British Columbia Top-down Survey and Root Cause Analysis

Derivation of a Measurement-Based Upstream Oil & Gas Methane Inventory for 2021

Presentation to BC MERC, March 11, 2022

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Creation of a Robust Measurement-Based Methane Inventory

- Central goal of BC OGRIS funded project with several important tasks:
  1. Upfront planning
     - Aerial survey design to enable a robust inventory
  2. Aerial survey using Bridger Photonics Gas Mapping LiDAR (GML)
  3. Algorithmic quantification of individual source emission rates
     - Combine multi-pass and multi-flight GML data
  4. Attribution of detected sources to Petrinex facilities and to major equipment types
     - Manual analysis of pass-by-pass aerial imagery, plot plans, facility volumetric reporting & production data, and ground survey notes
  5. In-field controlled release tests (critical leveraging of parallel work with NRCan)
     - Revised probability of detection functions describing GML sensitivity limits
  6. Large-scale controlled release tests
     - Semi-blinded tests to quantify accuracy of GML at relevant source rates

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Creation of a Robust Measurement-Based Methane Inventory

- Central goal of BC OGRIS funded project with several important tasks (***continued***):
  7. Monte Carlo analysis to quantify GML measurement uncertainties
     - Contribution of pass-by-pass measurement uncertainties to final inventory
  8. Mirror-Match Bootstrap analysis to quantify sample size uncertainties
     - Contribution of sample size effects to uncertainty of final inventory
  9. Inventory estimate of unmeasured non-pneumatic sources
     - Apply updated GML sensitivity data to previous OGI survey data for BC in Monte Carlo procedure
  10. Inventory estimate of unmeasured normally operating pneumatics
      - Additional analysis of ground data and scenarios bounding potential detectability of pneumatics
  11. Creation of a robust 2021 methane inventory
      - Additional scenarios considering different possible counts of facilities and wells
  12. Initial analysis and implications of inventory
      - Sources driving emissions, variations among key facility types, potential implications for regulation and mitigation, remaining knowledge gaps, next steps

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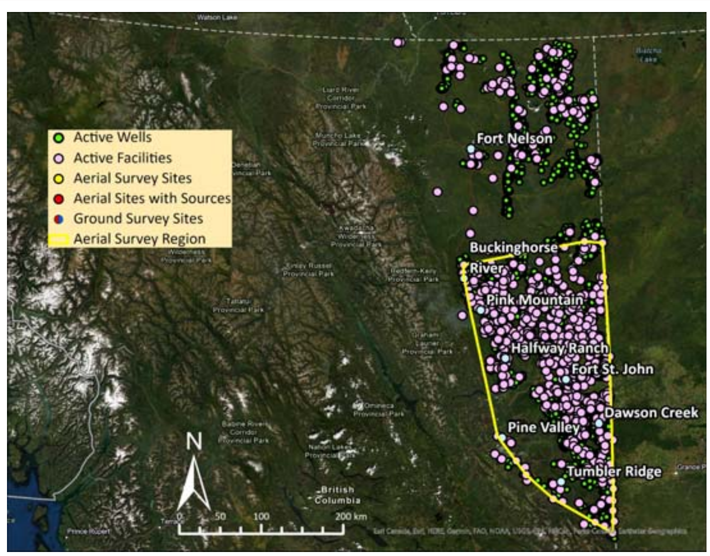
1. Aerial Survey Design

- ~10324 active wells
- ~1244 active facility IDs
- Initial random selection of sample constrained to/by:
  - Maintaining representativeness by subtype
  - Geographic constraints for feasibility of ground follow-up
  - Availability of imagery to define polygons and guide plane
  - Requirement to include sites from 2018/2019 surveys
  - Limited budget for aerial + ground work + analysis



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1. Survey Design

- Key Data Sources during planning:
  - BC Active facilities list as of June 28, 2021
  - Satellite imagery from ArcGIS, World imagery, and Google maps/earth
  - Subscription facility and infrastructure data from GDM Pipelines
  - Well activity data (linking UWI with license files, reporting facilities, etc.)
  - Petrinex Volumetric reporting for September and October 2021
  - Collaboration and input from BCOGC
    - Sort out inconsistencies and attempt to verify active status
    - Especially important for Compressor Stations which are non-reporting entities in Petrinex
  - Maximize sample to enable creation of a robust inventory, stratified by subtype

1. Survey Design

- Multiple challenges to work through:
  - Count data quality
  - Location limits (DLS/LSD and NTS)
  - Well surface locations and identification of offsite wells
  - Non-reporting facilities (i.e., compressor stations)
  - Confidential wells
  - Missing or out of date satellite imagery, etc., etc.,
  - Time!
    - Contract signed Sept. 10; plane in air on Sept. 11

Facility Counts: Data Challenges & Limitations

Facility Class	Facility Sub-Type	Sub-Type Name	"Active" in BC Public Facility List		Appearing in Petrinex			Included within Aerial Survey		
			June 28, 2021 (Planning Phase)	Nov. 17, 2021	Active during Aug., Sept., or Oct. 2021	Active during Oct. 2021	Active during Oct. 2021 – excl. "SHUTIN"	At Planning Phase (based on June 2021 counts)	Active in Petrinex in Sept. 2021	Active in Petrinex in Sept. 2021 excl. "SHUTIN"
Oil Bty.	311	Crude Oil Single-Well Battery	60	58	59	58	52	50 (83.3%)	48 (82.8%)	46 (88.5%)
	321	Crude Oil Multiwell Group Battery	6	5	5	5	3	3 (50.%)	3 (60.%)	3 (100.%)
	322	Crude Oil Multiwell Proration battery	36	35	35	35	35	31 (86.1%)	31 (88.6%)	29 (82.9%)
Gas Bty.	351	Gas Single Well Battery	29	28	29	28	22	22 (75.9%)	21 (75.%)	20 (90.9%)
	361	Gas Multiwell Group Battery	77	79	79	79	68	54 (70.1%)	54 (68.4%)	50 (73.5%)
	362	Gas Multiwell Effluent Measurement Battery	142	141	141	140	135	113 (79.6%)	113 (80.7%)	111 (82.2%)
O/G Bty.	393	Mixed Oil and Gas Battery	19	17	17	16	16	16 (84.2%)	16 (100.%)	16 (100.%)
Temp. Bty.	371	Gas Test Battery	4	3	2	2	2	1 (25.%)	1 (50.%)	1 (50.%)
	381	Drilling and Completing	2	2	1	1	1	1 (50.%)	1 (100.%)	1 (100.%)
Water	395	Water Hub Battery	33	33	34	34	33	22 (66.7%)	22 (64.7%)	22 (66.7%)
	901	Water Source	11	11	4	3	3	6 (54.5%)	1 (33.3%)	1 (33.3%)
	902	Water Source Battery	8	7	7	7	6	4 (50.%)	4 (57.1%)	4 (66.7%)

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Gas Plant	401	Gas Plant Sweet	26	25	25	25	25	21 (80.8%)	21 (84.%)	21 (84.%)
	402	Gas Plant Acid Gas Flaring < 1t/d Sulphur	23	23	23	23	22	19 (82.6%)	19 (82.6%)	18 (81.8%)
	403	Gas Plant Acid Gas Flaring > 1t/d Sulphur	4	4	4	4	4	2 (50.%)	2 (50.%)	2 (50.%)
	404	Gas Plant Acid Gas Injection	4	4	4	4	4	3 (75.%)	3 (75.%)	3 (75.%)
	405	Gas Plant Sulphur Recovery	4	4	4	4	4	3 (75.%)	3 (75.%)	3 (75.%)
	407	Gas Plant Fractionation	1	1	1	1	1	0/1	0/1	0/1
LNG Plant	451	LNG Plant	5	5	5	5	5	1 (20.%)	1 (20.%)	1 (20.%)
Injection	501	Enhanced Recovery Scheme	28	28	28	27	21	23 (82.1%)	23 (85.2%)	17 (81.%)
Disposal	503	Disposal	67	69	68	68	57	40 (59.7%)	40 (58.8%)	35 (61.4%)
	504	Acid Gas Disposal	7	7	7	7	7	6 (85.7%)	6 (85.7%)	6 (85.7%)
Storage	505	Underground Gas Storage	2	2	2	2	1	2 (100.%)	2 (100.%)	2 (200.%)
Compressor	601	Compressor Station	279	254	254	254	254	45 (16.1%)	45 (17.7%)	45 (17.7%)
Gathering	621	Gas Gathering System	135	139	140	139	105	92 (68.1%)	92 (66.2%)	73 (69.5%)
Treating	611	Custom Treating Facility	5	5	5	5	4	5 (100.%)	5 (100.%)	4 (100.%)

