Equipment per Facility Type

	Site Classification (Number of Sites Surveyed)											
Major Equipment List	**WT (123)**	**WO (31)**	**WC (51)**	**SWBT (3)**	**SWBO (7)**	**SWBC (4)**	**MPBO (7)**	**MGBT (15)**	**MGBO (4)**	**MGBC (2)**	**MEMT (12)**	**MEMC (7)**
Catalytic Heater	1.50	0.52	2.00	2.00	1.71	1.75	7.29	5.93	4.00	1.00	15.75	4.29
Catalytic Incinerator			0.02		0.14			0.07				
Dehydrator - Dessicant						0.25		0.20				0.29
Dehydrator - Glycol	0.02					0.25	0.57	0.40			1.17	0.29
Expansion Tank							0.14					
Flare KnockOut Drum	0.04		0.39	0.33	0.29	0.25	1.43	0.93	0.75		1.50	0.86
Gas Boot							0.14	0.07			0.08	
Gas Metering Building	0.01		0.06									0.14
Gas Pipeline Header	0.03		0.02		0.14	0.25	0.57	0.40	0.75	0.50	0.17	0.14
Gas Sample and Analysis System	0.02							0.07			0.25	0.29
Gas Sweetening Scavenger	0.02											
Gas Sweetening: Amine								0.07			0.08	
Gas Sweetening: Sulfinol								0.13				
Heat Trace System	0.01							0.33			0.25	
Incinerator							0.29	0.20	0.25		0.08	
LACT Unit							0.29					
Line Heater	0.08	0.03	0.31		0.14	0.50		0.07			0.17	0.14
Liquid Pipeline Header	0.02	0.13					0.71	0.20			0.08	
Liquid Pump							3.57	0.73			0.42	0.43
Lube Oil Tank							0.14					
Meter Building	0.10		0.37			0.25	0.14	0.20		0.50	0.17	0.14

Major Equipment List	Site Classification (Number of Sites Surveyed)											
	WT (123)	WO (31)	WC (51)	SWBT (3)	SWBO (7)	SWBC (4)	MPBO (7)	MGBT (15)	MGBO (4)	MGBC (2)	MEMT (12)	MEMC (7)
Pig Trap - Gas Service	0.19		0.47	0.67	0.43	0.50	1.00	2.87	0.75	0.50	3.08	1.00
Pig Trap - Liquid Service	0.05	0.32	0.02		0.14	0.25	0.86		0.50		0.08	0.14
Pneumatic Panel							0.14					
Pop Tank	0.01	0.13			0.43		0.71	0.07	0.75			
Power Generator (natural gas fired)	0.02					0.25	0.43	0.67	0.50		1.33	1.00
Process Boiler							0.43	0.13				0.43
Production Tank - Water	0.04				0.43	0.25	1.14	2.20	0.75		2.75	0.57
Production Tank Fixed Roof - Light Liquid	0.03	0.13	0.02	0.67	0.86	0.25	3.57	0.73	1.50		1.67	0.71
PumpJack		0.03										
Reciprocating Compressor - Electric Driver	0.03				0.14		0.86	0.67			1.83	1.29
Reciprocating Compressor – Natural Gas							0.14	0.27				0.14
Sand Separator	0.15	0.03		0.33				0.33				
Screw Compressor - Electric Driver				0.33								
Screw Compressor - Natural Gas							0.71	0.20			0.17	
Separator	0.31	0.26	0.10	0.33	0.86	1.50	3.43	2.33	1.50	0.50	2.75	1.86
Shipping Pump							0.14					
Stabilization Tower								0.07				
Storage Bullet	0.03	0.10	0.27		0.29		0.14				0.17	
Thermal Electric Generator	0.15	0.10	0.49	0.67	0.43			0.27	0.50	0.50	0.17	0.43
Treater							0.86	0.07				
Unit Heater	0.01											
Water Storage Unit		0.03										
Well Pump		0.68	0.02		0.71	0.50	0.14					
Wellhead (Gas Flow)	1.01	0.16	1.14	0.33	0.14		0.43	0.60			0.08	
Wellhead (Gas Pump)	0.03											
Wellhead (Oil Flow)		0.26			0.43	0.50	0.14					
Wellhead (Oil Pump)		0.58	0.02		0.43		0.14					
Wellhead (Water Injection)								0.07				

Table 8: Total Major Equipment by Facility Type

Major Equipment List	Site Classification (Number of Sites Surveyed)											
	WT (123)	WO (31)	WC (51)	SWBT (3)	SWBO (7)	SWBC (4)	MPBO (7)	MGBT (15)	MGBO (4)	MGBC (2)	MEMT (12)	MEMC (7)
Catalytic Heater	185	16	102	6	12	7	51	89	16	2	189	30
Catalytic Incinerator			1		1			1				
Dehydrator - Dessicant						1		3				2
Dehydrator - Glycol	2					1	4	6			14	2
Expansion Tank							1					
Flare KnockOut Drum	5		20	1	2	1	10	14	3		18	6
Gas Boot							1	1			1	
Gas Metering Building	1		3									1
Gas Pipeline Header	4		1		1	1	4	6	3	1	2	1
Gas Sample and Analysis System	2							1			3	2
Gas Sweetening Scavenger	2											
Gas Sweetening: Amine								1			1	
Gas Sweetening: Sulfinol								2				
Heat Trace System	1							5			3	
Incinerator							2	3	1		1	
LACT Unit							2					
Line Heater	10	1	16		1	2		1			2	1
Liquid Pipeline Header	3	4					5	3			1	
Liquid Pump							25	11			5	3
Lube Oil Tank							1					
Meter Building	12		19			1	1	3		1	2	1
Pig Trap - Gas Service	23		24	2	3	2	7	43	3	1	37	7
Pig Trap - Liquid Service	6	10	1		1	1	6		2		1	1

	Site Classification (Number of Sites Surveyed)											
Major Equipment List	**WT (123)**	**WO (31)**	**WC (51)**	**SWBT (3)**	**SWBO (7)**	**SWBC (4)**	**MPBO (7)**	**MGBT (15)**	**MGBO (4)**	**MGBC (2)**	**MEMT (12)**	**MEMC (7)**
Pneumatic Panel							1					
Pop Tank	1	4			3		5	1	3			
Power Generator (natural gas fired)	2					1	3	10	2		16	7
Process Boiler							3	2				3
Production Tank - Water	5				3	1	8	33	3		33	4
Production Tank Fixed Roof - Light Liquid	4	4	1	2	6	1	25	11	6		20	5
PumpJack		1										
Reciprocating Compressor - Electric Driver							1	4				1
Reciprocating Compressor – Natural Gas	4				1		6	10			22	9
Sand Separator	18	1		1				5				
Screw Compressor – Natural Gas				1								
Screw Compressor - Electric Driver							5	3			2	
Separator	38	8	5	1	6	6	24	35	6	1	33	13
Shipping Pump							1					
Stabilization Tower								1				
Storage Bullet	4	3	14		2		1				2	
Thermal Electric Generator	19	3	25	2	3			4	2	1	2	3
Treater							6	1				
Unit Heater	1											
Water Storage Unit		1										
Well Pump		21	1		5	2	1					
Wellhead (Gas Flow)	124	5	58	1	1		3	9			1	
Wellhead (Gas Pump)	4											
Wellhead (Oil Flow)		8			3	2	1					
Wellhead (Oil Pump)		18	1		3		1					
Wellhead (Water Injection)								1				

1.2.2 Component Counts

Major equipment counts were matched with average component-to-equipment ratios. Component-to-equipment ratios were derived either from Clearstone 2018 or actual component counts on major equipment for which there were no existing ratios (as outlined in Table 6). This approach was used to determine average component counts for the various site types considered in this study. Component counts in the field were acquired for process equipment observed in the field that was not in Clearstone 2018. Some components serviced different gas and liquid types (process gas, fuel gas, light liquid, and heavy liquid), which is differentiated in Table 9 and Table 10. No heavy liquid service was encountered in the study. Below is the list of all component types considered:

- Compressor Seals,
- Connector,
- Control Valve,
- Meter,
- Open-Ended Line,
- Pressure Relief Valves and Pressure Safety Valves (PRV/PSV),
- Pump Seal,

- Regulator,
- Thief Hatch, and
- Valve.

The thief hatch component type was added because their emission release characteristics are poorly represented by other component types. It was observed that the leaker and population leak factors differed significantly from connectors and OELs resulting in the creation of a separate component category. This component type may not be considered in other, similar studies. Historically, thief hatches were counted as a valve or a PRV. Because the leaker and population leak factors presented below for thief hatches are different than connectors and OELs (excessive pneumatic venting), separate components types are justifiable.

Gas component services included fuel gas and process gas, but fuel gas is aggregated with process gas. This is consistent with methods used in other fugitive emission factor studies.[28] Average (mean) component counts are calculated for each process equipment type using Equation 3 and are presented in Table 9 and Table 10.

Equation 3,

$$\bar{N}_{CC} = N_{CC}/N_{\mathrm{F/W}}$$

Where,

$\bar{N}_{CC}$ = average component count for a given facility subtype or well status,

N_{CC} = total number of components for a given facility subtype or well status (Clearstone 2018 or field survey),

$N_{F/W}$ = total number of a given facility subtype or well status surveyed.

Clearstone 2018 provides ranges for confidence intervals for their average components per major equipment type calculations, which are particularly wide for major equipment with few sample sizes. Some major equipment component counts, such as catalytic heaters (650 observed in Clearstone 2018), have tight confidence intervals ranging from 7-29% and 8-32% for lower and upper confidence intervals of multiple component types. These tighter confidence intervals are due to large sample sizes and less variation in component accounts across all catalytic heaters. However, there are also examples of large confidence intervals such as flare knockout drums (29 observed in Clearstone 2018), which have confidence intervals ranging from 45-100% and 58-308% for lower and upper confidence intervals of multiple component types. Which is a due to a combination of smaller sample sizes and large variability between component counts for individual flare knockout drums. The confidence intervals from the Clearstone study would conceptually carry over to the estimates of component counts for this study.

[28] Update of Fugitive Equipment Leak Emission Factors, CAPP 2014 (https://www.capp.ca/-/media/capp/customer-portal/publications/238773.pdf?modified=20180910181053)

As an example, current average gas connecter counts for wells (WT, WO, WC) are at 90-135 connectors per well. The factors that went into estimating the connectors for wells from the Clearstone 2018 study and the average major equipment per site classification. In the Clearstone 2018 study, a wellhead (which should be present at every well location) has 44 connectors, and accounts for ~30-40% of total connectors at a well (WT, WO, WC) in this study. Other major equipment that accounts for a significant portion of the average connector count for wells in this study include separators (25-30%), line heaters (4-24%), Flare Knockout Drum (16% for WC), and some reciprocating compressors (16% for WT). In the Clearstone 2018 study, there are 2 reciprocating and 3 screw compressors that were determined to be located on well sites for comparison. Clearstone 2018 surveyed 440 unique wells. This suggests that outliers may have significant impacts on average component calculations and qualitatively confirms the wide confidence intervals determined by others.

Table 9: Average Component Counts for Site Classifications

	Site Classification (Number of Sites Surveyed)											
Average Component Counts	**WT (123)**	**WO (31)**	**WC (51)**	**SWBT (3)**	**SWBO (7)**	**SWBC (4)**	**MPBO (7)**	**MGBT (15)**	**MGBO (4)**	**MGBC (2)**	**MEMT (12)**	**MEMC (7)**
Compressor Seal Process Gas	0.121				0.533		3.984	3.274			6.940	5.154
Connector Fuel Gas	0.014	0.003	0.015	0.021	0.016	5.958	0.016	11.158	0.016	0.016	0.318	6.848
Connector Light Liquid	33.551	87.356	43.051	58.709	156.122	149.706	896.869	353.374	166.894	37.203	427.718	263.286
Connector Process Gas	128.750	94.786	136.466	207.814	307.817	397.255	1730.206	1,230.841	378.599	119.572	2,075.041	1,323.392
Control Valve Fuel Gas						0.042		0.033				0.048
Control Valve Light Liquid	0.389	0.469	0.667	0.708	1.340	1.270	6.088	3.152	1.119	0.364	4.157	2.697
Control Valve Process Gas	0.451	0.243	0.297	1.078	1.226	2.142	8.988	5.866	2.703	0.672	9.608	5.713
Meter Fuel Gas						0.042		0.033				0.048
Meter Light Liquid	0.152	0.120	0.065	0.180	0.360	0.631	4.742	1.405	0.631	0.210	1.351	1.033
Meter Process Gas	0.498	0.342	0.358	0.731	1.151	2.204	6.278	3.927	2.062	0.813	5.170	3.124
Open-Ended Line Fuel Gas	0.016							0.667			0.500	
Open-Ended Line Light Liquid	0.037	0.132	0.270	0.245	0.645	0.178	2.393	0.773	1.301		1.070	0.017
Open-Ended Line Process Gas	0.111	0.067	0.038	0.447	0.239	0.326	1.764	1.032	0.285	0.104	1.993	1.135
PRV/PSV Fuel Gas	0.008					0.125		0.433			0.250	0.143
PRV/PSV Light Liquid	0.000	0.002	0.000	0.008	0.010	0.003	2.519	0.459	0.018		0.275	0.271
PRV/PSV Process Gas	0.961	0.747	0.611	2.422	2.629	3.960	15.587	10.182	3.323	1.039	15.840	10.074
Pump Seal Light Liquid		0.631	0.021		0.466		3.889	0.767			0.436	0.448
Regulator Fuel Gas	0.117	0.052	0.222	0.382	0.194	0.083		0.749	0.227	0.227	0.437	0.289
Regulator Light Liquid	0.018	0.004		0.040				0.040				
Regulator Process Gas	3.710	2.948	4.868	3.837	7.734	11.473	36.953	24.572	12.551	2.809	49.472	24.608
Thief Hatch Light Liquid	0.013	0.052	0.008	0.267	0.343	0.100	1.429	0.293	0.600		0.667	0.286
Thief Hatch Process Gas	0.008	0.033	0.005	0.173	0.222	0.065	0.924	0.190	0.388		0.431	0.185
Valve Fuel Gas						1.000		2.267				1.143
Valve Light Liquid	6.949	19.933	9.491	11.618	32.151	28.580	189.719	69.018	33.655	7.000	76.025	45.945
Valve Process Gas	27.673	18.226	31.738	25.024	50.185	72.769	223.016	170.630	78.501	30.277	244.432	136.396

Table 10: Total Component Counts for Site Classifications

	Site Classification (Number of Sites Surveyed)											
Total Component Counts	**WT (123)**	**WO (31)**	**WC (51)**	**SWBT (3)**	**SWBO (7)**	**SWBC (4)**	**MPBO (7)**	**MGBT (15)**	**MGBO (4)**	**MGBC (2)**	**MEMT (12)**	**MEMC (7)**
Compressor Seal Process Gas	15				4		28	49			83	36
Connector Fuel Gas	2	0	1	0	0	24	0	167	0	0	4	48
Connector Light Liquid	4,127	2,708	2,196	176	1,093	599	6,278	5,301	668	74	5,133	1,843
Connector Process Gas	15,836	2,938	6,960	623	2,155	1,589	12,111	18,463	1,514	239	24,900	9,264
Control Valve Fuel Gas						0		1				0
Control Valve Light Liquid	48	15	34	2	9	5	43	47	4	1	50	19
Control Valve Process Gas	55	8	15	3	9	9	63	88	11	1	115	40
Meter Fuel Gas						0		1				0
Meter Light Liquid	19	4	3	1	3	3	33	21	3	0	16	7
Meter Process Gas	61	11	18	2	8	9	44	59	8	2	62	22
Open-Ended Line Fuel Gas	2							10			6	
Open-Ended Line Light Liquid	5	4	14	1	5	1	17	12	5		13	0
Open-Ended Line Process Gas	14	2	2	1	2	1	12	15	1	0	24	8
PRV/PSV Fuel Gas	1					1		7			3	1
PRV/PSV Light Liquid	0	0	0	0	0	0	18	7	0		3	2
PRV/PSV Process Gas	118	23	31	7	18	16	109	153	13	2	190	71
Pump Seal Light Liquid		20	1		3		27	12			5	3
Regulator Fuel Gas	14	2	11	1	1	0		11	1	0	5	2
Regulator Light Liquid	2	0		0				1				
Regulator Process Gas	456	91	248	12	54	46	259	369	50	6	594	172
Thief Hatch Light Liquid	2	2	0	1	2	0	10	4	2		8	2
Thief Hatch Process Gas	1	1	0	1	2	0	6	3	2		5	1
Valve Fuel Gas						4		34				8
Valve Light Liquid	855	618	484	35	225	114	1,328	1,035	135	14	912	322
Valve Process Gas	3,404	565	1,619	75	351	291	1,561	2,559	314	61	2,933	955

1.2.3 Pneumatic Devices

1.2.3.1 Pneumatic Device Counts

Pneumatic devices driven by natural gas, propane, instrument air, solar, and electric were inventoried at each location surveyed during the study. 2120 pneumatic devices were observed in the field survey and inventoried, with 725 gas driven pneumatics, 891 instrument air, 419 electric, 11 propane, 59 solar, and 6 were classified as 'other'. Figure 7 below delineates the pneumatic inventory by device type and driver type. The majority (1395 of 2120) of devices are not driven by natural gas and as such will not contribute to site or facility level methane emissions. The pneumatic device types considered are the following:

- Pump,
- Level Controller,
- Transducer,
- Level Switch,
- High Level Shut Down Switch,
- Positioner,
- High Pressure Shut Down Switch,
- Pressure Controller,
- Pressure Switch,
- Plunger Lift Controller,
- Temperature Switch, and
- Other

Figure 7 and Figure 8 presents the distribution of pneumatics by drive and device type. The most common pneumatic device types are pumps, level controllers, and transducers, with a majority of them running on instrument air or electric drives.

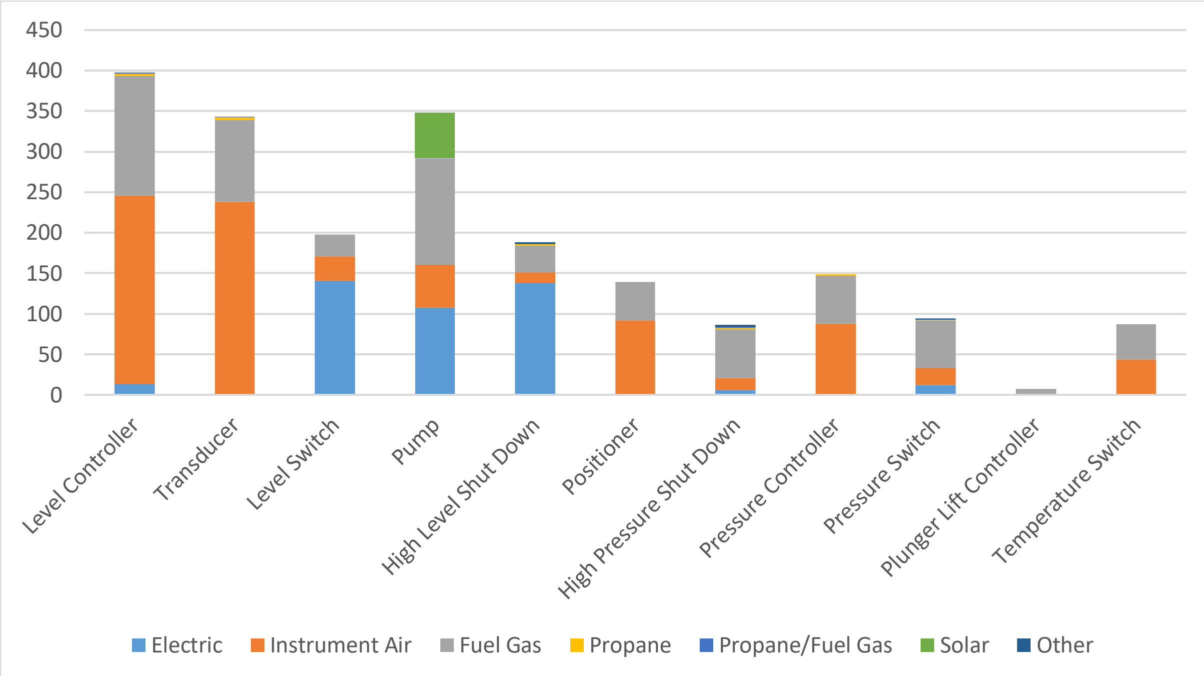


Figure 7: Observed Pneumatic Devices and Equivalents

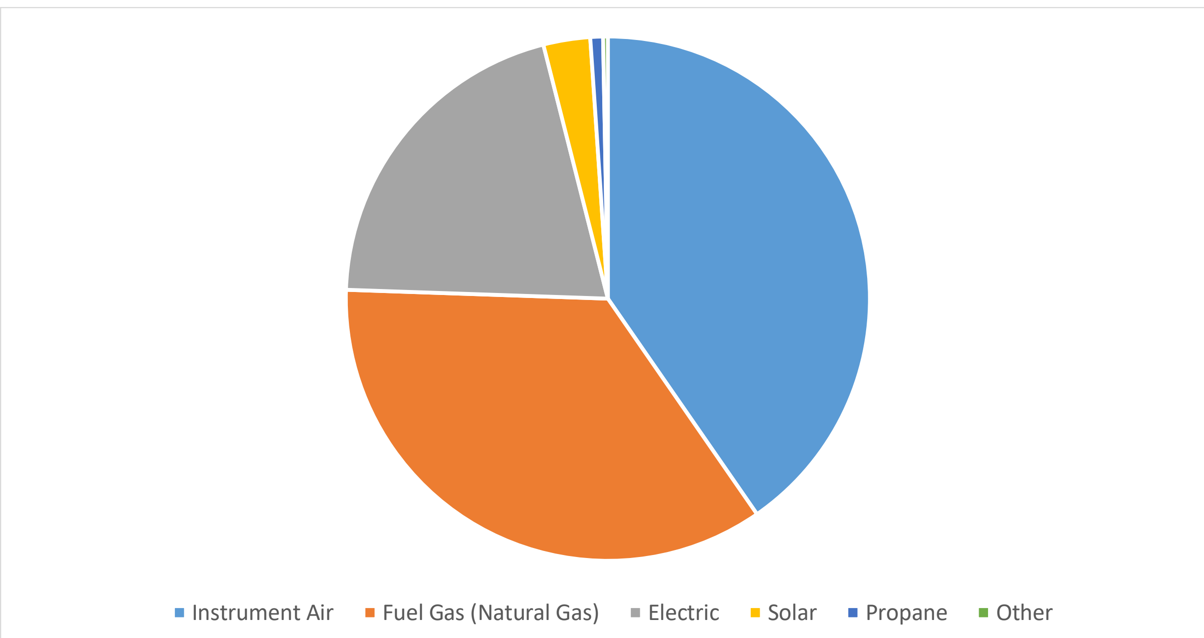


Figure 8: Pneumatic Device Distribution by Drive Type

Table 11 and Table 14 present the average pneumatic devices per site type for all, high bleed gas, low bleed gas, and no bleed (electric, solar, propane, air, other) drive type pneumatics. The majority (65%) of pneumatics are no bleed and are assumed to not emit natural gas from normal operation. For the no bleed pneumatics, 16 were fueled by propane, and are aggregated with no-bleed pneumatics as they would not emit methane. The make and models of all fuel gas pneumatics are included in ***Appendix A: Data Tables***.

High and low bleed designations were based on the vent rate used, and not necessarily manufacturer specifications. The latest studies such as Spartan 2018 re-affirm manufacturer static bleed rates, but quantification of release rates using other than manufacturer specifications was included for completeness and comparison to other studies (see Section 2.1.4).

Table 11: Average Pneumatic Types by Site Classification (All Drives)

	Site Classification (Number of Sites Surveyed)											
Site Average Pneumatic Device Types	**WT (123)**	**WO (31)**	**WC (51)**	**SWBT (3)**	**SWBO (7)**	**SWBC (4)**	**MPBO (7)**	**MGBT (15)**	**MGBO (4)**	**MGBC (2)**	**MEMT (12)**	**MEMC (7)**
Level Controller	0.55	0.32	0.18	1.33	1.43	1.50	8.00	5.60	2.25		9.67	3.71
Transducer	0.49	0.07	0.41	1.67		2.25	5.29	5.53	1.50		6.17	6.43
Level Switch	0.30	0.13	0.24	0.67	0.43	1.50	0.57	2.27	1.00		4.50	5.43
Pump	1.04	0.58	1.57	2.33	1.29	1.25	4.14	4.20	2.00	1.00	4.92	2.14
High Level Shut Down	0.25	0.03	0.18	0.67	0.43	0.25	0.86	3.40			6.67	0.57
Positioner	0.25	0.07	0.12	1.00			2.86	1.93	1.25		2.75	1.43
High Pressure Shut Down	0.10	0.48	0.10	0.67	1.86	0.25	0.71	1.53	0.50		0.33	0.43
Pressure Controller	0.13	0.13	0.10		1.57	0.75	5.71	1.13	1.00		2.67	2.43
Pressure Switch	0.32	0.03	0.57				0.43	1.13			0.25	0.27
Plunger Lift Controller	0.01	0.03	0.06					0.13				
Temperature Switch	0.11	0.03	0.39		0.14	1.25	1.14	0.27			2.00	1.14
Other	0.02	0.07	0.04				0.14					

Table 12: Average High Bleed Pneumatics by Site Classification (Natural Gas Drive Only)

	Site Classification (Number of Sites Surveyed)											
Site Average HB Pneumatics	**WT (123)**	**WO (31)**	**WC (51)**	**SWBT (3)**	**SWBO (7)**	**SWBC (4)**	**MPBO (7)**	**MGBT (15)**	**MGBO (4)**	**MGBC (2)**	**MEMT (12)**	**MEMC (7)**
Level Controller	0.35	0.13	0.12	1.33	0.86		0.57	1.40	0.75			
Transducer	0.29	0.03	0.26	0.33		0.25		0.13	1.25			0.43
Level Switch	0.03			0.33	0.29							
High Level Shut Down	0.02				0.14							
Positioner	0.21	0.03	0.08					0.40				
High Pressure Shut Down												
Pressure Controller	0.12	0.07	0.06		1.43	0.75	0.86	0.60	0.50		0.50	
Pressure Switch												
Plunger Lift Controller												
Temperature Switch												
Other	0.02											

Table 13: Average Low Bleed Pneumatics by Site Classification (Natural Gas Drive Only)

	Site Classification (Number of Sites Surveyed)											
Site Average LB Pneumatics	**WT (123)**	**WO (31)**	**WC (51)**	**SWBT (3)**	**SWBO (7)**	**SWBC (4)**	**MPBO (7)**	**MGBT (15)**	**MGBO (4)**	**MGBC (2)**	**MEMT (12)**	**MEMC (7)**
Level Controller	0.07	0.13	0.04		0.29	0.75	0.29	0.87	0.50		1.00	
Transducer	0.13	0.03	0.08	1.33				0.73				
Level Switch	0.02		0.06			0.25		0.07			0.50	
High Level Shut Down	0.07	0.03	0.16		0.14	0.25	0.14	0.07			0.50	
Positioner												
High Pressure Shut Down	0.07	0.45	0.06	0.67	1.29			0.47				
Pressure Controller												
Pressure Switch	0.28		0.45					0.07				
Plunger Lift Controller												
Temperature Switch	0.11	0.03	0.35		0.14	1.00		0.07				
Other												

Table 14: Average No Bleed Pneumatics by Site Classification

Site Classification (Number of Sites Surveyed)

Site Average NB[29] Pneumatics	WT (123)	WO (31)	WC (51)	SWBT (3)	SWBO (7)	SWBC (4)	MPBO (7)	MGBT (15)	MGBO (4)	MGBC (2)	MEMT (12)	MEMC (7)
Level Controller	0.07	0.13	0.02		0.29	0.75	7.14	3.20	0.75		8.67	3.71
Transducer	0.07	0.03	0.06			2.00	5.14	4.67			6.17	6.00
Level Switch	0.25	0.13	0.10	0.33	0.14	1.00	0.57	2.07	1.00		4.00	5.43
Pump	0.53	0.36	1.14	0.67	0.57	1.00	2.14	1.40	0.75	1.00	2.17	0.86
High Level Shut Down	0.16		0.02	0.67	0.14		0.71	3.20			6.17	0.57
Positioner	0.03		0.02				2.86	1.53	0.25		2.75	1.43
High Pressure Shut Down	0.01	0.03	0.02		0.29		0.29	0.67	0.50		0.33	0.43
Pressure Controller	0.01		0.02		0.14		4.86	0.53	0.50		2.17	2.43
Pressure Switch	0.04	0.03	0.10				0.43	1.07			0.25	0.29
Plunger Lift Controller												
Temperature Switch						0.25	1.14	0.20			2.00	1.14
Other	0.01	0.07					0.14					

Figure 9 compares high and low bleed pneumatics by controller type. High bleed are assumed for pneumatic makes and models with vent rates over 0.17 m^3/hour, with low bleed being below 0.17 m^3/hour. As outlined above, a similar methodology to determine vent rates used in Clearstone 2018 was applied. There are a total of 725 gas-driven pneumatics, with 403 high bleed, 321 low bleed, and one was unknown as the make and model was not discernable.

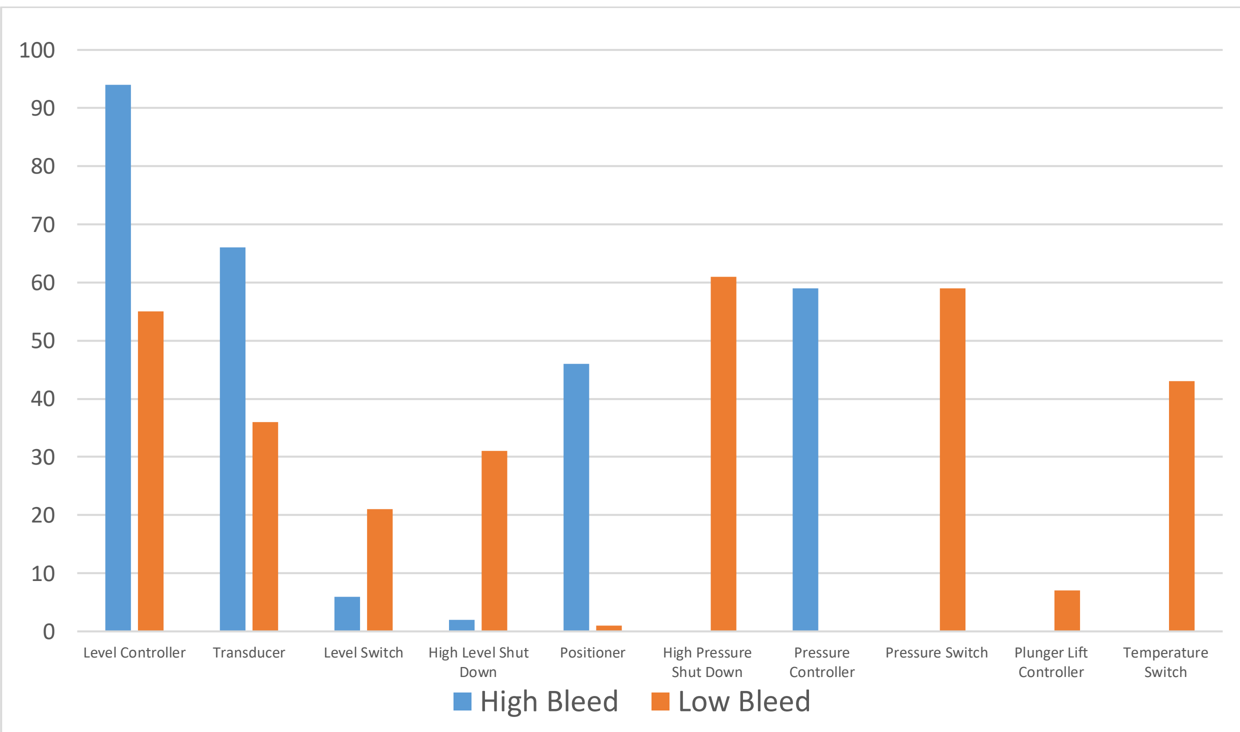


Figure 9: High Bleed and Low Bleed Pneumatics by Control Instrument Type

1.2.3.2 Pneumatics Control Instrument Venting

In this study, vented emissions from pneumatic devices were not measured during the field study. Pneumatic venting was calculated using available literature and publicly available data on normal operational vent rates based on the make and model of the pneumatics which provides a method to

[29] Drive Types: Electric, Solar, Propane, Air

perform site level comparisons. This method is similar compared to other studies such as Clearstone 2018 and Greenpath 2016. There are a wide variety of published pneumatic device vent rates. The pneumatic venting results below are based on the considered sources described in Section 1.1. Only fuel gas pneumatics were assumed to vent methane as part of normal operations. Pneumatic venting rates are summarized below in Table 15 which indicates the weighted average of the estimated vent rates for each type of device and site.