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Meter Station	631	Field Receipt Meter Station	66	69	57	57	57	39 (59.1%)	33 (57.9%)	33 (57.9%)
	632	Interconnect Receipt Meter Station	52	52	15	14	14	18 (34.6%)	5 (35.7%)	5 (35.7%)
	637	NEB Reg. Field Receipt Meter Station	56	56	12	12	12	46 (82.1%)	8 (66.7%)	8 (66.7%)
	638	NEB Reg. Interconnect Receipt Meter Station	10	10	8	8	8	6 (60.%)	5 (62.5%)	5 (62.5%)
Pipeline	204	Gas Transporter	2	3	3	3	3	1 (50.%)	1 (33.3%)	1 (33.3%)
	207	Oil Pipeline	1	5	5	5	4	0/1	0/5	0/4
	208	NGL Pipeline	0	1	1	1	1	0/0	0/1	0/1
	209	NEB Regulated Pipeline	3	3	1	1	1	2 (66.7%)	0/1	0/1
Terminal	671	Tank Farm Loading / Unloading Terminal	2	2	2	2	2	1 (50.%)	1 (50.%)	1 (50.%)
	672	NEB Regulated Terminal	1	1	0	0	0	0/1	0/0	0/0
	673	Third Party Tank Farm Load / Unload Term.	22	21	22	21	12	11 (50.%)	11 (52.4%)	8 (66.7%)
	675	Railcar Loading / Unloading Terminal	1	1	1	1	0	0/1	0/1	0/0
	676	NGL Hub Terminal	1	1	1	1	1	1 (100.%)	1 (100.%)	1 (100.%)
Waste	701	Surface Waste Facility	10	10	10	10	10	8 (80.%)	8 (80.%)	8 (80.%)
Total			**1244**	**1224**	**1121**	**1112**	**1015**	**718 (57.7%)**	**650 (58.5%)**	**604 (59.5%)**

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Well Counts: Data Challenges & Limitations

	"Active" in BC Public List	Linked with Active Facilities in Petrinex				Included within Aerial Survey		
Bore Fluid	Well Surf ACTIVE (June 28, 2021)	Well Surface Active in Petrinex Oct. 2021 (WITH Shutin)	Well Surface Active in Petrinex Oct. 2021 (No Shutin)	(OFFSITE) Well Surface in Petrinex Oct. 2021 (WITH Shutin)	(OFFSITE) Well Surface in Petrinex Oct. 2021 (NO Shutin)	Well Surface ACTIVE (June 28, 2021)	(OFFSITE) Well Surface in Petrinex Sept. 2021 (WITH ShutIn)	(OFFSITE) Well Surface in Petrinex Sept. 2021 (NO ShutIn)
AGAS	9	9	8	7	6	4 (44.4%)	2 (28.6%)	1 (16.7%)
GAS	8261	8101	7270	7920	7107	865 (10.5%)	721 (9.1%)	647 (9.1%)
MGAS	710	705	662	702	659	23 (3.2%)	21 (3.%)	21 (3.2%)
MOG	4	2	2	1	1	1 (25.%)	0/1	0/1
MOIL	174	174	151	174	151	0/174	0/174	0/151
OIL	675	619	583	551	521	81 (12.%)	28 (5.1%)	28 (5.4%)
SOLV	0	0	0	0	0	0/0	0/0	0/0
UND	0	3	3	3	3	0/0	3 (100.%)	3 (100.%)
WATR	388	365	316	322	281	30 (7.7%)	6 (1.9%)	5 (1.8%)
XXXX-Gas	94	unk.	unk.	unk.	unk.	unk.	unk.	unk.
XXXX-Oil	9	unk.	unk.	unk.	unk.	unk.	unk.	unk.
Total	**10324**	**9978**	**8995**	**9680**	**8729**	**1004 (9.7%)**	**781 (8.1%)**	**705 (8.1%)**

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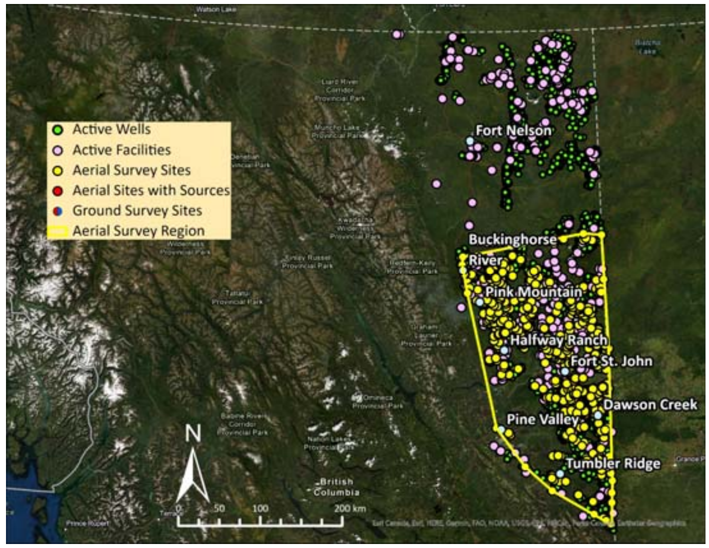
2021 British Columbia Top-down Survey and Root Cause Analysis

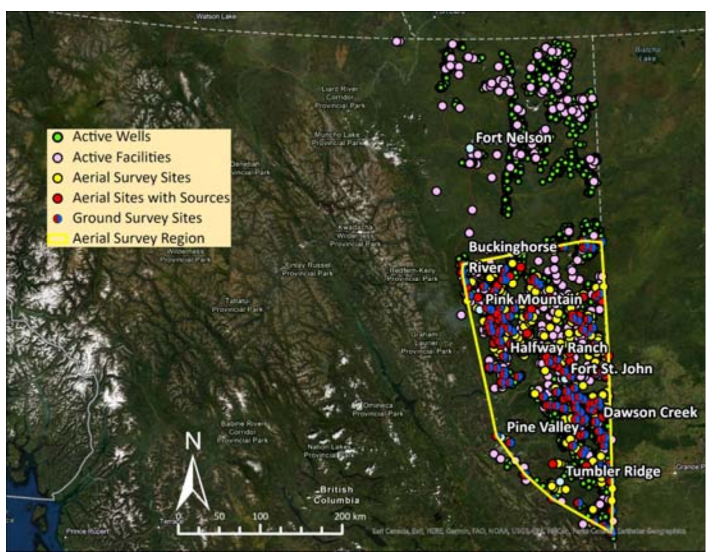
- ~10324 active wells
- ~1244 active facility IDs
- Sample of 508 ***sites*** chosen:
  - 718 active Petrinex IDs
  - 1004 active wells
  - Distribution of subtypes representative of province
  - Includes 137 still active sites from prior 2018/2019 surveys



2021 British Columbia Top-down Survey and Root Cause Analysis

Within sample of 508 sites:

- Final processed data from Bridger contained 527 quantified sources at 184 sites
  - 16 additional sources detected but not quantified for 543 total final detections
  - Four additional sites with unquantified plumes
- Ground team sent to inspect 227 sources
  - Included 195 identified as final sources by Bridger at 75 sites

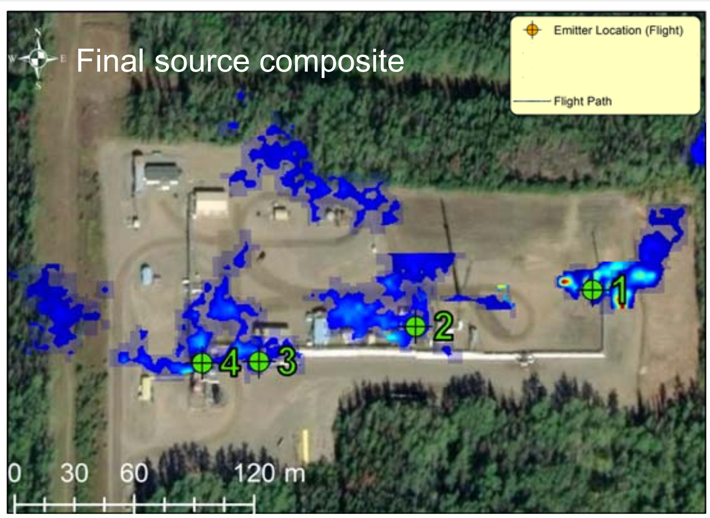


2. Aerial Surveys using Bridger Photonics Gas Mapping LiDAR (GML)

- Patented Aerial LiDAR technology developed through ARPA-E program
- Measures a ~128-m wide swath on the ground at resolution of ~1-2 m
  - A sensor field of view of 31° and nominal flight altitude of 168-230 m
- Path-integrated methane concentrations within the laser swath are combined to produce 2D imagery of detected plumes
- 3D information of the gas plume location/elevation plus with wind speed and other topographic information used to compute methane emission rates
- Relatively new technology that continues to improve

3. Quantification of Source Emission Rates across Multiple Passes & Flights

- Sites have one or more passes
- Flights with detected emissions are revisited in a subsequent day
- Source quantification for inventory development purposes requires interpretation of data from each pass



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4a. Attribution of GML-Detections to Sources

- Combining satellite imagery, geo-located aerial photos, plot plans, & ground survey data to attribute

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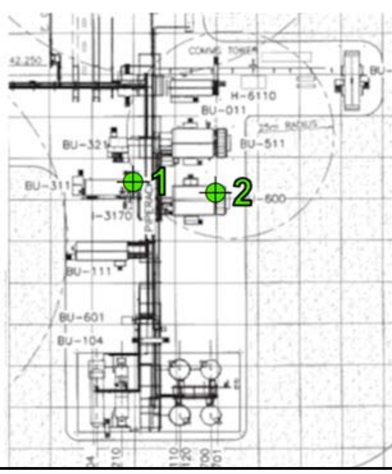
4a. Attribution of GML-Detections to Sources

- Plot Plans provide a site schematic and equipment list
- Match Sources to Plot Plan



EQUIPMENT/BUILDING LIST AND LOCATION

TAG NO.	DESCRIPTION
BU-011	MCC/IA BUILDING
BU-111	SLUG CATCHER BUILDING
BU-131	SEPARATOR BUILDING
BU-311	DEHYDRATION UNIT BUILDING
BU-321	FUEL GAS DEHY BUILDING
BU-511	COMPRESSOR #1 BUILDING
BU-521	COMPRESSOR #2 BUILDING
BU-541	RECYCLE COMPRESSOR BUILDING
BU-921	GENERATOR BUILDING
BU-931	METERING BUILDING
FS-9110	FLARE STACK
I-3170	INCINERATOR
M-4410	ODOUR SCRUBBER
M-4420	ODOUR SCRUBBER
M-4430	ODOUR SCRUBBER
S-1340	METHANOL TANK
S-4110	750 BBL PRODUCED WATER TANK
S-4120	750 BBL PRODUCED WATER TANK
H-6110	TBD
TK-700	750 BBL PRODUCED WATER TANK
TK-701	750 BBL PRODUCED WATER TANK
S-4210	CONDENSATE STORAGE TANK
V-104	CONDENSATE STORAGE TANK
S-9330	CORROSION INHIBITOR TANK
V-9120	LP FLARE KNOCK-OUT DRUM
V-9130	HP FLARE KNOCK-OUT DRUM

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4b. Attribution of Detected Sources to Subtypes

- Inventory is calculated as a stratified sample of subtypes
- Each detected source is manually reviewed
  - Linked with a specific Petrinex facility ID and subtype or well type
  - Much better data quality and resolution than federal inventory approach, but same premise
- Attribution is often straightforward, but becomes complicated when multiple Petrinex IDs located within same location / site
  - Solved through painstaking review of:
    - facility plans,
    - high-resolution aerial photos plus plume imagery,
    - production accounting data,
    - well locations,
    - pipeline connections,
    - ground logs

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Subtype Attribution Example 1: BC_137 (Simple site with single Petrinex ID)

- Site 137:
  - Contained within a single land unit (LSD-SEC-TWP-RGWM)
  - Single Petrinex facility ID (pink dot)
- BCBTXXXXXXX
  - Petrinex subtype 361
    - Gas Multiwell Group Battery
  - Only active facility contained in Site 137's land unit (LSD-SEC-TWP-RGWM)
- Flare emission assigned to subtype 361

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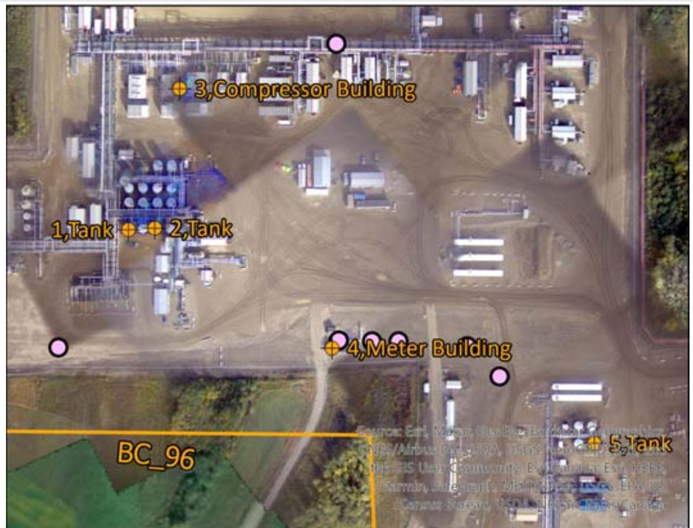
Subtype Attribution Example 2: BC_96
(Large complex location with multiple Petrinex IDs)

- Site 96 spans several land units (LSD-SEC-TWP-RGWM)
- Site 96 contains:
  - 5 detected source; and
  - 7 Petrinex facility IDs (pink dots) in main land unit
    - GP, GS, Gas BT (2x), Oil BT, IF, MS
- Sources attributed to facility IDs analyzing plot plans, meter schematics, and volumetric activity data



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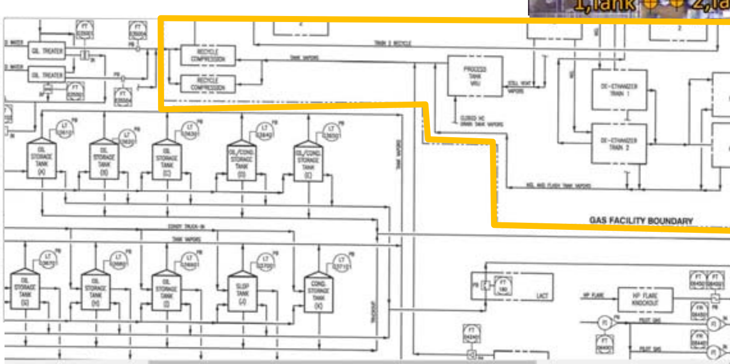
Subtype Attribution Example 2: BC_96
(Large complex location with multiple Petrinex IDs)

- 7 Petrinex facility IDs (pink dot) within main land unit
  - GP, GS, Gas BT (2x), Oil BT, IF, MS
- Oil tank sources 1 and 2 assigned to Oil BT (subtype 322) from MS



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- Compressor source assigned to GP (subtype 401) by reported fuel use during survey month
  - GS, 1 Gas BT reported 0 fuel use

FACILITY	ACTIVITY	PRODUCT	VOLUME	LOCATION	SUBTYPE	Month
BT	FUEL	GAS	18.1	03-XX-XXX-XXW6	322	01-Sep-21
GP	FUEL	GAS	842.1	03-XX-XXX-XXW6	401	01-Sep-21
BT	FUEL	GAS	26.6	03-XX-XXX-XXW6	362	01-Sep-21
BT	FUEL	GAS	20.6	03-XX-XXX-XXW6	322	01-Oct-21
BT	FUEL	GAS	41.6	03-XX-XXX-XXW6	362	01-Oct-21
GP	FUEL	GAS	881.4	03-XX-XXX-XXW6	401	01-Oct-21

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- Compressor source assigned to GP (subtype 401) by reported fuel use during survey month
- Meter Building assign to Meter Station (subtype 637)
- Tank source 5 assigned to GP

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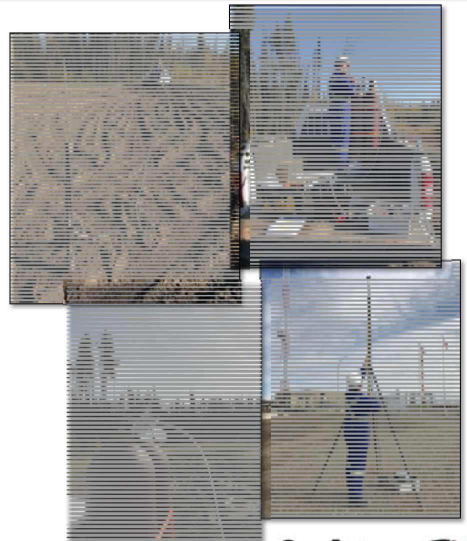
5. Field Work to Quantify GML Sensitivity Limits

- Blinded, controlled release studies to infer GML detection sensitivity
- Three years of field data (N = 190):
  1. B.C., September 2019: N = 23
  2. Saskatchewan, August 2020: N = 52
  3. Saskatchewan, September 2021: N = 115
- Small fully-blinded release rates (< 5.2 kg/h)