Table 15: Average Natural Gas Pneumatic Device Vent Rates (m^3/hour)

	Site Classification (Number of Sites Surveyed)											
Average Estimated Pneumatic Venting (m^3/hour)	**WT (123)**	**WO (31)**	**WC (51)**	**SWBT (3)**	**SWBO (7)**	**SWBC (4)**	**MPBO (7)**	**MGBT (15)**	**MGBO (4)**	**MGBC (2)**	**MEMT (12)**	**MEMC (7)**
Level Controller	0.21	0.14	0.36	0.26	0.20	0.01	0.18	0.16	0.16		0.01	
Transducer	0.31	0.26	0.47	0.17		0.37	0.14	0.15	0.33			0.51
Level Switch	0.19	0.00	0.10	0.26	0.05	0.09		0.09			0.01	
Pump	0.73	0.71	0.44	0.47	0.77	0.14		0.67	0.61		0.58	0.75
High Level Shut Down	0.03	0.01	0.02		0.05	0.05	0.01	0.09			0.01	
Positioner	0.51	0.40	0.55	0.14				0.54	0.14			
High Pressure Shut Down	0.06	0.06	0.05	0.05	0.06	0.14	0.14	0.09				
Pressure Controller	0.67	0.17	0.58		0.91	1.09	1.53	0.36	0.21		0.21	
Pressure Switch	0.04		0.05					0.02				
Plunger Lift Controller	0.14	0.14	0.14					0.14				
Temperature Switch	0.04	0.04	0.05		0.04	0.04		0.04				
Other	0.14	0.14	0.14									
Overall Average	0.35	0.22	0.24	0.25	0.40	0.27	0.64	0.27	0.30		0.10	0.65

1.2.3.3 Pneumatic Pumps

Table 16 and below present data on average pneumatic pumps per site classification. Due to limitations during the field survey, the chemical injection rates were not available (for example, many inactive pumps during September). The average vent rate for pneumatic pumps was determined in the same method as the other pneumatic devices described in Section 1.1 as no vent rates were measured during the field survey. This was done to facilitate comparison of site level vent rates from pneumatic pumps. The type of chemical injected is available and summarized in Table 17 and Table 18 below by the number of pumps observed per chemical injection and site classification. Chemical type may imply whether pumps are seasonal or continuous, but this was not been quantitatively assessed within the scope of this study.

Table 16: Average Chemical Injection Pumps per Site

	Site Classification (Number of Sites Surveyed)											
Average Pumps per Site	**WT (123)**	**WO (31)**	**WC (51)**	**SWBT (3)**	**SWBO (7)**	**SWBC (4)**	**MPBO (7)**	**MGBT (15)**	**MGBO (4)**	**MGBC (2)**	**MEMT (12)**	**MEMC (7)**
Total Methanol Pumps	0.68	0.19	0.90	1.00	0.86	0.75	0.71	1.00	1.50	0.50	1.00	0.43
Total Other Chemical Pumps	0.33	0.35	0.65	1.33	0.43	0.50	1.43	1.47	0.50	0.50	1.42	1.00
Gas Driven Methanol Pumps	0.28	0.16	0.29	1.00	0.71	0.25		0.60	1.25		0.08	0.29
Gas Driven Other Chemical Pumps	0.20	0.03	0.14	0.67				0.47			0.17	0.29
No Bleed Methanol Pumps	0.40	0.03	0.61		0.14	0.50	0.71	0.40	0.25	0.50	0.92	0.14
No Bleed Other Chemical Pumps	0.13	0.32	0.51	0.67	0.43	0.50	1.43	1.00	0.50	0.50	1.25	0.71

Table 17: Overall Number of Pneumatic Pumps by Chemical Injection Type

Chemical Type Injected	Number of Gas Driven Pumps	Number of Non-Emitting Pumps
Corrosion Inhibitor	20	55
Methanol/Corrosion Inhibitor mix	13	4
Methanol	69	105
Other	23	50
Scale Inhibitor	0	1

Scavenger	2	1

Table 18: Number of Pumps by Chemical Injection Type and Site Classification

Site Classification	Chemical Type Injected	Number of Gas Driven Pumps	Number of Non-Gas Driven Pumps	Average Release Rate of Gas-driven (m^3/hr)
WT	Corrosion inhibitor	10	12	0.80
WT	Methanol/Corrosion Inhibitor mix	6	3	0.67
WT	Methanol	29	46	0.77
WT	No chemical in Tank	0	1	
WT	Other	13	2	0.84
WT	Scale Inhibitor	0	1	
WT	Scavenger	1	0	0.93
WO	Corrosion inhibitor	0	4	
WO	Methanol	5	1	0.90
WO	Other	1	6	0.57
WC	Corrosion inhibitor	5	19	0.62
WC	Methanol/Corrosion Inhibitor mix	3	0	1.02
WC	Methanol	12	31	0.69
WC	Other	2	7	0.80
SWBT	Corrosion inhibitor	0	1	
SWBT	Methanol/Corrosion Inhibitor mix	2	0	0.93
SWBT	Methanol	1	0	0.57
SWBT	Other	2	1	0.98
SWBO	Corrosion inhibitor	0	3	
SWBO	Methanol	5	1	0.75
SWBC	Corrosion inhibitor	0	1	
SWBC	Methanol	1	2	1.02
SWBC	Other	0	1	
MPBO	Methanol	0	5	
MPBO	Other	0	10	
MGBT	Corrosion inhibitor	1	4	0.93
MGBT	Methanol/Corrosion Inhibitor mix	2	0	0.93
MGBT	Methanol	7	6	0.78
MGBT	Other	5	10	0.78
MGBT	Scavenger	1	1	0.57
MGBO	Corrosion inhibitor	0	1	
MGBO	Methanol	5	1	0.75
MGBO	Other	0	1	
MGBC	Corrosion inhibitor	0	1	
MGBC	Methanol/Corrosion Inhibitor mix	0	1	
MEMT	Corrosion inhibitor	2	5	0.78
MEMT	Glycol	0	0	
MEMT	Methanol	1	11	0.57
MEMT	Other	0	10	
MEMC	Corrosion inhibitor	2	4	0.78
MEMC	Methanol	2	1	0.67
MEMC	Other	0	1	

1.2.4 Equipment Fugitive Emissions

In the data received from the field survey, all detected methane emissions (excluding normal pneumatic operation) were classified into two categories; leaks (equipment fugitive sources) and vents (venting sources). In the field survey, 284 leaks were detected and quantified.

A summary of the equipment fugitives detected and quantified at different site types is outlined in Table 19.

Table 19: Equipment Fugitives Summary by Site Type

Site Class-ification	Number of Sites Visited	Sites with one or more leaks	Average Leak Rate (Leaker Population)	Average Leak Rate (General Population)	Main Contributor to Leak Rate	Most Common Leak Type
		(%)	(m3/day/site)			
WT	**123**	17%	9.29	1.59	Open-ended Lines (Excessive Pneumatic Venting)	Connectors
WO	**31**	39%	8.68	3.36	Thief Hatches	Connectors
WC	**51**	55%	5.6	3.07	Valves	Connectors
SWBT	**3**	67%	30.9	20.6	Valves	Valves and Open-ended Lines (Excessive Pneumatic Venting)
SWBO	**7**	57%	14.13	8.08	Open-ended Lines (Excessive Pneumatic Venting)	Open-ended Lines (Excessive Pneumatic Venting), Connectors, and Valves
SWBC	**4**	75%	7.17	5.38	Valves	Valves
MPBO	**7**	71%	34	24.29	Thief Hatches	Valves and Connectors
MGBT	**15**	67%	20.33	13.55	Open-ended Lines (Excessive Pneumatic Venting)	Connectors
MGBO	**4**	25%	17.93	4.48	Open-ended Lines (Excessive Pneumatic Venting)	Open-ended Lines (Excessive Pneumatic Venting) and Connectors
MGBC	**2**	0%	0	0		
MEMT	**12**	83%	33.69	28.08	Connectors	Connectors

Site Class-ification	Number of Sites Visited	Sites with one or more leaks	Average Leak Rate (Leaker Population)	Average Leak Rate (General Population)	Main Contributor to Leak Rate	Most Common Leak Type
		(%)	(m3/day/site)			
MEMC	**7**	71%	19.69	14.07	Connectors	Connectors

1.2.4.1 Leak Distribution

Figure 10 presents the number of leaks detected per site. 166 of the 266 sites surveyed had no leaks detected. And most (88 of 101) of the remaining sites had fewer than 4 leaks per site. 13 sites had 5 or more leaks per site, with 3 sites having more than 10 leaks (11, 11, and 16 leaks for those 3 sites).

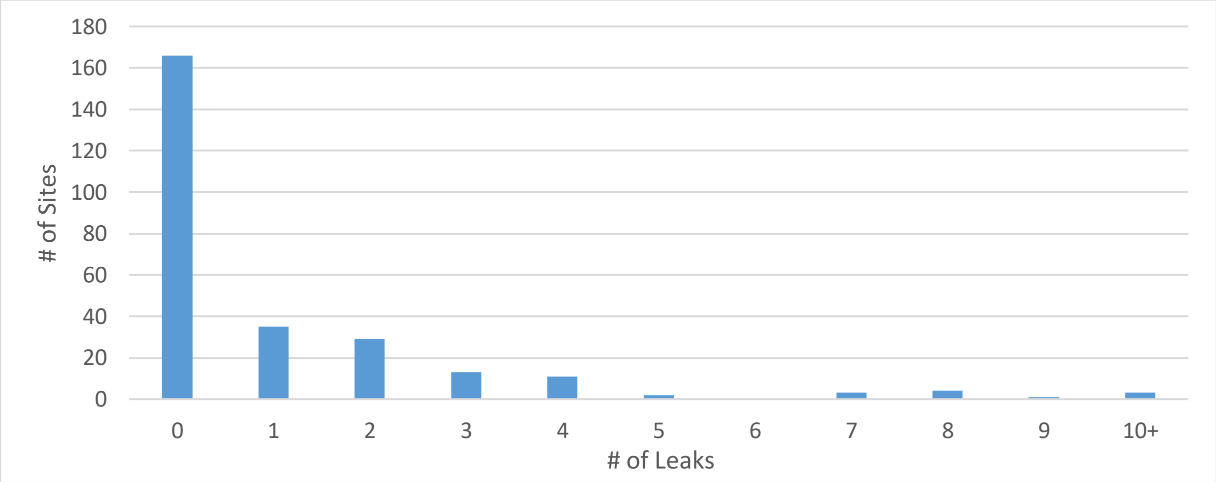


Figure 10: Distribution of leaks observed per facility survey

Figure 11 presents the maximum, minimum, and average leaks detected per site type. The two average bars indicate the average per leaking site and the average per site type overall which includes sites with no leaks. The average amount of leaks per site classification (where leaks are detected) is under 5 for all site types with an overall average of 2.8 leaks per site where leaks are detected, or an overall average of 1.1 leaks per site (includes sites with no leaks detected).

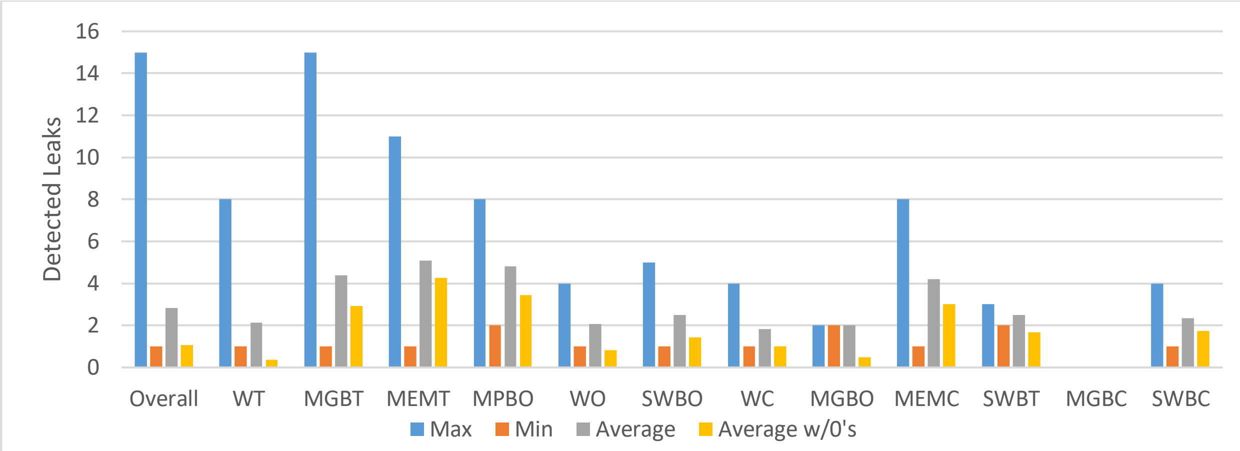


Figure 11: Number of Leaks Detected at Site Classifications (maximum, minimum, average (of non-zero), average (including zeros))

Leak emissions were measured or estimated when observed during the field study as outlined in the field data collection procedures. The volumetric measurements or estimates were recorded along with the ambient conditions. Using the ambient conditions and the volumetric measurements/estimates, a corrected volumetric leak rate was calculated using the combined gas law. Figure 12 below presents the percentage of leaks (by volume) by the number of sources and has been size ordered from greatest volumetric leak sources to least. It is seen that most of the emissions are from a small percentage of sources, 51 and 80 % of emissions from 8.7 and 26.7 % of sources respectively.