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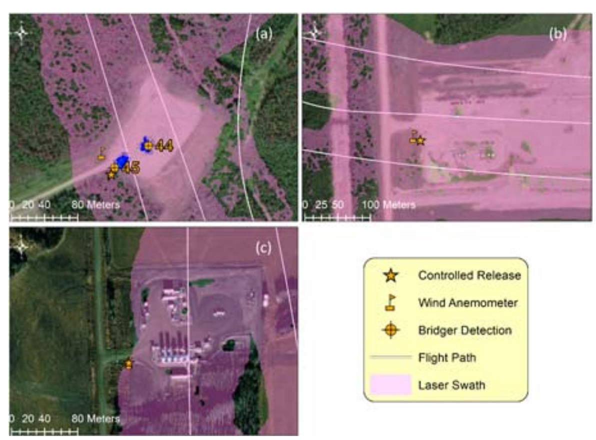

M.R. Johnson, D.R. Tyner, A.J. Szekeres (2021) Blinded evaluation of airborne methane source detection using Bridger Photonics LiDAR, *Remote Sensing of Environment*, 259, 112418. (doi: 10.1016/j.rse.2021.112418)

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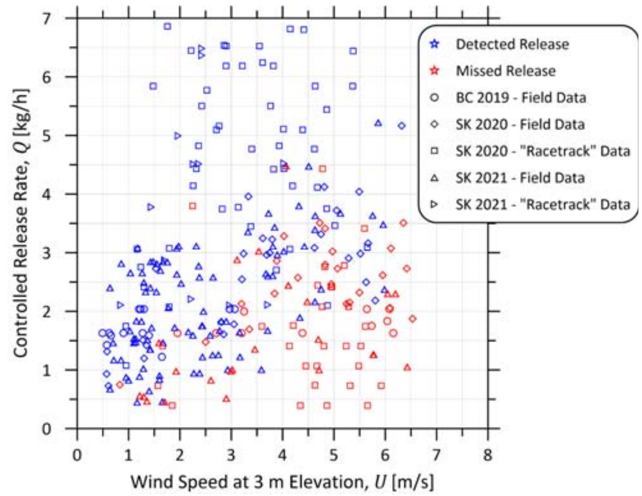
5. Field Work to Quantify GML Sensitivity Limits

- Three years of controlled-releases
  - Aircraft altitude reductions from 230 m (2019) to 168 m (2021)



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- Three years of controlled-releases
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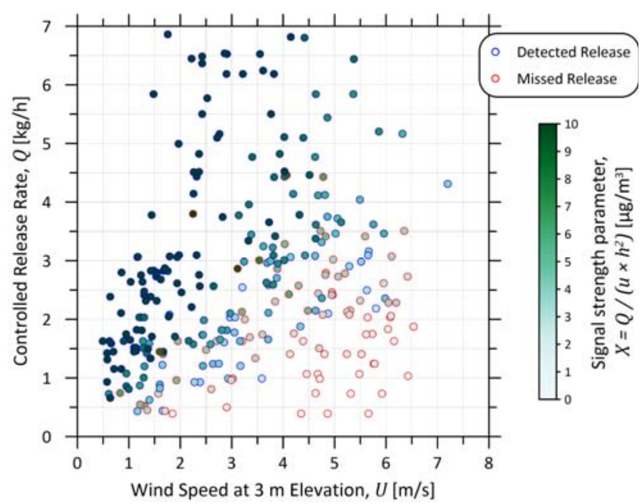
- Bridger's signal strength is sensitive to:
  - Plume concentration
    - **Emission rate (Q)**
    - Wind speed (U)
  - Aircraft altitude above ground (h)
  - Albedo/reflectivity of the ground
- Data correlate well with new *signal strength parameter,* $X = \frac{Q}{Uh^2}$



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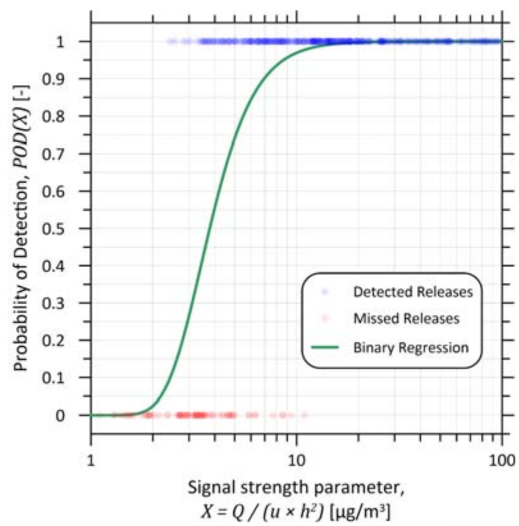
- Data correlate well with new *signal strength parameter,* $X = \frac{Q}{Uh^2}$
- Binary regression gives source probability of detection (POD) at any wind and altitude



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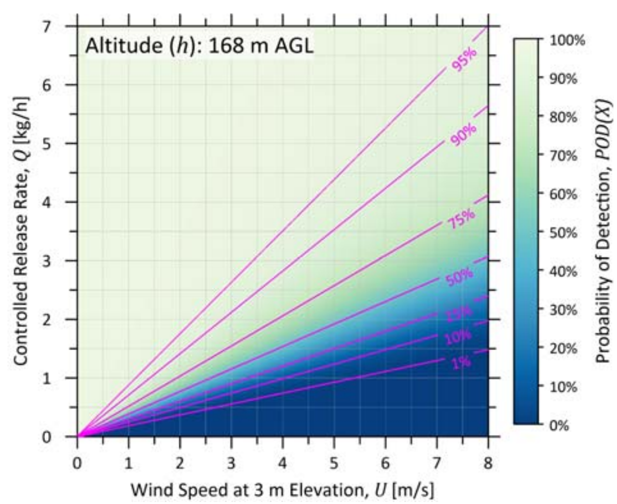
5. Field Work to Quantify GML Sensitivity Limits

- ***Generalized continuous*** sensitivity function
  - Can compute probability of detection for any source at any altitude and wind speed
    - Example plot for 168 m AGL
  - Used when estimating unmeasured sources below detection limits
  - Bounds missed detections when comparing pass data within Monte Carlo analysis



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Comparing Bridger Sensitivities in 2019 vs. 2021

	2019	2021
Target Altitude	230 m	168 m
Median windspeed during flights [m/s]	1.9 m/s	5.0 m/s
Mean windspeed during flights [m/s]	2.8 m/s	4.8 m/s
Mean Sensitivity during flights [kg/h]	**1.77 kg/h**	**1.84 kg/h**

- Lower altitudes in 2021 vs. 2019, but generally higher wind speeds
  - Resulting in-field sensitivities are not statistically different (p=0.46, Welch Test)

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6. Field Work to Quantify GML Accuracy

- Semi-blinded larger releases to test Bridger quantification uncertainty
- Two years of “racetrack” data (N = 313):
  - Saskatchewan, August 2020 : N = 151
  - Saskatchewan, September 2021 : N = 162
    - Releases up to 66 kg/h

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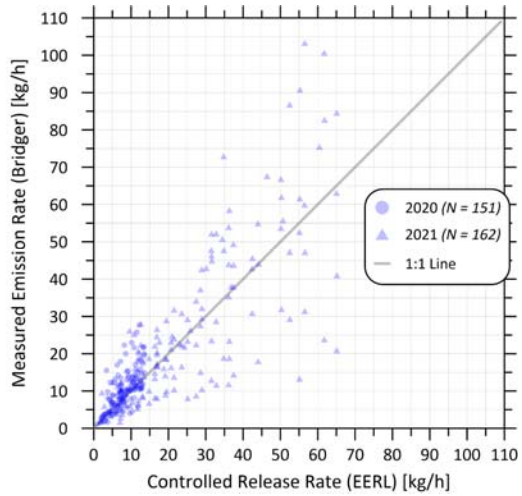

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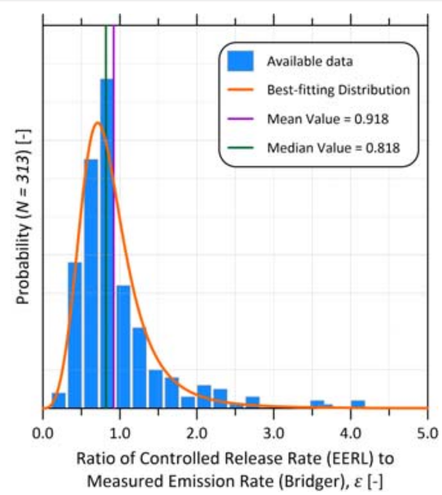
- Two years of "racetrack" data (N = 313):
  - Saskatchewan, August 2020 : N = 151
  - Saskatchewan, September 2021 : N = 162
    - Releases up to 66 kg/h
- Quantified uncertainty distribution over a relevant range of source rates
  - Allows uncertainties to be propagated into inventory calculations