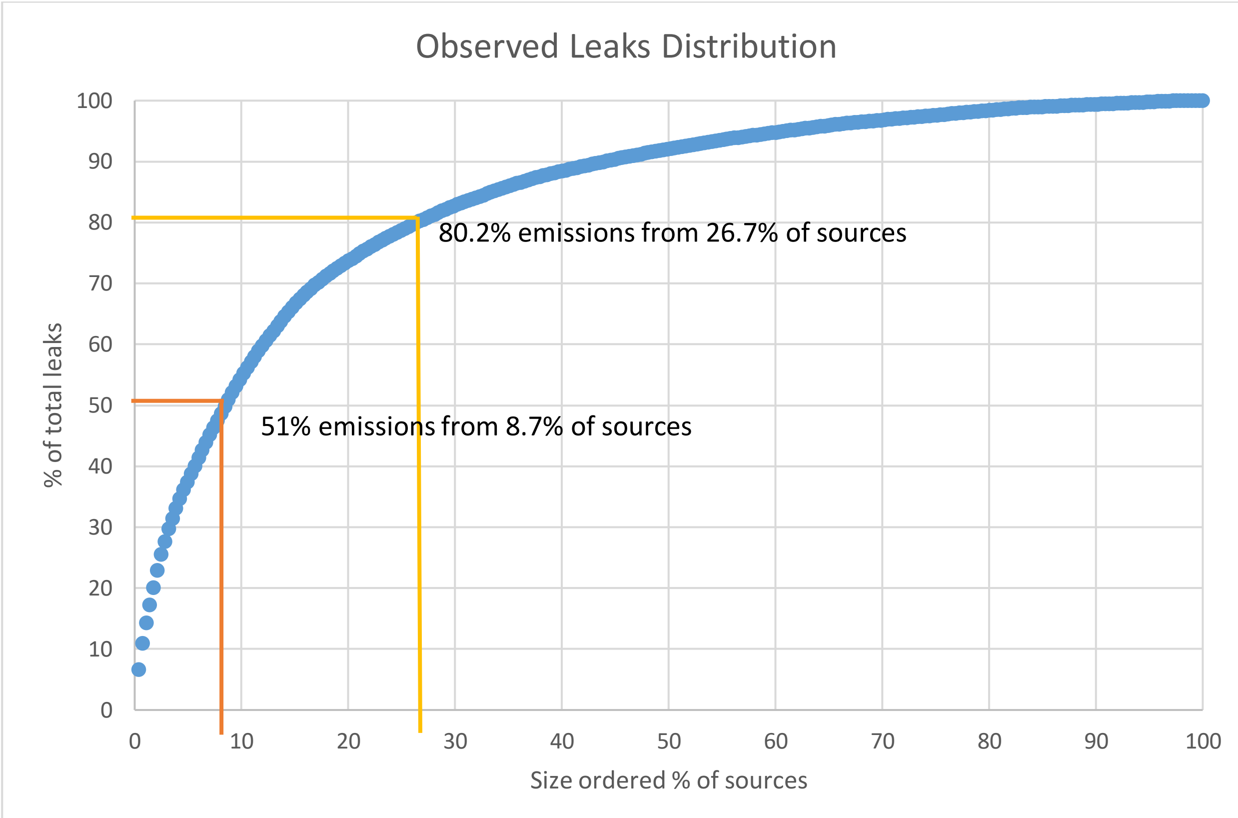


Figure 12: Observed Leak Distribution by Emission Magnitude per Source

Figure 13 below presents leak volumetric data by magnitude of the leak to the overall percentage of leak emissions detected. In the field survey, sources that were not able to be measured due to leak source location were estimated which is differentiated in Figure 13. It is seen that the majority of the larger emissions sources (7 of top 10 sources) were not measured directly as per **Field Data Collection**.

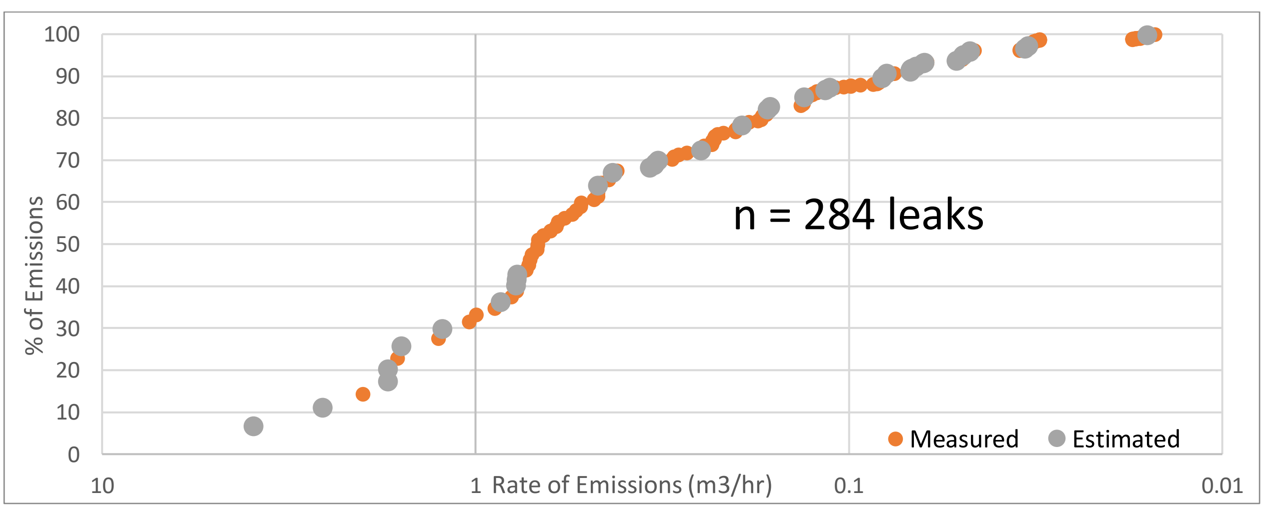


Figure 13: Magnitude of Leak Measurements and Estimates

Table 20 below presents the number of leaks per component type surveyed. There are two types of gas and liquid services (Process Gas & Fuel Gas, Light Liquid & Heavy Liquid although Heavy Liquid was not observed). There were only 4 emissions that were categorized as fuel gas. Therefore, fuel gas and process gas fugitive emissions were combined as ‘gas’ component service. There was no information collected which could offer insight into sour and sweet gas fugitives as it was out of the scope of the study. No leaks were detected for heavy liquid component service, and therefore all liquid service leaks (only connectors) are in light liquid service.

The leaker factor, total leakage, and average/median leak magnitude are also presented in Table 20. The median is shown to illustrate that the majority of leaks are smaller than the average, but large leaks significantly increase the average leak rate which is shown in Figure 12 and Figure 13. Leaker factor is the ratio of the number of leaks detected over the estimated total amount of the considered component type. An estimated 38% of thief hatches were leaking, whereas all other component types are under 6%, with the lowest leaker factor being .007% (liquid connectors). Thief Hatches also have the highest average, median, and site level leak rates which suggests that Thief Hatches are currently responsible for a significant portion of overall methane leak emissions (3% of overall leak sources, 17% of overall leak emissions).

Table 20: Summary of Leak Field Survey and Results

Component Type	Component Service	Total Components	Number of Leaks	Leaker Factor	Total Leakage (m^3/hr)	Avg Leak rate (m^3/hr)	Median Leak (m^3/hr)
Connector	Gas	96,823	154	0.0016	17.96	0.12	0.05
Connector	Liquid	30,259	2	0.00007	0.25	0.12	0.12
Control Valve	Gas	420	18	0.04	5.84	0.32	0.20
Meter	Gas	307	6	0.02	1.222	0.20	0.03
Excessive Pneumatic Venting	Gas	725	42	0.06	14.55	0.35	0.17
PRV/PSV	Gas	764	2	0.002	1.20	0.60	0.60
Regulator	Gas	2,405	24	0.01	5.34	0.22	0.13
Thief Hatch	Gas	21	8	0.38	10.07	1.26	0.62
Valve	Gas	14,776	22	0.001	2.24	0.10	0.07
Pump Seal	Gas	71	4	0.06	0.43	0.11	0.07

1.2.4.2 Leak Emissions Intensity

Methane emissions from the field survey, other than regular pneumatic operations, are classified as either leaks or vents. The results from the leaks are summarized below in Table 21 classified by component type and component service. Component service has been summarized as either gas or liquid (process and fuel gas are combined as gas; only light liquid component service leaks were observed). Table 22 summarizes the leak rate results into five considered components for time series modeling parameters, the mapping to these five components is displayed in the third column. Table 23 splits the results of Table 22 for each site classification. Confidence intervals were not determined for Table 23 as sample sizes were too small to confidently determine confidence intervals.

Confidence intervals for leaking components were determined using an empirical bootstrap analysis. This analysis is based on the principle that as the sample size increases, the histogram of many samples from a population converges to the probability histogram for that population. Consequently, the confidence interval bands narrow as the sample size increases. In this analysis, we use 10,000 bootstrapped samples (sampling with replacement) to calculate the 95% confidence interval around the sample mean. The results are presented in the tables below.

Table 21: Component Leak Rate Results and Component Mapping

Component Type	Component Service	Modeling Parameter Component Mapping	Total Components	Number of Leaks	Total Leakage (m^3/hr)	Avg Leak rate (m^3/hr)	Median Leak (m^3/hr)	CI Low (2.5th percentile) (m^3/hr)	CI High (97.5th Percentile) (m^3/hr)
Connector	Gas	Connector	96,823	154	17.36	0.11	0.05	0.09	0.16
Connector	Liquid	Connector	30,259	2	0.24	0.12	0.12	0.12	0.13
Control Valve	Gas	Valve	420	18	5.64	0.31	0.19	0.17	0.57
Meter	Gas	Connector	307	6	1.18	0.20	0.03	0.04	0.84
Open-Ended Line*	Gas	Excessive Pneumatic Venting	N/A*	42	14.06	0.33	0.16	0.24	0.49
PRV/PSV	Gas	PRV/PSV	764	2	1.16	0.58	0.58	0.33	0.82
Regulator	Gas	Valve	2,405	24	5.16	0.21	0.13	0.06	0.19
Thief Hatch	Gas	Valve	21	8	9.73	1.22	0.60	0.15	0.33
Valve	Gas	Valve	14,776	22	2.17	0.10	0.07	0.53	2.35
Pump Seal	Gas	Connector	71	4	0.41	0.10	0.07	0.06	0.17

**The Open-Ended Line category was exclusively used to characterize excessive or exceptional pneumatic venting, so calculating the number of components is not meaningful*

Table 22: Component Leak Rate Results – Mapped

Component	Total Components	Number of Leaks	Total Leakage (m³/hr)	Avg Leak rate (m³/hr)	Median Leak rate (m³/hr)	CI Low (2.5%, m³/hr)	CI High (97.5%, m³/hr)
Connector	127,502	166	18.55	0.12	0.05	0.09	0.15
Valve	23,948	66	12.59	0.19	0.08	0.14	0.28
Excessive Pneumatic Venting	N/A	42	13.59	0.33	0.16	0.23	0.47
PRV/PSV	794	2	1.12	0.56	0.56	0.32	0.80
Thief Hatch	54	8	9.40	1.18	0.58	0.51	2.26

Table 23: Mapped Component Leak Rate Results by Site Classification

Site Classification	Component Type	Total Components	Number of Leaks	Total Leakage (m³/hr)	Avg Leak Rate (m³/hr)	Median Leak (m³/hr)
WT	Compressor Seal	14.9	0			
	Connector	15,899.2	24	1.33	0.06	0.05
	Valve	3,459.2	8	0.71	0.10	0.07
	Excessive Pneumatic Venting	177.0	13	5.54	0.43	0.43
	PRV/PSV	589.9	0			
	Thief Hatch	2.7	0			
WO	Compressor Seal	0.0	0			
	Connector	2,945.2	12	0.74	0.06	0.05
	Valve	572.1	7	0.92	0.14	0.03
	Excessive Pneumatic Venting	13.0	4	0.46	0.12	0.02
	PRV/PSV	115.9	0			
	Thief Hatch	2.0	2	2.07	1.03	1.03
WC	Compressor Seal	0.0	0			
	Connector	6,978.8	33	2.50	0.08	0.07
	Valve	1,633.8	15	2.65	0.17	0.07
	Excessive Pneumatic Venting	36.0	3	1.16	0.39	0.44
	PRV/PSV	290.7	0			
	Thief Hatch	0.7	0			

Site Classification	Component Type	Total Components	Number of Leaks	Total Leakage (m^3/hr)	Avg Leak Rate (m^3/hr)	Median Leak (m^3/hr)
SWBT	Compressor Seal	0.0	0			
	Connector	625.7	1	0.05	0.05	0.05
	Valve	78.3	2	1.74	0.87	0.87
	Excessive Pneumatic Venting	8.0	2	0.71	0.35	0.35
	PRV/PSV	19.9	0			
	Thief Hatch	1.3	0			
SWBO	Compressor Seal	3.7	0			
	Connector	2,162.8	3	0.73	0.24	0.13
	Valve	359.9	3	0.37	0.13	0.08
	Excessive Pneumatic Venting	20.0	3	0.85	0.28	0.16
	PRV/PSV	73.9	0			
	Thief Hatch	4.0	1	0.32	0.32	0.32
SWBC	Compressor Seal	0.0	0			
	Connector	1,621.8	1	0.12	0.12	0.12
	Valve	303.8	6	0.75	0.13	0.03
	Excessive Pneumatic Venting	4.0	0			
	PRV/PSV	62.6	0			
	Thief Hatch	0.7	0			
MPBO	Compressor Seal	27.9	0			
	Connector	12,147.6	7	0.53	0.08	0.05
	Valve	1,623.1	7	1.31	0.18	0.03
	Excessive Pneumatic Venting	10.0	4	0.30	0.08	0.06
	PRV/PSV	367.3	2	1.16	0.58	0.58
	Thief Hatch	15.3	4	3.56	0.89	0.48
MGBT	Compressor Seal	49.1	0			
	Connector	18,689.3	33	2.83	0.09	0.02
	Valve	2,681.9	4	1.93	0.48	0.53
	Excessive Pneumatic Venting	49.0	7	3.42	0.49	0.19
	PRV/PSV	539.1	0			
	Thief Hatch	7.3	0			
MGBO	Compressor Seal	0.0	0			
	Connector	1,518.8	1	0.03	0.03	0.03
	Valve	324.4	0			

Site Classification	Component Type	Total Components	Number of Leaks	Total Leakage (m^3/hr)	Avg Leak Rate (m^3/hr)	Median Leak (m^3/hr)
	Excessive Pneumatic Venting	13.0	1	0.69	0.69	0.69
	PRV/PSV	64.2	0			
	Thief Hatch	3.3	0			
MGBC	Compressor Seal	0.0	0			
	Connector	240.8	0			
	Valve	61.9	0			
	Excessive Pneumatic Venting	0.0	0			
	PRV/PSV	0.0	0			
	Thief Hatch	0.0	0			
MEMT	Compressor Seal	83.3	0			
	Connector	24,966.2	38	8.34	0.22	0.06
	Valve	3,048.4	7	0.69	0.10	0.11
	Excessive Pneumatic Venting	8.0	4	0.65	0.16	0.16
	PRV/PSV	792.0	0			
	Thief Hatch	13.3	1	3.79	3.79	3.79
MEMC	Compressor Seal	36.1	0			
	Connector	9,333.8	13	1.94	0.14	0.06
	Valve	1,003.1	7	1.93	0.28	0.24
	Excessive Pneumatic Venting	7.0	1	0.10	0.10	0.10
	PRV/PSV	245.8	0			
	Thief Hatch	3.3	0			

1.2.4.3 Dehydrator Leaks

18 leaks from glycol dehydration systems were observed during the survey (and one vent, see Section 1.2.5.4). The composition of glycol dehydrator gas release is unknown and may include increased concentrations of non-methane gas. Dehydrator leaks originated from two component types, connectors and valves (8 valve, 10 connector sources) and are summarized in Table 24.

Table 24: Dehydrator Leaking Summary

m^3/hour	Total Equipment Count	Number of Leaks	Total Leak Rate	Average leak Rate	Average Leak rate for total population
Dehydrator - Glycol	29	18	2.854	0.159	0.098

1.2.5 Vents

Venting emissions, along with leaks, were measured or estimated during the field survey. 101 vents were measured/estimated during the survey and originate from 4 component types (Open-Ended Line Gas + Liquid service, Thief Hatch, and Compressor Seals), compared to the 10 component types logged for leaks.

1.2.5.1 Vent Distribution

Figure 14 below presents the number of sites with how many vents were detected and measured/estimated excluding normal pneumatic venting. The vast majority of sites (186 of 266 sites visited) had no vents detected excluding pneumatics, with 67 sites having a single vent detected and the remaining having 2-5 vents per site.