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7. Measured Inventory Development with Robust Uncertainty Analysis

- Two key components of the uncertainty analysis:
  - Uncertainty from the accuracy of Bridger's **quantification**
    - Applies to each individual measurement pass for each detected source
    - Pass-level uncertainties propagate to uncertainties in site- and subtype-level emissions
  - Uncertainty from **sample size** and **finite population** effects
    - Accounts for uncertainties due to the finite number of sites sampled within each subtype
    - Applies to site-level emissions (including zeros) when scaling by provincial counts
- To our knowledge, this is the first study to explicitly consider both contributions to the overall uncertainty of the measured inventory
  - Potentially a significant advance for creating robust, measurement-based inventories

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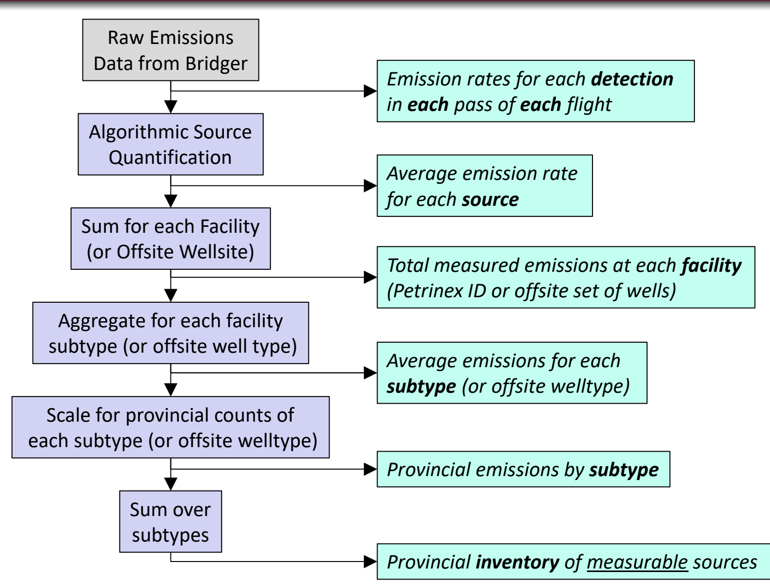
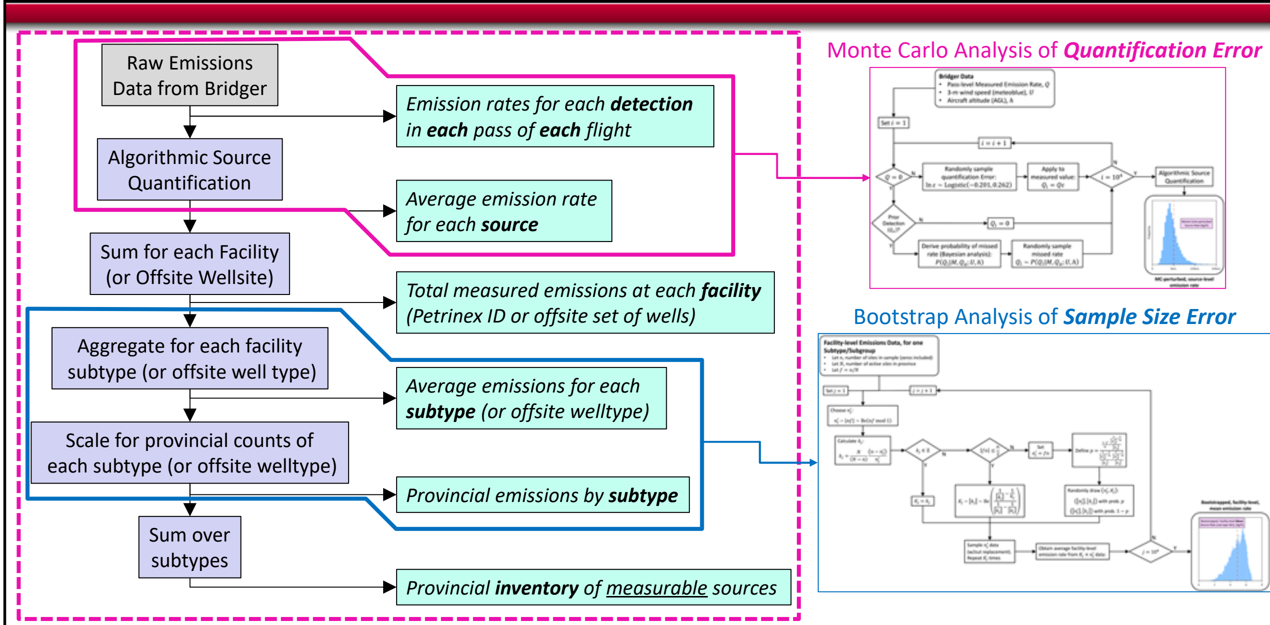
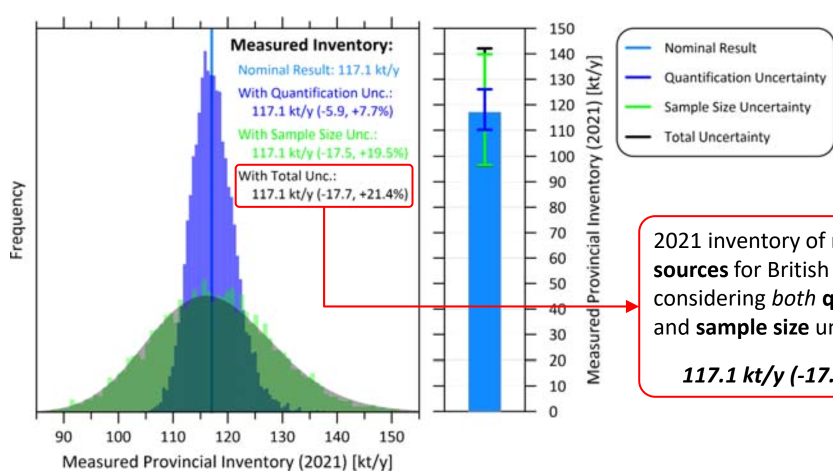
Framework for Calculating the Inventory – "Simple" Case without Uncertainty



Framework for Calculating Measurement & Sample Size Uncertainties



2021 *Measured Source* Inventory



2021 inventory of **measured sources** for British Columbia, considering *both* **quantification** and **sample size** uncertainties:

117.1 kt/y (-17.7, +21.4%)

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9/10. Unmeasured Source Contributions to the Inventory

- Bridger technology misses <u>many</u> sources
  - Sources below its sensitivity limit such as
    - Leaking fittings, valves, small vent lines etc.
    - Normally operating pneumatic instruments and pumps
  - Intermittent sources that may be important yet infrequent
  - Other sources missed for various reasons
    - e.g., near standing water or moist ground, obscured by other equipment or sources, near edge of laser swath, etc.

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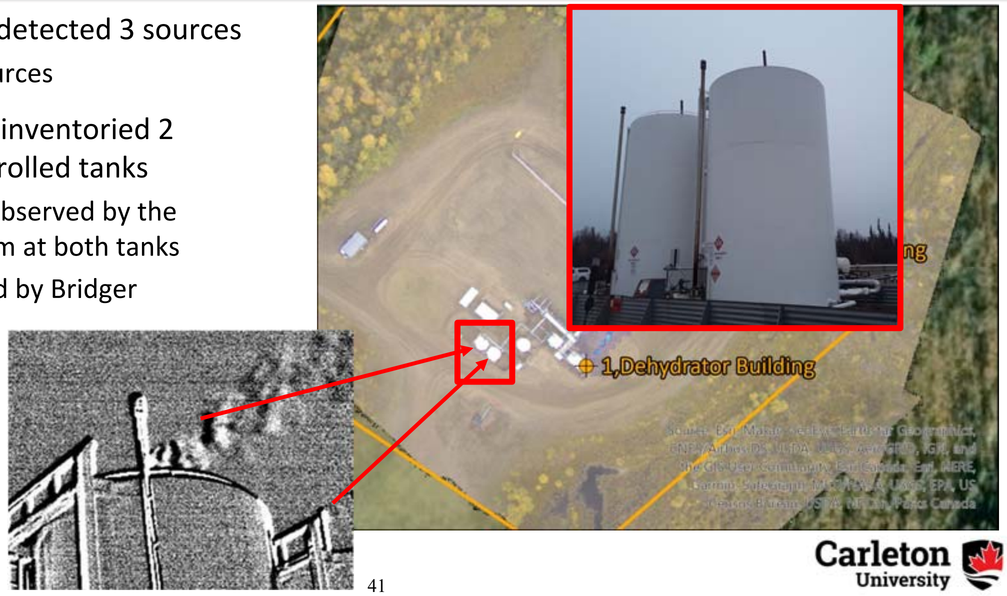
Missed Sources Example #1: BC_286 (Tanks)