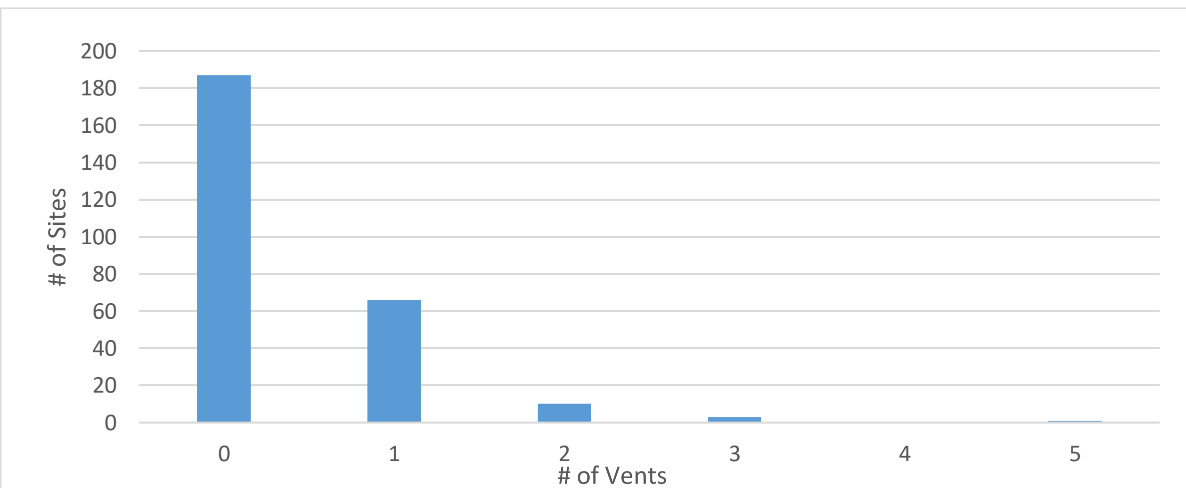


Figure 14: Number of Sites with Number of Detected Vents

Figure 15 below presents the maximum, minimum, average, and average with no detected vent sites included. The overall results are similar to those in Figure 11 for Leaks. It is seen that compared to leaks, most site types had fewer vents across the board, with the maximum vents at a single site being 5.

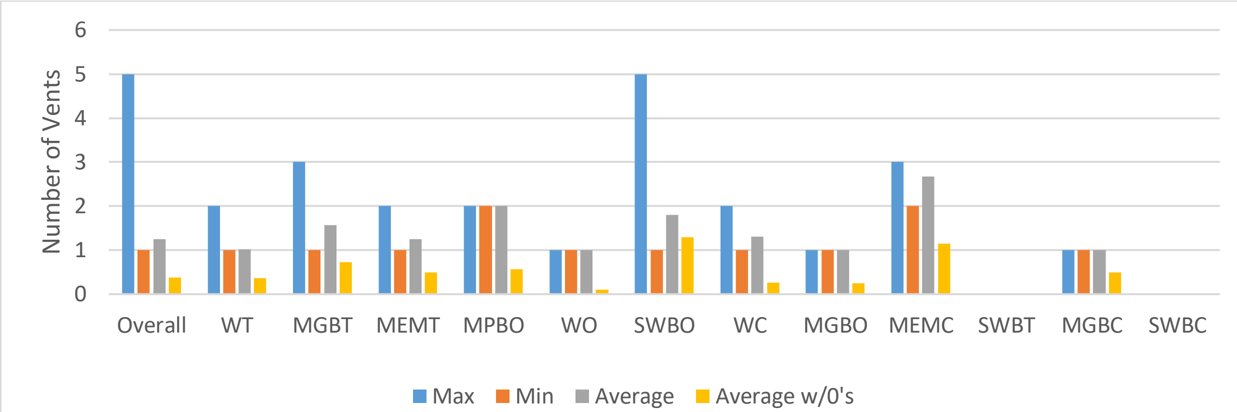


Figure 15: Number of Observed Vents

The source of vents is summarized by major equipment in Figure 16. Four major equipment types (Light Liquid and Water Production Tanks, Reciprocating Compressor, and Gas Flow Wellheads (Surface Casing Vents)) are responsible for ~94% of overall venting emissions with Tanks being the largest major equipment emitter (at 65% of total venting emissions, 25% of which were from Water Production Tanks). All other major equipment that perform regular venting that were captured during the survey did not contribute significantly to overall venting emissions. What is not reflected in this data are operations that release methane episodically unless an episodic release was occurring during the survey. Episodic methane venting emissions by nature are not continuous, and difficult to measure and quantify through surveys such as the one performed in this study as they are snapshots at a point in time, not continuous monitoring.

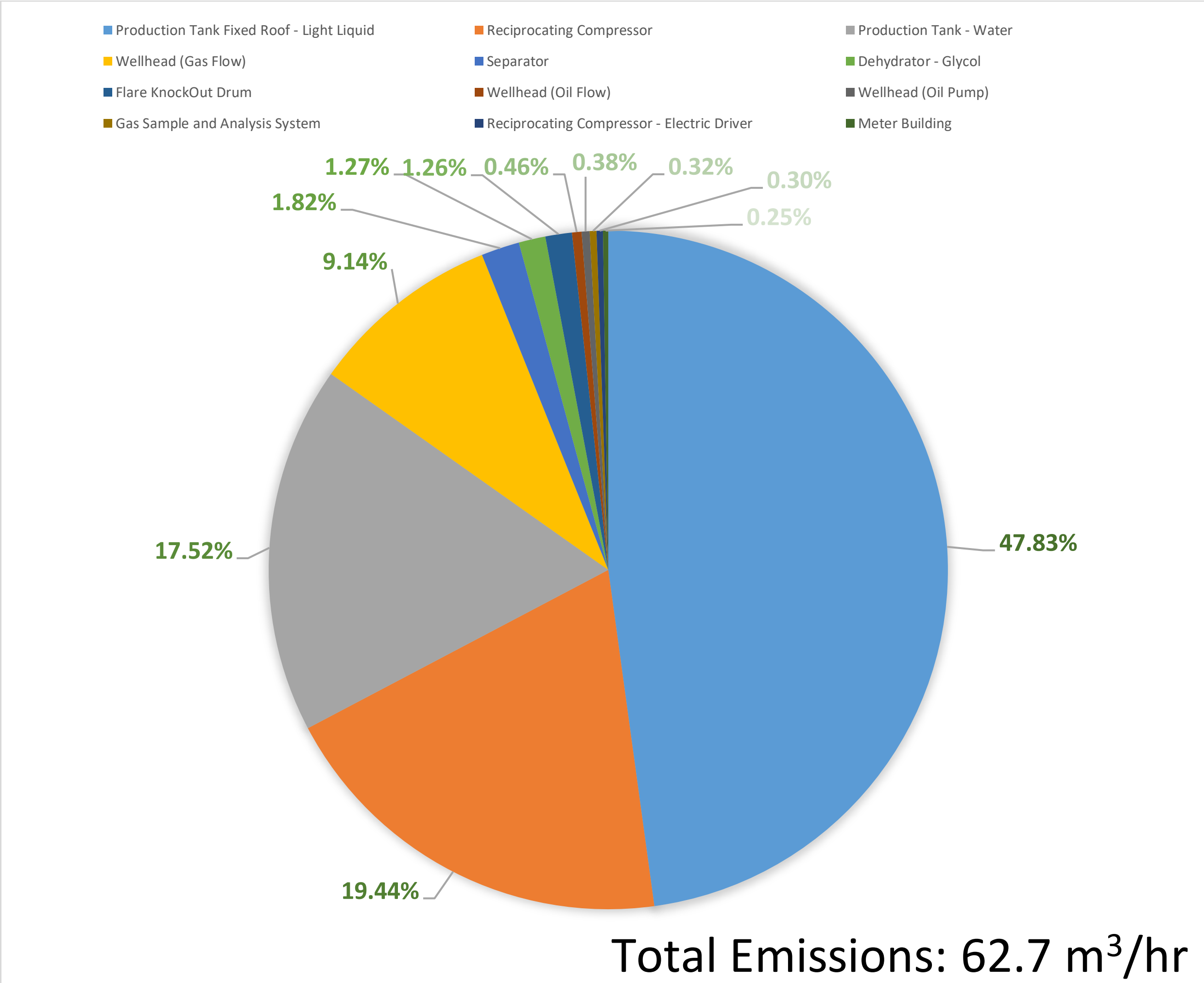


Figure 16: Venting Emissions by Major Equipment Source

1.2.5.2 Tank Venting

Tanks were one of the largest individual sources of emissions that were detected during the MEFS field survey, with a total of 12 vents and 12 leaks detected. 6 of these vents, from Light Liquid Tanks, accounted for nearly 48% of the total observed vented emissions across all sites, and the other 6 vents were observed from Produced Water Tanks. Venting from Produced Water Tanks was confirmed to be hydrocarbon and not steam, but gas compositions were not assessed during the study. CAPP (2005)[30] suggests negligible hydrocarbon emissions from Produced Water Tanks so further study may be required to determine or update gas composition from these sources. The summary of the tank venting and leaking is summarized in Table 25 and Table 26 below. The observed tank vents are uncontrolled and the observed tank fugitives

[30] A National Inventory of Greenhouse Gas (GHG), Criteria Air Contaminant (CAC) and Hydrogen Sulphide (H2S) Emissions by the Upstream Oil and Gas Industry, Volume 3 Methodology for Greenhouse Gases, CAPP, 2005 (Available at https://www.capp.ca/publications-and-statistics/publications/86223)

are from controlled tanks. Of the 12 leaks detected, 8 were from thief hatches, with 2 from PRV/PSV and 2 from connectors.

Table 25: Tank Venting Results

m^3/hour	Total Equipment Count	Number of Vents	Total Vent Rate	Average Vent Rate per Source	Average Vent Rate for Total Equipment Population
Production Tank Fixed Roof - Light Liquid	81	6	31.04	5.17	0.38
Production Tank - Water	90	6	11.37	1.90	0.13

Table 26: Tank Leaks Summary

m^3/hour	Total Equipment Count	Number of Leaks	Total Leak Rate	Average Leak Rate per Source	Average Leak Rate for Total Equipment Population
Production Tank Fixed Roof - Light Liquid	81	12	11.51	0.96	0.14

1.2.5.3 Compressor Seal Venting

There were 18 instances of compressor seal venting that were observed during the study. The vent rate and source of these vents are summarized in Table 27 and

Table 28 below. Table 27 presents the overall vent rate averages and median in m^3/hr of gas.

Table 28 presents the amount of each type of compressor at the site classifications, along with how many vents were observed to be tied to flare.

Table 27: Compressor Seal Vent Rate Results

	Component Service	Total Compressors	Total Compressor Seal Components	# of Vents	Total Vent Reate	Average Vent Rate (per Vent)	Average Vent Rate Per Compressor	Median Vent Rate (Of Sources)
Compressor Seal	Gas	69	215	18	12.68	0.68	0.17	0.17

Table 28: Compressor Count and Compressor Vent Controls by Site Classification

	Site Classification (Number of Sites Surveyed)												
Total Compressors (Compressors Tied into Flare) by Type	WT	WO	WC	SWBT	SWBO	SWBC	MPBO	MGBT	MGBO	MGBC	MEMT	MEMC	Total
Reciprocating Compressor	4				1		6(1)	10 (5)			22 (8)	9	52
Screw Compressor - Electric Driver							5 (1)	3			2		10
Reciprocating Compressor - Electric Driver							1	4 (1)				1 (1)	6
Screw Compressor				1									1

1.2.5.4 Dehydrator Vents

Only a single instance of dehydrator venting was captured during the MEFS field survey. Table 29 summarizes the results from Dehydrator venting. The composition of glycol dehydrator gas release is unknown and may include increased concentrations of non-methane gas. The single vent case component source was an OEL.

Table 29: Dehydrator Venting Summary

m^3/hour	Total Equipment Count	Vents	Total Vent Rate	Average Vent Rate per Source	Average Vent Rate over Total Equipment Population

Dehydrator - Glycol	29	1	0.825	0.825	0.028

1.3 Chapter 1 Summary

Upstream oil and gas wells and batteries in BC share certain characteristics with other jurisdictions, including the most common methane emission sources in pneumatic control instruments, chemical injection pumps, tanks and compressors. As has been found elsewhere, the distribution of methane emissions among BC operations is highly skewed, with small numbers of sources contributing a large proportion of total emissions and wide confidence intervals on average values.

For a variety of potential reasons, BC operations also exhibit particular unique characteristics including a significant population of non-emitting process control and chemical injection equipment. Routine venting does not appear to occur at most wells and batteries in BC.

Chapter 2: Comparison to Contemporary Studies

Comparing emissions across components and equipment between different studies is difficult for two main reasons. First, survey practices and operators use different definitions and categorization of components that are not standardized across studies. Second, source detection technologies exhibit significant performance variations based on weather conditions and operator expertise. Studies done with the same technology but under varying seasonal weather will exhibit different leak-size distributions.

Due to methodological similarities a comparison to Clearstone 2018 is more adjacent than some other studies. Total natural gas released from all sources in that study comprised 33% pneumatics, 28% from production tanks, 20% from equipment fugitives, and 16% from heavy oil well casing vents in Alberta. This compares with the results of this study corresponding to 66% from pneumatics, 15% from production tanks,[31] and 17% from other equipment fugitives. Note: the remaining emissions were from other sources (e.g. non-tank venting).

2.1.1 Estimated Pneumatic Venting Emissions

Figure 17 shows the device-level emissions in this study (red) compared to the Greenpath 2016[32] study (blue). While most vented emissions are similar, two components stand out – the pressure controller where BC has almost double the emissions of AB, and pump-related emissions where BC has 40% lower emissions than AB. In addition, many pneumatic device types in AB were assumed to emit "significantly lower" than 0.17 m^3/hr, while the BC data implies that these small sources can have non-trivial emissions (e.g., plunger lift controllers).

[31] 15% comprises 9% venting from light liquids tanks, 3% venting from produced water tanks, and 3% tank fugitives.
[32] Greenpath 2016 Alberta Fugitive and Vented Emissions Inventory Study, Greenpath Energy, 2016 (Available at https://www.aer.ca/documents/GreenPathAER%20Survey-Methane.pdf)

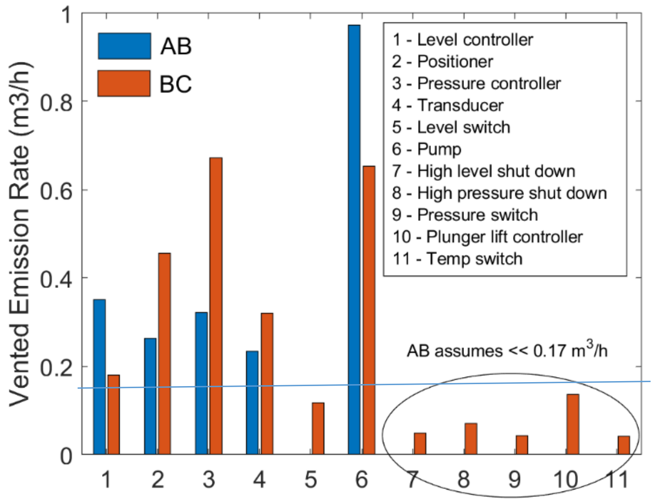


Figure 17: Comparison of vented emissions between this study (red) and Greenpath 2016 study in AB (blue).

2.1.2 Fugitive Emissions

Leaks or fugitive emissions exhibit varied behavior. Across all component types analyzed, BC emissions are uniformly lower than AB emissions. However, it should be noted that fugitive emissions that were unable to be measured directly were estimated, which can lead to significant discrepancies in total emissions measurements. This is mitigated to the extent possible by the fact that the same contractor (Greenpath Energy) conducted both surveys and employed the same estimation methodology.

Furthermore, the error bars for each component-level emissions source is large (2 – 3x the measured emissions) because of two reasons – (a) the sample size is typically small, and (b) total emissions are dominated by a few very large emitters, resulting in a larger upper bound on the estimates.

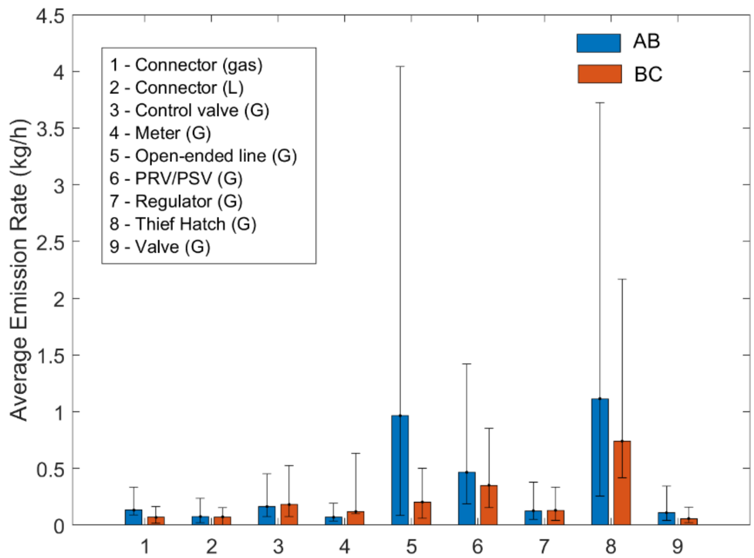


Figure 18: Comparison of fugitive emissions between this study (red) and Clearstone 2018 study in AB (blue).

2.1.3 Compressor Emissions

There have been many recent studies in the US and Canada that measured emissions associated with compressor stations. While some studies report emissions factors which typically represented population-averaged emissions, others report average emission rate from leaking compressors. Table 30 shows the population-averaged emissions factors comparison from four recent studies. It is important to note that although population averaged emissions factor in the US GHG inventory is similar to that observed during this field campaign, other peer-reviewed study published in the US often show significantly higher emissions (see for e.g., Mitchell et al.).[33] Further research is required to better understand the leak size distributions across compressor emissions.

Compressor emissions from this study are estimated at approximately the same value as EPA GHGI for small reciprocating compressors across a population of nearly 36,000 units.

Table 30: Population-Average Emissions Factor

Study	Region	Equipment type	Leak counts	Component Counts	Emissions Factor type	Emissions Factor (kg/h/source)
Clearstone	AB (2018)	RC		139	Population	0.206
Clearstone	AB (2018)	RC	27		Leaking	1.082
EPA GHGI	US (2016)	RC (small)		35930	Population	0.141
EPA GHGI	US (2016)	RC (large)		136	Population	8.099
Mitchell et al[33]	US (2015)	RC	34		Leaking	27.512
Greenpath	AB (2017)	RC		296	Population	2.459

[33] Mitchell et al. (2015) Environ. Sci. Technol. **49** 3219.

BC MEFS	**BC (2019)**	**RC[34]**		**69**	**Population**	**0.14**
BC MEFS	**BC (2019)**	**RC[34]**	**18**		**Leaking**	**0.40**

**RC = Reciprocating Compressors (rod packing)*

2.1.4 Pneumatic Demographics

Figure 19 below presents a comparison of the split between pneumatic device types between the Greenpath study performed in 2016 in Alberta and this survey in BC but excludes the BC pumps count. It is interesting to note that the ratios of each pneumatic device type are different in BC and AB, for example, there are more level controllers in the overall pneumatic device population compared to BC. In the BC study, pneumatic device types in Figure 19 excludes pressure switches (10%), level switches (4.6%), and other unidentified pneumatics (0.7%) as those were not included in Greenpath's 2016 pneumatics classification.

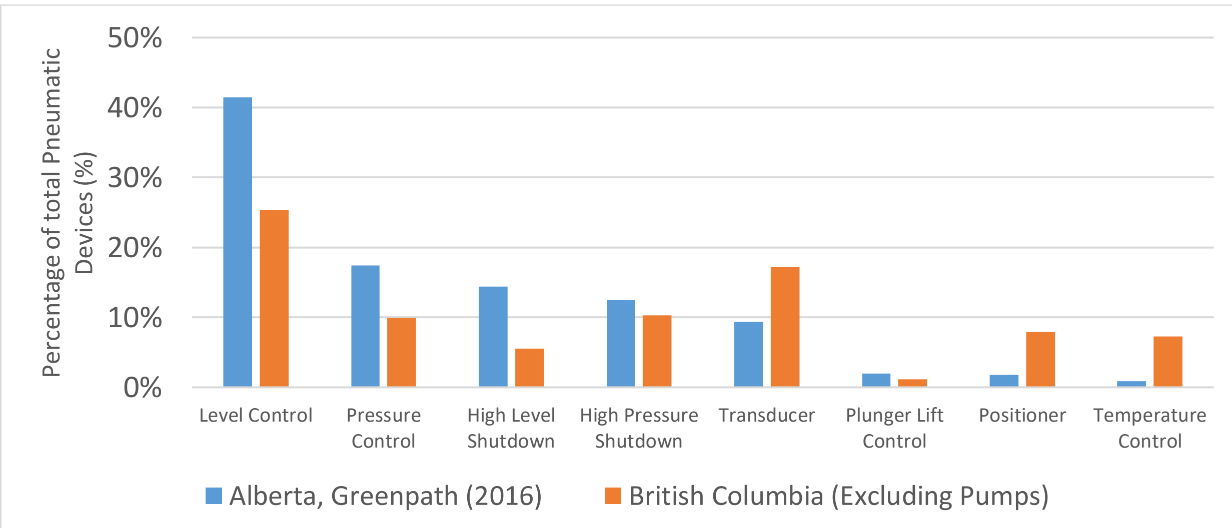


Figure 19: Pneumatic Device Type Ratio Comparison Between Alberta Greenpath Study and BC MEFS

2.2 Chapter 2 Summary

Direct comparison across studies with differing methodologies, timeframes, field teams, and other elements is often difficult. Due to methodological similarities a comparison to Clearstone 2018 is more adjacent than some other studies.

Relative to that study, pneumatic venting was estimated to represent a higher proportion of total venting in BC, despite the prevalence of non-emitting equipment, partly as a result of methodological differences (certain types of gas-driven pneumatic control instruments were assigned vent rates of zero in Clearstone 2018), and partly as a result of some a small number of extremely large emissions from surface casing vent flows and thief hatches. Overall the studies generally agree on the dominant emission sources in upstream oil and gas, with important differences.

[34] Size of compressors was not recorded, assumed to be biased towards smaller equipment since none of the sites surveyed were registered as compressor stations. Note average methane concentration assumed to be 86%.

Fugitive emissions are inherently difficult to compare due to large confidence intervals in most datasets, but again generally agrees across many component types.

Compressor emissions from this study were estimated at approximately the same value as EPA GHGI for small reciprocating compressors across a population of nearly 36,000 units.

Chapter 3: Fugitive and Episodic Emissions Management Practices

In Chapter 1, modeling parameters that could be determined from the field survey data were developed. Supplementing snapshot field observations with historical records was included in the study design in order to support the development and refinement of policy/scenario modeling parameters. Temporal variation and impacts to emission sources over time should be accounted for when parameters are developed. The modeling parameters for certain emission sources can have an explicit temporal component that considers emissions variation over time (e.g. months/years), which would not be observed by the snapshot exercise of field observation.

To obtain these data on longer term variations a voluntary Corporate Data Request (CDR) was prepared for the participating companies to provide historical fugitive emission management data, as well as other types of methane emission information that was not possible to observe while on-site. The data that were received included information on fugitive repair times, fugitive history, and other sources of methane emissions (including information on episodic emissions and emission control systems). This information supplemented the field observations, where applicable, in order to account for temporal variations in modeling parameter development.

The analytical approach largely follows the description in Section 1.1 Analytical Approach, in addition to the descriptions provided herein.

3.1 Leak Repair Times

A total of 11 CDR responses were received which covered 51 of the 266 locations surveyed in this study's survey. A histogram of repair times for leaks is presented in Figure 20. Not all facilities from the CDR included repair times, 12 sites, which represented repair intervals from a total of 36 repairs. The most common timeframe to perform a repair is within 16 days, with the average repair time of the reported facilities at 45 days. The data provided, while it offers insight into timeframe to perform repairs, may not be representative of broader industry practices due to a small sample size and limited information contextualizing the types of repairs required.

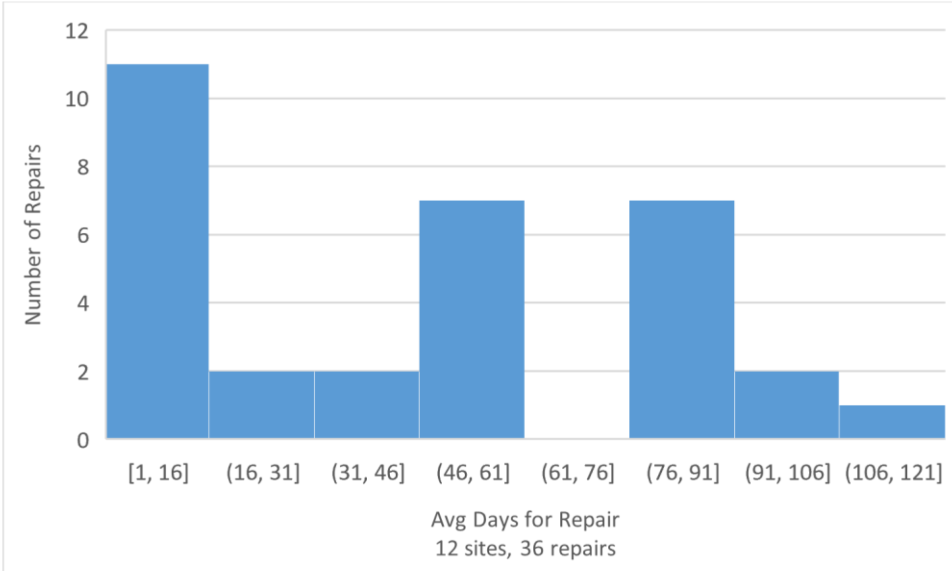


Figure 20: Histogram of Reported Repair Times from CDR

3.2 Leak Occurrence Rate

The leak occurrence rate was calculated based on the facilities that reported a 'last Fugitive Survey' in the CDR. The following equation was used to calculate the leak occurrence rate;

$$\frac{(L_{MEFS} - L_{LL})}{M_{MEFS-LL}}$$

Where,

L_{MEFS} = Number of leaks detected during the MEFS field survey

L_{LL} = Number of leaks detected and not repaired during the previous LDAR survey

$M_{MEFS\text{-}LL}$ = Months between the MEFS field survey and the previous LDAR survey

The results of the leak occurrence rate by facility is presented in Table 31 below. All leaker factors labelled as 'Negative' in Table 31 have a negative leaker factor because the non-repaired leaks from the previous LDAR survey is more than the number of leaks detected during the MEFS field survey. This likely reflects a limitation of the repair information provided. There are 4 instances where the leaker factor is not calculated, and the cell has been left blank. These 4 facilities either performed their "previous" LDAR survey after the MEFS field survey or reported the MEFS field survey as their last LDAR survey.

Table 31: Leak Occurrence Rate based on CDR Reported Facilities

Anonymous Identifier	Facility Type	Leaks from BC MEFS Study	Leaks Detected from CDR Responses	Leaks Repaired from CDR Responses	Leaks Not Repaired from CDR Responses	Months between Last LDAR and BC CAS Survey	Leaker Factor (leaks/month)
188	MPBO	0	0	0	0	2	Negative[35]
252	MPBO	7	2	0	2	23	0.22
55	MEMC	8	7	0	7	0	
125	WC	2	0	0	0	24	0.08
25	WC	3	0	0	0	23.5	0.13
17	MPBO	3	2	0	2	0.5	2.00
192	MEMT	3	1	0	1	21	0.10
111	MEMC	7	3	0	3	19	0.21
44	MEMT	11	17	0	17	9.5	Negative
72	WC	1	4	0	4	20	Negative
169	WC	0	0	0	0	23.5	Negative
102	MEMC	0	1	0	1	1	Negative
107	MEMT	2	4	4	0	17	0.12
152	MEMT	4	4	3	1	0	
14	MEMT	5	4	4	0	7	0.71
15	MEMT	11	7	0	7	1	4.00
69	MEMT	6	4	0	4	13	0.15
143	MGBT	1	2	2	0	9	0.11
145	MGBT	1	2	2	0	18	0.06
245	MEMT	1	4	0	4	23	Negative
71	MEMT	3	1	0	1	1	2.000
162	MGBT	2	4	3	1	0	
253	WC	0	0	0	0	25	Negative
80	WC	4	0	0	0	24	0.17
167	WC	2	0	0	0	26	0.08
86	WC	2	0	0	0	26	0.08
172	WC	3	1	0	1	24	0.08
88	WC	1	1	0	1	23	Negative
33	MGBO	0	7	7	0	7	Negative
224	MGBT	2	3	2	1	5	0.20
165	SWBO	2	7	4	3	7	Negative
178	MGBT	4	3	3	0	2	2.00
133	WT	0	6	1	5	21	Negative
186	WT	1	5	5	0	7	0.14
225	WC	0	0	0	0	25	Negative
45	WT	1	1	1	0	7	0.14
6	MGBC	0	1	0	1	22	Negative
42	SWBT	0	0	0	0	23.5	Negative
240	WT	0	1	1	0	17	Negative
103	WT	3	0	0	0	23	0.13
249	WT	0	2	2	0	7	Negative
223	WT	0	9	7	2	5	Negative
190	WT	0	1	0	1	18	Negative
251	WT	3	3	3	0	0	

Generally, component-specific detail was not provided but if we assume that all leaks from the previous LDAR survey to the MEFS survey are repaired, it is possible to calculate a leak occurrence rate based on

[35] Indicates likely repair data gap – number of unrepaired leaks from prior survey higher than observed number of leaks in subsequent (MEFS) survey

the equation below by component type, as those data are available from the MEFS survey.[36] A leak occurrence rate for PRV/PSV's was not able to be calculated as no leaks were detected during the MEFS field survey at the 51 facilities that provided CDR responses.

Equation 4,

$$Leak\ Occurence\ Rate_{by\ component\ type} = \frac{\sum_{i=1}^{N}\left(Cl_i - Cl_{i,t-1}\right)/M_i}{\sum_{i=1}^{N} Ct_i}$$

Where,

Cl_i = are the number of leaking components by type detected from the i[th] facility inspection,
$Cl_{i,t-1}$ = are the number leaks detected but not repaired from the inspection previous to the i[th] facility inspection. Note: $\left(Cl_i - Cl_{i,t-1}\right)$>=0,
M_i = is the number of months since the last inspection from the i[th] facility,
Ct_i = is the total number of components by type at the i[th] facility, and
N = is the total number of facilities for which field study data is available.

The leak occurrence factors by each component type are presented in Table 32 below. The calculation assumes that $Cl_{i,t-1}$ is equal to 0 (all previously detected repairs were repaired) to be able to calculate a leak occurrence rate with the available responses. The sample size is also provided for context.

*Table 32: Leak Occurrence Rate by Component Type**

	Thief Hatch	PRV/PSV	Valve	Connector	Excessive Pneumatic Venting (Previously OELs)
Leaker Factor (Leaks/Month)	0.0115	0	0.0013	0.0004	0.0064
Sample Size (# of leaks used for calculation)	4	0	16	67	5

**These results assume that all leaks from the previous LDAR survey to the MEFS survey are repaired and that all detected leaks during the MEFS survey are new.*

3.3 Other Sources and Controls

In Cap-Op's 2017 report *Other Sources of Methane Emissions in the Oil and Gas Sector* a number of less significant methane sources were identified.[37] The CDR included information on these, including episodic emissions such as depressure events and compressor gas starts, as well as information regarding emission control systems associated with these events. Very few responses provided information so these data are summarized at a very high level as follows:

- More compressor gas start systems were controlled than not
    - Control via tie-in to flare, air-start (instrument air) or electric drive
- Wide variability in number of compressor starts per year
- More dehydrators were controlled than not
    - Control via flare, vapor recovery unit

[36] This assumption is supported by the company reported information as it typically reported the same number of leaks detected as leaks repaired, when information was available, however these data represent a very small subset of the study sites.

[37] Other Sources of Methane Emissions in the Oil and Gas Sector, Cap-Op Energy, 2017. Available by request from ECCC or Cap-Op Energy.