- Aerial survey detected 8 sources
  - No tank sources
- Ground team inventoried 10 active onsite tanks
  - 3 controlled (VRU) tanks
  - 7 uncontrolled tanks
- Ground team detected emissions at 6 of 7 uncontrolled tanks
  - All missed by Bridger

Missed Sources Example #2: BC_253 (Tanks)

- Aerial survey detected 3 sources
  - No tank sources
- Ground team inventoried 2 active uncontrolled tanks
  - Emissions observed by the ground team at both tanks
  - Both missed by Bridger



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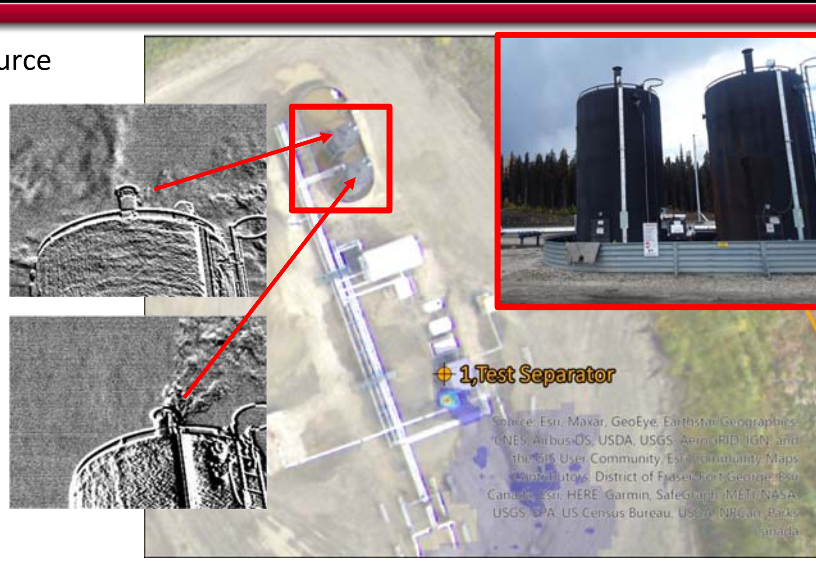
Missed Sources Example #3: BC_438 (Tanks)

- Aerial survey detected 1 source
  - No tank sources
- Ground team inventoried 2 active uncontrolled tanks
  - Emissions observed at both tanks
  - Both missed by Bridger



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Missed Sources Example #4: BC_144 (Compressor Rod Packing Vent)

- Aerial survey compressor emissions dominated by exhaust emissions
  - Plume is directly over exhaust (muffler)
- Ground team noted rod packing emissions at the same compressor
  - Not detected in aerial survey

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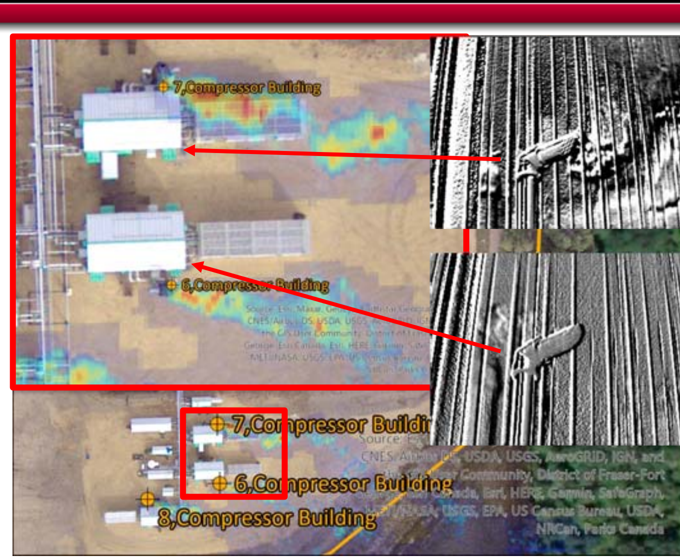
Missed Sources Example #5: BC_41 (Compressor Rod Packing Vent)

- Aerial survey measured compressor exhaust emissions
  - Plumes directly over exhaust (mufflers)
- Ground team observed rod packing emissions at the same compressors
  - Not detected in aerial survey



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Aerial vs. Ground Team Detections at Common Sources

- Comparison of aerial and ground team detection rates confirms significance of missed sources:

Equipment	Control	Bridger Detection Rate	Ground Crew Detection Rate
Tanks	Uncontrolled	17% (15/89)	57% (44/77[a])
	Controlled	10% (19/185)	n/a[b]
Compressor Buildings	Gas-Driven – Uncontrolled	75% (64/85)	87% (74/85)
	Gas-Driven – Controlled	78% (39/50)	n/a[c]
	Electric-drive – Uncontrolled	33% (9/27)	96% (26/27)
	Electric-drive – Controlled	0% (0/22)	n/a[c]

[a] Ground team visited 89 tanks but only accessed 77 to check for emissions
[b] Ground team only inspected controlled tanks when specifically directed to a source (i.e., not a survey). Ground team did attempt to quickly scan all uncontrolled tanks at each site to check for visible (OGI) emissions
[c] Since OGI cannot distinguish methane in exhaust, no other sources for ground team to inspect on a controlled compressor

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9/10. Calculating Contributions from Unmeasured Sources

- 2019 BC aerial & ground survey study (Tyner & Johnson, EST 2021) gives direct insight into frequency and potential importance of missed sources
- Key data sets for BC:
  - 2019 Aerial Survey and Ground Survey Comparison (Tyner & Johnson, EST, 2021)
  - 2018 OGI ground survey of ***non-pneumatic*** sources (Robinson et al., 2018)
  - 2018 pneumatic component count inventory (Robinson et al., 2018)
- Additional reference data for manufacturer-specific pneumatic equipment emission factors:
  - Prasino Group (2013) field measurement data for pneumatic equipment in BC
  - Spartan Controls (2018) study of pneumatic controllers

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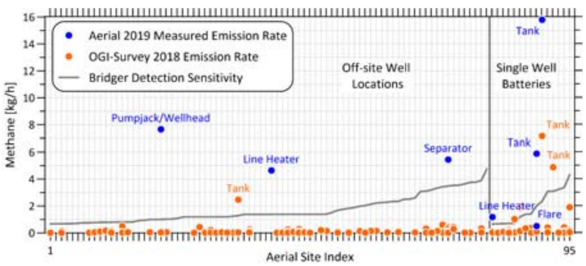
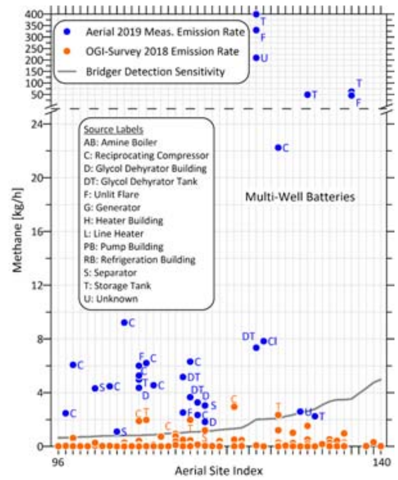
9. Unmeasured Non-Pneumatic Sources – 2019 Study Data

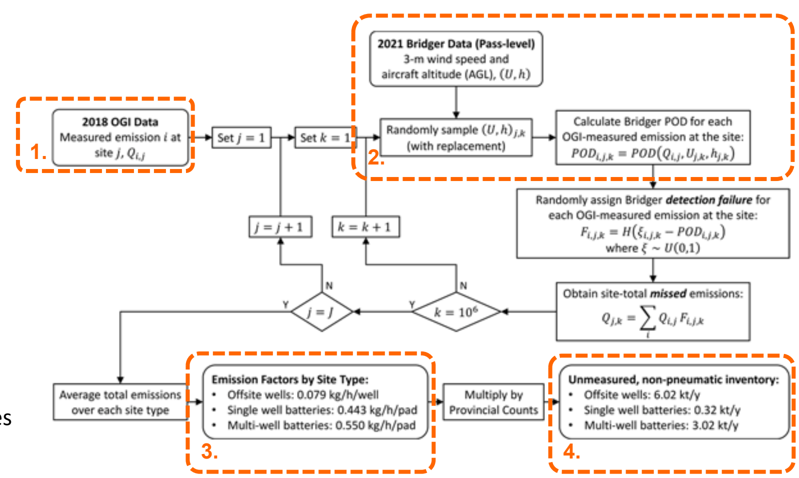
- At same subset of facilities:
  - Aerial survey: 80 sources (1802 kg/h)
  - OGI survey: 357 source (74 kg/h)
- **OGI data a good measure of missed sources below Bridger sensitivity limit (*excl. pneumatics*)**
  - Update with 2021 sensitivity limit