- More depressure events were controlled than not
    - Control via flare
- Average reported volume per depressure event was less than 10 m^3/event

3.4 Chapter 3 Summary

Obtaining highly specific historical data on fugitive and episodic emissions is influenced by a number of factors including a wide variety of emission management practices and reporting systems. By matching voluntarily provided corporate historical data with field observations a high-level characterization of the performance of fugitive emissions management at specific sites can be understood over time. Understanding episodic emissions and the different ways they are being managed by companies provides an additional layer of context for time-series modeling.

Chapter 4: Long Term Methane Emission Drivers

Note: All results are based on discussions from the workshop participants as Cap-Op and DXD intentionally assumed an objective, observational role in the working discussions. Cap-Op and DXD input to the sessions was limited to clarification, facilitation and guidance.

4.1 Temporal State Definition

4.1.1 Distant Past

The distant past temporal state was defined as pre-2009 and, importantly, this was effectively prior to the current level of greenhouse gas reporting in British Columbia. Participants broadly viewed this period as the "single well pad era" and agreed that production in British Columbia was dominated by single-well oil and gas production. While some groups accounted for production in the 1980s and 1990s, others provided their experience from the 2000s. Less pipeline infrastructure was in place and conventional production (without hydraulic fracturing) was most common. This period was also characterized by appraisal and exploration of the natural fields in British Columbia (especially the Horn and Montney basins). While individual companies may have piloted certain methane abatement technologies and CAPP Best Management Practice for Fugitive Emissions Management (CAPP BMP)[38] was beginning to be used (around 2007), focused attention to methane management across industry was limited. Sour gas management and facilities design, not methane emissions awareness, drove conservation behaviour that may have otherwise been absent in sweet gas regions. Production was driven by economics and basic compliance with the regulations of the day. This was noted in slight contrast to current conditions, where more comprehensive consideration is also given to regulations, emissions, climate change and social factors that may have a future impact on operations. Participants agreed that the regulatory environment was very different than the one observed in today's production. Dry gas, not wet gas, was the dominant product and, relative to today, more field compression and less processing occurred. It was also noted that some drivers may have counter-balanced influence, for example the prevalence of single-well pads would drive up equipment to facilities ratios but lower numbers of processing facilities and gas plants in the field would drive ratios down.

[38] Best Management Practice for Fugitive Emissions Management, CAPP, 2007. Available at https://www.capp.ca/publications-and-statistics/publications/116116

4.1.2 Recent Past

The recent past temporal state was defined as the period from 2010 to 2015. This period was marked by a shift from dry gas to liquids rich gas and the development of the Montney. Horizontal drilling technology had significantly improved, and very little conventional drilling was occurring. This period, referred to as the "multi well pad era," also saw dramatic increases in the use of multi-well pads, driving down equipment to facility ratios. Pipeline infrastructure increased to meet development needs and Producers began to pilot programs and design infrastructure to drive efficiencies. In contrast to the distant past, this period saw that factors beyond economics had to be given consideration. Social issues, movements against hydraulic fracturing, environmental activism and climate change began to impact the industry. Leak Detection and Repair (LDAR) had been implemented at some large facilities and some producers had implemented full LDAR programs across their fleets, in part driven by CAPP BMP and other publications. This period was also volatile economically. By 2010/2011, the industry had begun to recover from the global economic crash in the late 2000s and by 2012, the industry in BC was seeing an increase in exploration and drilling. However, 2014 saw another economic downtown in the oil and gas industry of Western Canada that impacted BC producers. Opportunities surrounding coastal liquefied natural gas (LNG) facilities grew and contracted with the market; several proposed LNG projects extended into the current and future time periods.

4.1.3 Future

The future temporal state was defined as a post-methane regulation implementation scenario, between 2020 and 2030, where all producers would be operating to achieve compliance with applicable regulations, and that equivalency of provincial programs has been completed and approved. LNG and the potential growth of the industry associated with it dominates this period. In addition to being a driver for new assets, LNG development could bring legacy assets back online. Producers will continue to maximize the efficiency of multi-well pad design, further decoupling production and footprint. Liquids rich production and horizontal drilling practices are expected to continue, with even better horizontal drilling technology coming online. There is the potential that the Clean Fuel Standard (CFS) may drive the stabilization of domestic demand and the price of natural gas. As producers consistently show proactive compliance with the regulations, the focused interest that Non-Governmental Organizations (NGOs) and governments currently have on methane emissions from oil and gas operations may begin to ease. Additionally, as producers and regulators see full implementation of the regulations, year over year, there is the potential that LDAR requirements may decrease, as more data is available to inform efficient yet effective emissions reductions.

4.2 Assessment of Drivers

Results of the workshop were assessed for each modeling driver. Each group's assessment was plotted over time, showing their interpretation of the directionality and magnitude of change of these drivers for each temporal period.

Issues that make temporal forecasting difficult include acquisitions/sales, as well as change in ownership and working interest partners. In addition to making factors like equipment counts and prevalence of low bleed pneumatics (in other words, physical factors), changes in ownership also generally result in "legacy staff" no longer being associated with sites and facilities. For example, while field assets may be acquired, it is not always the case that the operators working on those sites go with the sale.

4.2.1 Equipment to Facility Ratios

Participants identified multiple factors that impact equipment to facility ratios:

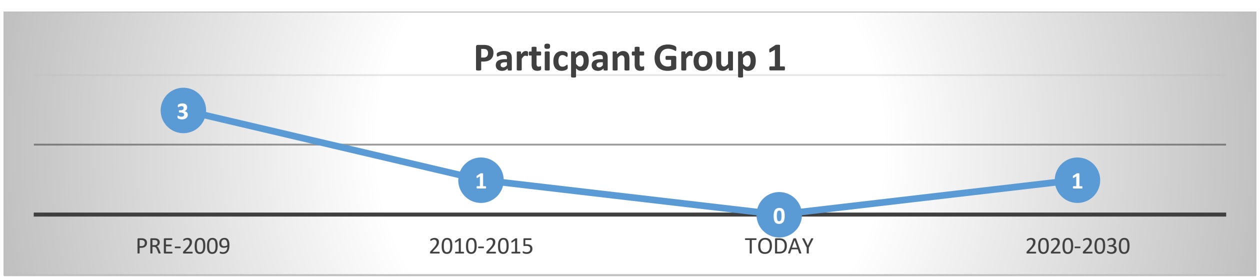
- Level of gas processing required, related to dry gas vs. wet gas;
- Prevalence of gas plant facilities;
- Trend from single-well pads in the past to multi-well pads (i.e., concentration of equipment and/or prevalence of larger pad-level equipment);
- Amount of compression occurring in the field; and
- Fundamentally different equipment for different products (sweet or sour; dry gas or wet gas).

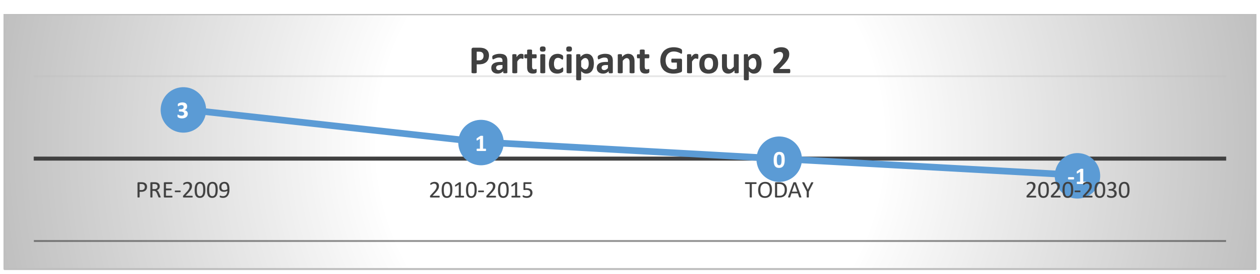
Distant Past: some characteristics of pre-2009 operations would translate to more distinct pieces of equipment, and some would translate to fewer. In general, the consensus was that the dominance of single-well pads meant more equipment in the field, per well pad.

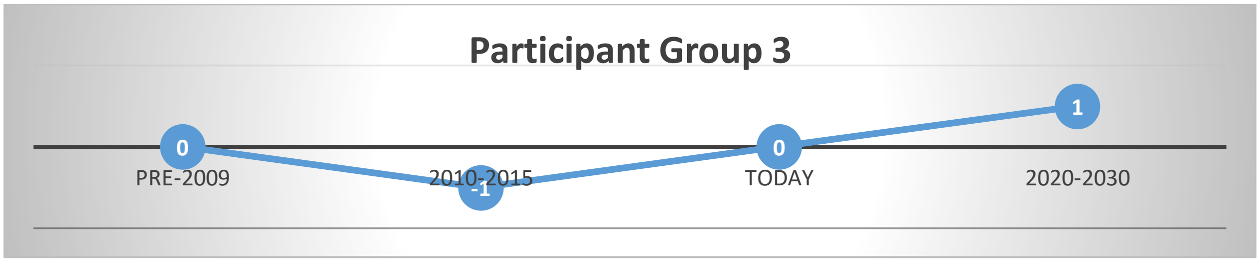
Recent Past: this period saw a concentration of equipment on smaller footprints with the shift to multi-well pads and industry participants generally felt that equipment to facility ratios were lower than the pre-2009 period. However, in general, equipment to facility ratios were higher relative to current operations with a shift to wet gas from dry gas, as field processing facilities became more prevalent.

Future: future operations will continue to see a trend towards centralized facilities, which will result in more and larger equipment per facility, but fewer facilities. If growth is seen due to LNG, absolute amounts of equipment in the field will increase. Electrification (dual feed) will require more processing and abatement equipment. Increased processing and fractionation will result in increased equipment, as more oil and water are handled. On a per-well basis, amount of equipment will decrease; however, more intense processing will result in larger equipment and likely higher equipment ratios.

Workshop consensus on directionality and magnitude of change in the future: ↑ *(1)*







4.2.2 LDAR Inspection Frequency

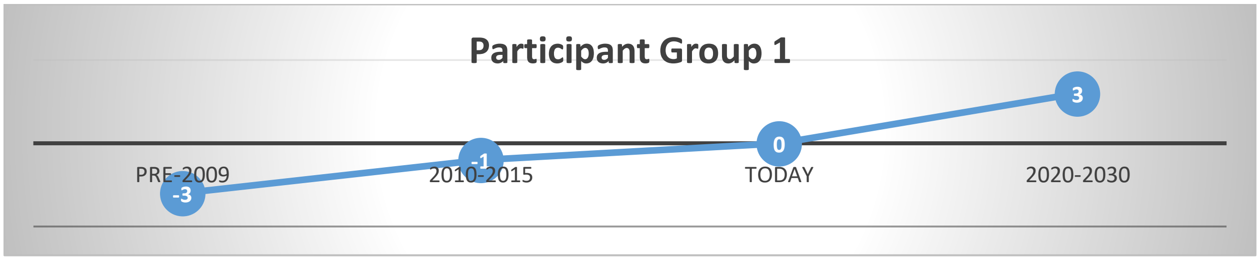
Broadly, and with a high degree of consensus, implementation of LDAR programs was lower in the past than today and will be higher in the future than currently.

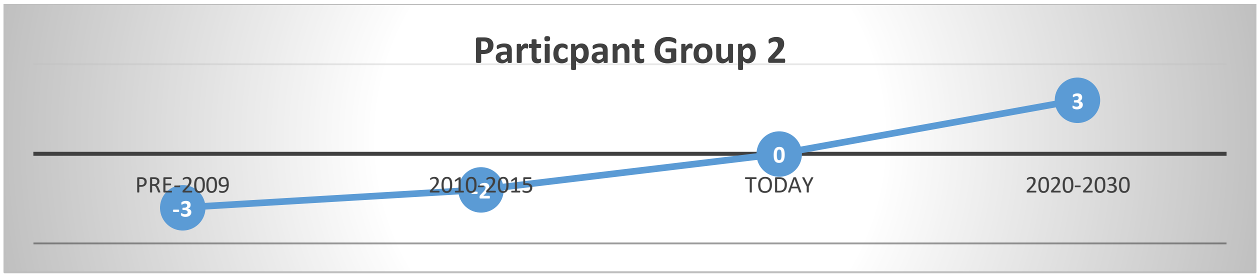
Distant Past: effectively no LDAR programs were in place. CAPP published the Best Management Practice for Fugitive Emissions in 2007 with implementation beginning in the following years, so LDAR guidance and definitions had not yet achieved wide awareness.

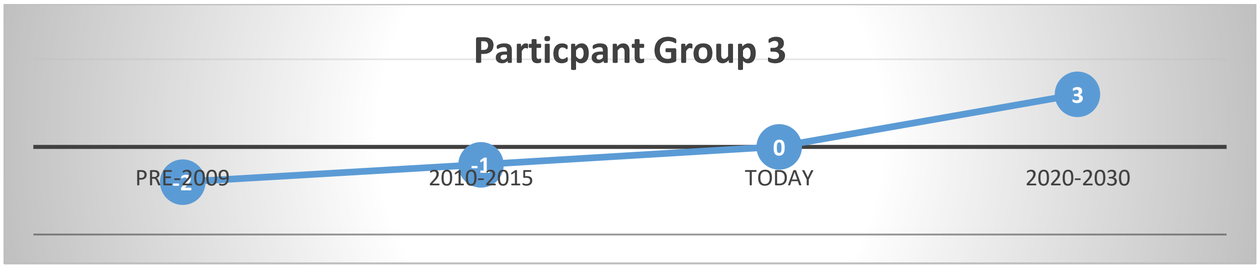
Recent Past: LDAR implementation varies with each Producer but was generally lower than currently. Risk-based LDAR was conducted for gas plants and larger facilities, but not individual well sites. The guidance in BMP was not prescriptive or required by regulation, and some Producers conducted no LDAR.

Future: implementation of the regulations will result in an increase in LDAR programs. Mandatory LDAR will drive the development of cost-effective emissions detection programs. Following implementation of regulations for 2 – 5 years, a decrease in frequency may be observed as regulations accommodate and approve alternative LDAR programs. Despite a reduction in frequency, emission reductions will remain stable.

Workshop consensus on directionality and magnitude of change in the future: ↑↑↑ *(3)*







4.2.3 Prevalence of High Bleed Pneumatics

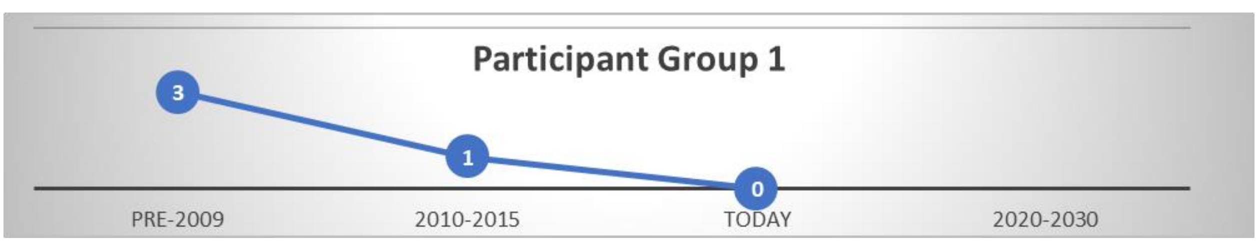
The prevalence of high bleed pneumatics was much higher in the distant past relative to current operations, and Participants were aligned on this model driver.

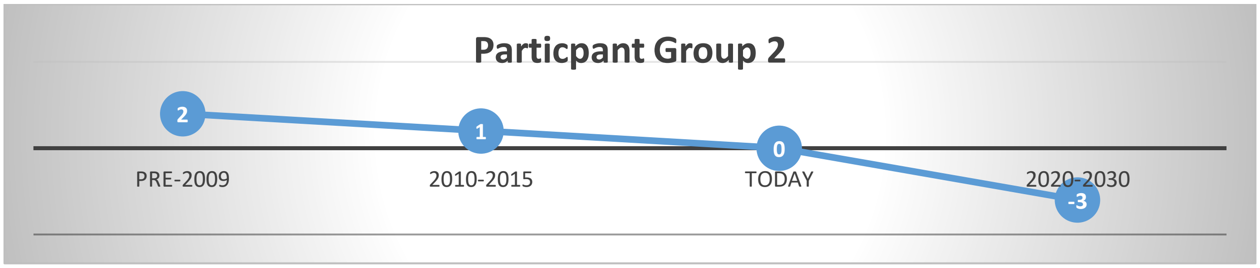
Distant Past: far more high bleed pneumatics were in operation than current practices, as they were cost effective and no regulation in place to limit their use. In a number of applications, low-bleed pneumatics were not commercially available. However, some participants noted that in the past, more sour gas was being produced, and, due to safety concerns, sour production is often no-bleed; this consideration shifted one group's rating from a magnitude of 3 to 2.

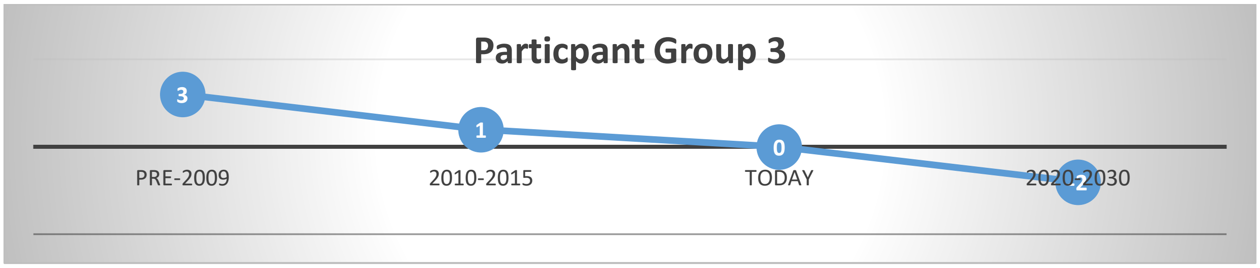
Recent Past: use of high bleed pneumatics in recent years had decreased as new builds began to include low bleed pneumatics and energy efficient programs/pilots were implemented. Retro-fits were not yet common. One market-dominant supplier of control instruments began manufacturing high-quality low bleed pneumatics, which became increasingly cost effective, and towards the end of the time period some high-bleed models were phased out entirely.

Future: once the regulations have been implemented, only certain legacy high bleed pneumatics will be in operation. The absolute magnitude of the reduction of high bleed use depends on any given producer's inventory. For producers with low numbers of high bleed pneumatics, the absolute magnitude will be small but the relative magnitude will approach 100%. Participant Group 1 intentionally left this blank but discussed the context of their answer with the group.

Workshop consensus on directionality and magnitude of change in the future: ↓↓↓ *(-3)*







4.2.4 Prevalence of Methane Mitigation Technologies

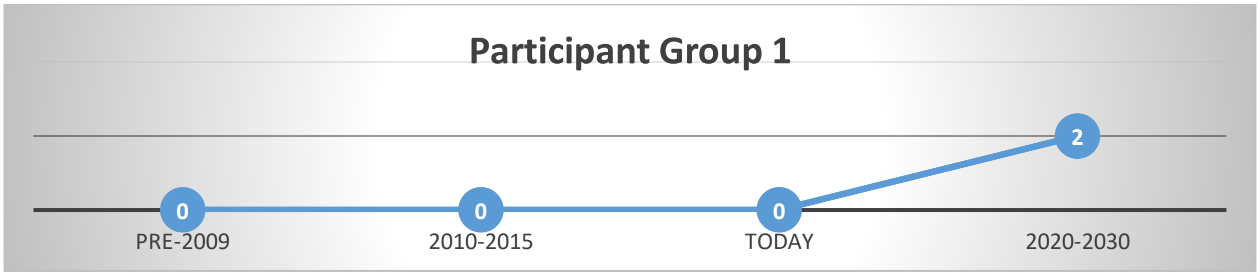
Broadly, there was good consensus that focus on methane mitigation has generally increased over time.

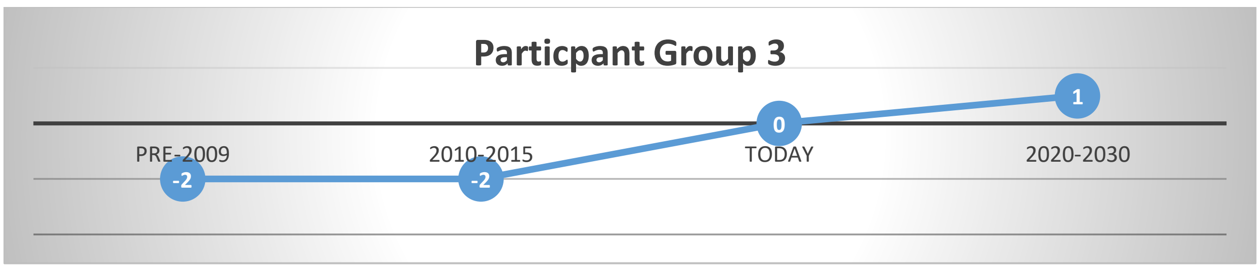
Distant Past: Generally, less mitigation was conducted than currently, and flaring was more prevalent. Less vapour recovery occurred than in current operations, and commercially available technologies were more limited.

Recent Past: increasingly, instrument air devices were being used and vapour recovery units were installed. Flaring and venting were both more prevalent relative to current operations. Technologies like VRUs and incinerators were not cost effective.

Future: Implementation of the regulations will result in an increase in mitigation and may also drive the development of more efficient or cost-effective technologies. Participants expect an increased use of vapour recovery units (VRUs), vent gas capture (for conservation or destruction) and enclosed combustors. However, given that many technologies are currently already in use on some facilities, the magnitude of change will not be 3.

Workshop consensus on directionality and magnitude of change in the future: ↑↑ *(2)*





4.2.5 Level of Preventative Maintenance

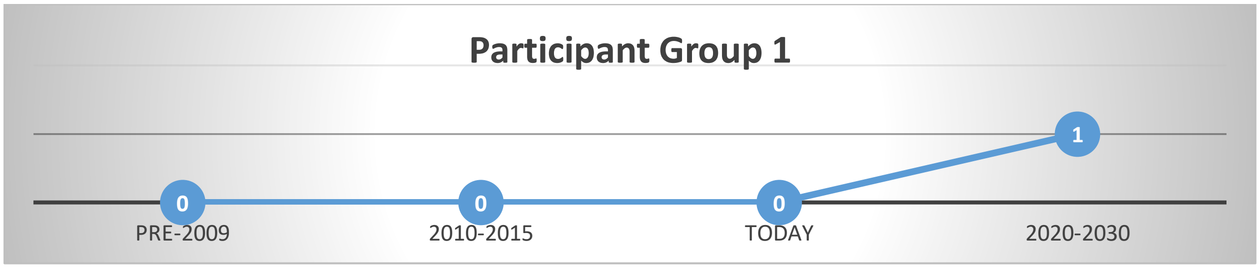
Participants identified that the level of preventative maintenance any given Producer achieves will not likely change over time as it is typically driven by things like safety as opposed to emissions. Preventative maintenance will vary from Producer to Producer, but any given Producers maintenance program will generally remain constant over time. Regular turnarounds have always occurred and will continue, for a variety of reasons unrelated to methane emission reductions.

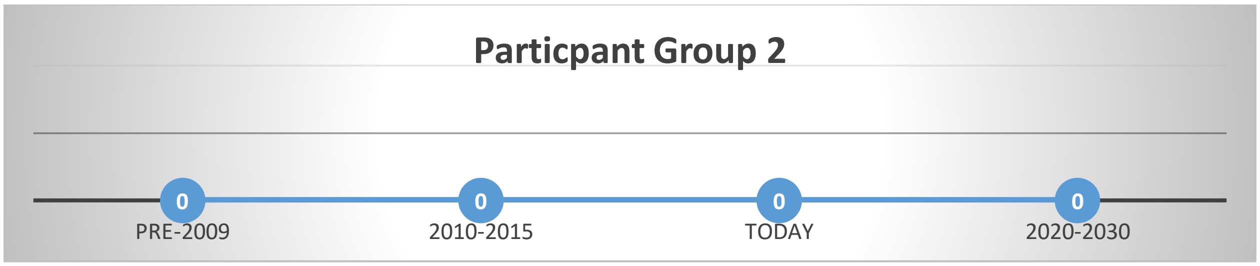
Distant Past: no change.

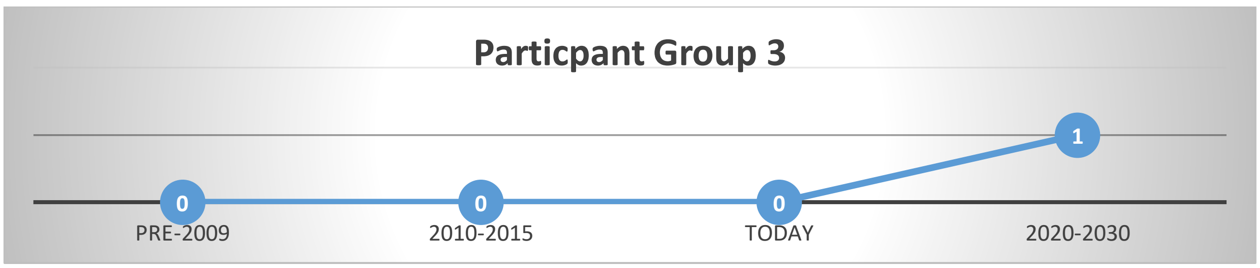
Recent Past: no change.

Future: Only within the context of the future did Participants anticipate a change in preventative maintenance programs. As new technologies are brought in to service a growing industry, preventative maintenance programs may increase in magnitude. Additionally, mandatory LDAR may be an incentive for Producers to implement regular maintenance in advance of detection surveys. The use of big data management and analytics was seen as a potential shift that would create more efficient preventative maintenance.

Workshop consensus on directionality and magnitude of change in the future: ↑ *(1)*







4.2.6 Prevalence of Non-Emitting Pneumatic Devices

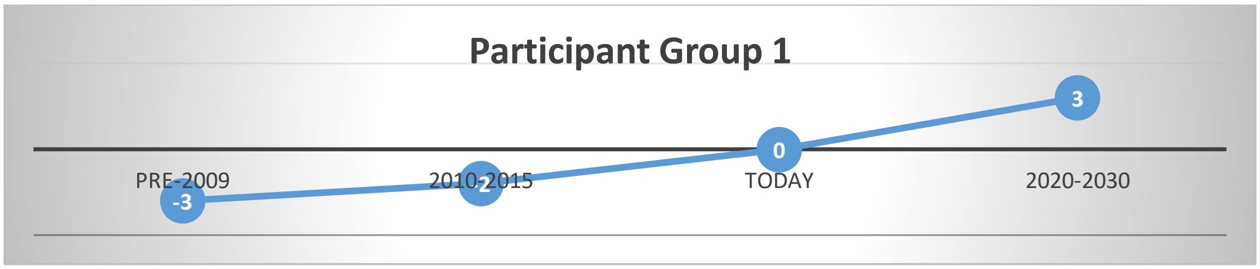
There was broad consensus in the workshop that the prevalence of non-emitting pneumatic devices increases through time, although magnitude of change can depend on many factors, including operations of individual Producers.

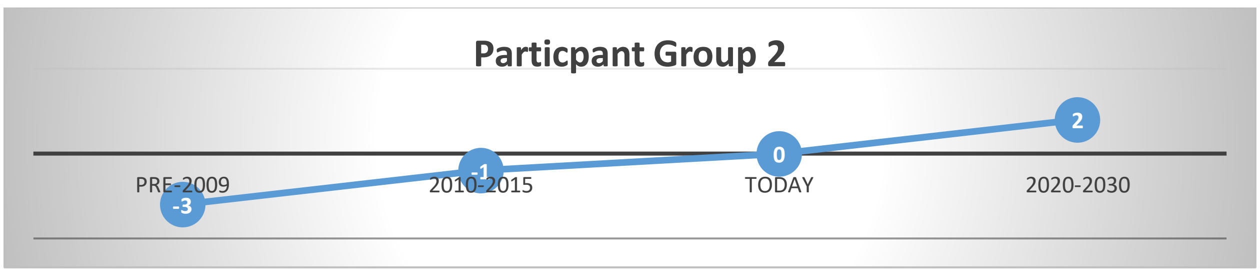
Distant Past: Significantly fewer non-emitting pneumatic devices were in operation pre-2009. Some Participant Groups indicated that, generally, non-emitting pneumatics were not in operation at all.

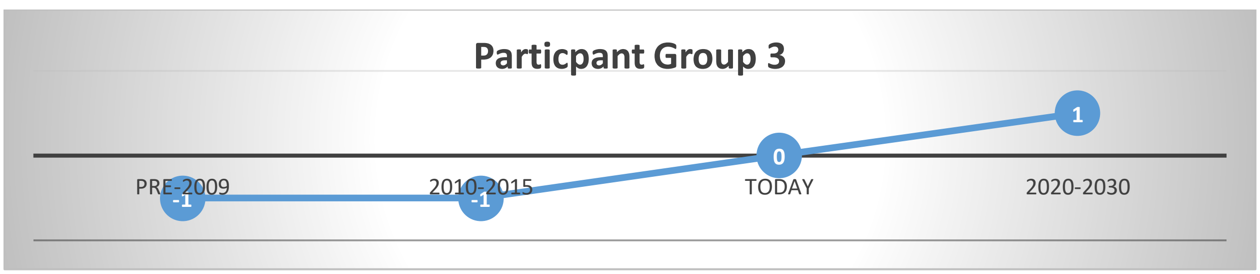
Recent Past: Over this period, well electrification projects became more prevalent, as did solar-powered devices and other remote power options such as thermoelectric generators.

Future: Most new builds will have non-emitting pneumatics. Having access to cost-competitive electricity from the grid is a significant consideration in increasing non-emitting pneumatics. Assuming that by 2022, pneumatics will be switched out, this driver will only experience a small magnitude increase as new technologies come online. Most new facilities will be non-emitting in their control and chemical injection systems, equivalent to a magnitude of 3 decrease; however, legacy facilities with some emitting pneumatic devices will continue to exist resulting in a magnitude of 2 decrease.

Workshop consensus on directionality and magnitude of change in the future: ↑↑ *(2)*







4.3 Potential for Incentivization

In closing the afternoon, participants were individually asked to provide general opinions on potential types of future market conditions or incentives that may drive implementation or a reduction technology or method sooner than the implementation of regulations, or to a magnitude that goes beyond what is required for compliance.

Electricity

- Collaboration between Producers and various levels of government to get Producers access to cost-competitive electricity; and
- Access to cost-competitive electricity from the grid is a key component of success and growth in the BC fields.

Incentives

- Offer carbon offsets as an incentive;
- Use programming structures already utilized by other programs, such as the Clean Infrastructure Royalty Credit Program;
- Expand the flexibility of current and future incentives to allow for the combination of different incentives programs to drive increase in participation;
- Offer incentives for condensing wells to superpads (lower footprint);
- Offer incentives for research and development that will drive lower production costs; and
- Offer incentives for early adopters of technology or programs.

4.4 Chapter 4 Summary

Three temporal states – distant past, recent past, and future – were interrogated across six specific focus areas in terms of the direction and relative magnitude of change from the "present" observed in the field study. The workshop leveraged industry experience to guide subjective changes to modeling parameters over different time periods, including forecasting and backcasting of methane emissions in British Columbia.

Broad agreement, especially with historical time periods, was achieved within the workshop in terms of defining a narrative of oil and gas production in the province and defining a potential future scenario. Assessment of methane emission modeling drivers was evaluated from a variety of perspectives, and insights into key drivers that might influence parameters of interest for time-series modelling was determined.

Closing

The British Columbia Methane Emissions Field Study incorporated a broad scope of field data, corporate data, and temporal trends in order to inform time-series modeling of methane emissions in British Columbia. The development of BC-specific methane emissions parameters can also improve understanding of the characteristics that make the province unique, those which are consistent with other jurisdictions, and can elicit the next round of questions to be answered for further improvement.

Appendix A: Data Tables

See supplemental attachment.

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