Inventory Contribution of Unmeasured, Non-Pneumatic Sources

- Combine:
  1. 2018 OGI survey data
  2. 2021 Bridger sensitivity by pass
3. Derive updated emission factors non-pneumatic sources ***below detection limits***:
   - Offsite wells: 0.079 kg/h/well
   - SWB: 0.443 kg/h/pad
   - MWB: 0.550 kg/h/pad
4. Scale by provincial counts
   - Conservatively assume ***zero*** unmeasured non-pneumatic sources at subtypes:
     - 631-640 (meter stations)
     - 621 (gathering systems)
     - 204-209, 371, 381, 395, 503-505



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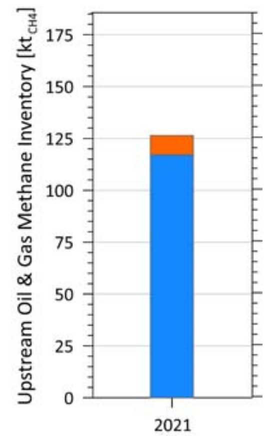
Inventory Contribution of Unmeasured, Non-Pneumatic Sources

- Unmeasured, non-pneumatic sources are approximately 8% of the *measured* inventory and decreased by ~15% from 2019 estimate

Site Type	EF, [kg/h/pad]	Unmeasured, non-pneumatic B.C. Inventory, [kt/y]
Offsite Well	0.0787	6.02
Single-well Battery	0.443	0.32
Multi-well Battery	0.550	3.02
Total		**9.36**



- Source OGI data ***exclude*** normally-operating pneumatic equipment and pumps…

10. Inventory Contribution from Pneumatic Sources

- In general, Bridger's GML not expected to detect pneumatic device emissions
  - Manufacturer bleed rates are always well below Bridger sensitivity limits in the field
  - In-field emission factors (e.g. Allen et al., Prasino, etc.) also well-below Bridger sensitivity
- Nevertheless, there might still be cases where Bridger detects multiple pneumatics tied to a common line or "super-emitter" pneumatic devices
- **Review ground-team inspection reports to estimate maximum fraction of pneumatic devices that might be captured within Bridger measurement data**

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Inventory Contribution from Pneumatic Sources

- Ground team investigated 227 sources, incl. 195 identified as final sources by Bridger
  - Only 24 had potential to include contributions from pneumatic devices
    - 16 cases (heater buildings, separator buildings, gas lift building, pump building, fuel gas skid) where pneumatic devices are main components
    - 8 cases of pneumatics associated with other components such as catadyne heaters, crank case vents, solenoids / regulators, tank vent, compressor seals
  - For all 24 cases:
    - Bridger estimated emission rates exceed expected manufacturer bleed rates (median of **12.3** times higher)
    - Bridger estimated emission rates exceed available field emissions factors (median of **9** times higher)
- Implies that any pneumatics that might be captured would be ***well outside normal operating*** conditions

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Inventory Contribution from Pneumatic Sources

- Both Bridger sensitivity limits and analysis of ground team inspection data suggest that **normally operating pneumatics are not captured** in Bridger measurements
- Estimate inventory contribution from ***normally operating pneumatics*** using BC-specific count data from Robinson et al., 2018 with updated facility and well counts
- In addition, run a scenario to ***conservatively exclude*** a prorated fraction of pneumatics where there is potential for pneumatics to be included in Bridger data
  - Conservatively *ignore* that any detections presumably represent abnormal pneumatics
- In all scenarios, ***conservatively* assume no emissions** from pneumatics at following subtypes:
  - **601 (Compressor Stations)**, 401-407 (Gas Plants), 621 (Gas Gathering systems), 631-638 (meter stations), 204-209, 371, 381, 395, 451, 501-505, 611, 671-676, 901-902
    - Ground data shows at least some of these will have emissions we are conservatively neglecting

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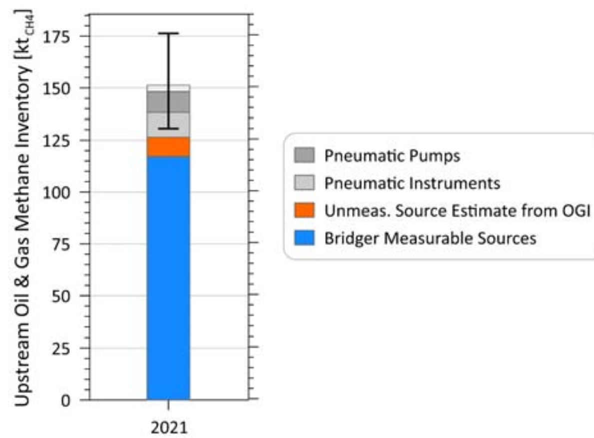
Inventory Contribution from Pneumatic Sources

- Normally operating pneumatic instruments and pumps expected to add ~24.8 kt to inventory
  - Likely misses some contributions from abnormal pneumatics
  - Conservatively assumes zero pneumatic emissions at many subtypes
    - – Assumes air-driven systems ignoring counter-examples in ground data
- Conservatively reducing pneumatic fraction to allow for possible Bridger detects cuts ~3 kt (2% from inventory)
  - Negligible within uncertainties



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Influence of Facility & Well Counts on Inventory

Facility Class	Facility Sub-Type	Sub-Type Name	"Active" in BC Public Facility List		Appearing in Petrinex			Included within Aerial Survey		
			June 28, 2021 (Planning Phase)	Nov. 17, 2021	Active during Aug., Sept., or Oct. 2021	Active during Oct. 2021	Active during Oct. 2021 – excl. "SHUTIN"	At Planning Phase (based on June 2021 counts)	Active in Petrinex in Sept. 2021	Active in Petrinex in Sept. 2021 excl. "SHUTIN"
Oil Bty.	311	Crude Oil Single-Well Battery	60	58	59	58	52	50 (83.3%)	48 (82.8%)	46 (88.5%)
	321	Crude Oil Multiwell Group Battery	6	5	5	5	3	3 (50.%)	3 (60.%)	3 (100.%)
	322	Crude Oil Multiwell Proration battery	36	35	35	35	35	31 (86.1%)	31 (88.6%)	29 (82.9%)
Gas Bty.	351	Gas Single Well Battery	29	28	29	28	22	22 (75.9%)	21 (75.%)	20 (90.9%)
	361	Gas Multiwell Group Battery	77	79	79	79	68	54 (70.1%)	54 (68.4%)	50 (73.5%)
	362	Gas Multiwell Effluent Measurement Battery	142	141	141	140	135	113 (79.6%)	113 (80.7%)	111 (82.2%)
O/G Bty.	393	Mixed Oil and Gas Battery	19	17	17	16	16	16 (84.2%)	16 (100.%)	16 (100.%)
Temp. Bty.	371	Gas Test Battery	4	3	2	2	2	1 (25.%)	1 (50.%)	1 (50.%)
	381	Drilling and Completing	2	2	1	1	1	1 (50.%)	1 (100.%)	1 (100.%)
Water	395	Water Hub Battery	33	33	34	34	33	22 (66.7%)	22 (64.7%)	22 (66.7%)
	901	Water Source	11	11	4	3	3	6 (54.5%)	1 (33.3%)	1 (33.3%)
	902	Water Source Battery	8	7	7	7	6	4 (50.%)	4 (57.1%)	4 (66.7%)

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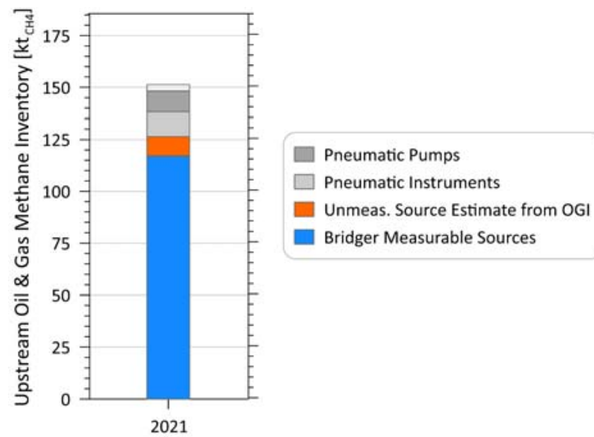
Influence of Facility & Well Counts on Inventory

- Options for calculating inventory:
  - I. "Active facility List"
    - Should be complete but appears that industry slow to update inactive sites
  - II. Active facilities appearing in Petrinex
    - Misses confidential wells and not all activities accessible in data
    - 601s are non-reporting entities
  - III. Active facilities appearing in Petrinex but excluding shut-in
    - More restrictive still
    - Excludes cycling facilities that remain pressurized



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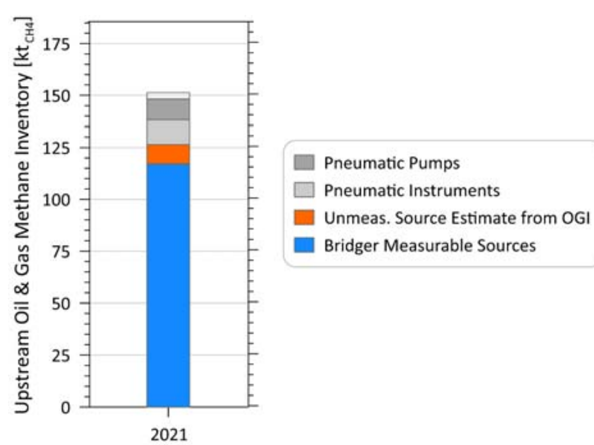
  - III. Active facilities appearing in Petrinex but excluding shut-in
    - Further excludes cycling facilities that remain pressurized



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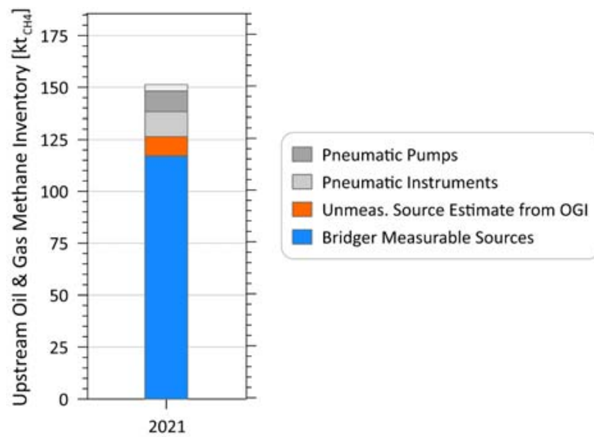

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Influence of Facility & Well Counts on Inventory

- Options for calculating inventory:
  - II. Active facilities appearing in Petrinex
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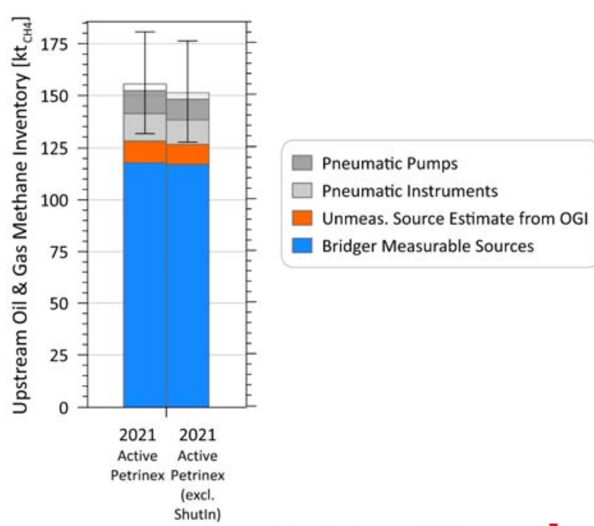
    - Further excludes cycling facilities that remain pressurized
- No difference in measurable sources
- Small differences in OGI & pneumatics which scale directly with counts



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Influence of Facility & Well Counts on Inventory

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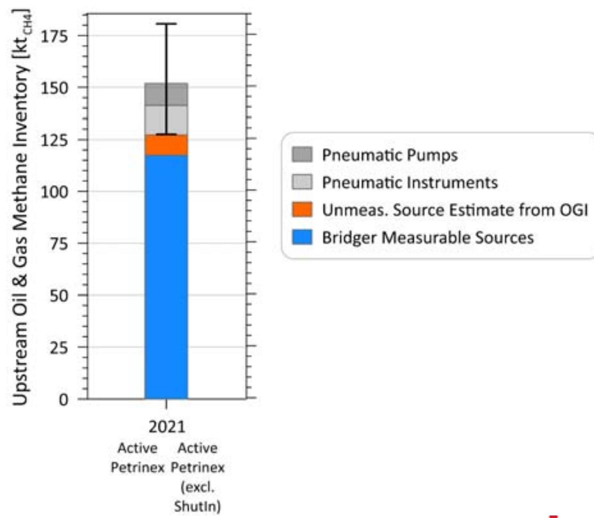
    - Misses confidential wells etc.
  III. Active facilities appearing in Petrinex but excluding shut-in
    - Further excludes cycling facilities that remain pressurized
- No difference in measurable sources
- Small differences in OGI & pneumatics which scale directly with counts
- Include count range with & without derated pneumatics in error bars



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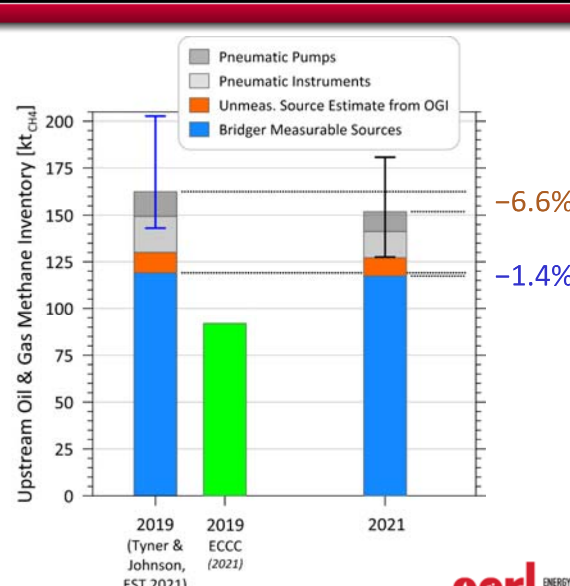
2021 BC Upstream Oil & Gas Methane Inventory

- 2021 Methane Inventory
  - 151.9 kt CH_4 (127-181 kt CH_4)
- Change from 2019 within error bars
  - Measurable sources consistent (nominal 1.4% decrease)
  - Measurable sources alone remain well above ECCC inventory
  - Nominal 6.6% decrease in overall inventory
    - Different driven largely by changes in counts in bottom-up calculation
    - Contributions from pneumatics / unmeasured sources largest source of uncertainty



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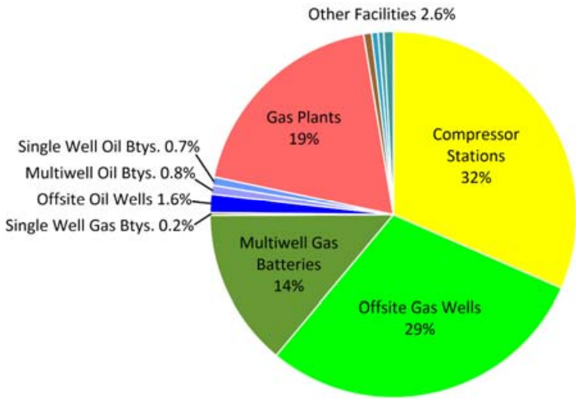
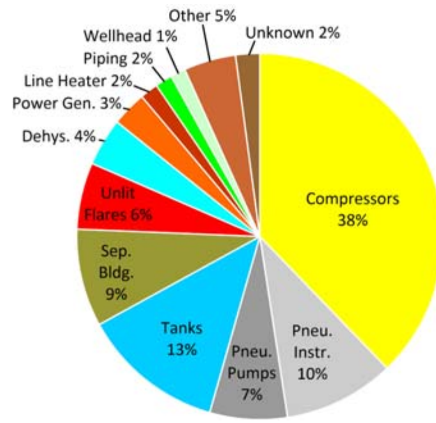
2021 BC Upstream Oil & Gas Methane Inventory

Methane Contribution by Facility Type



Methane Contribution by Source Type



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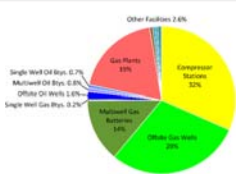
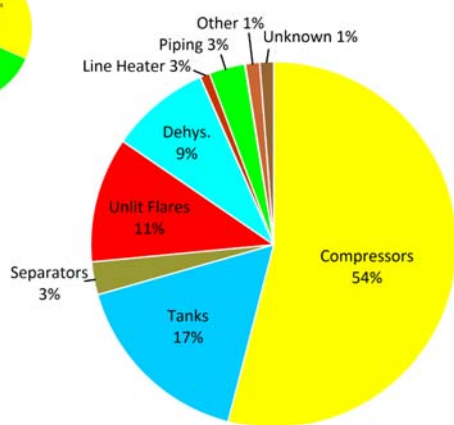
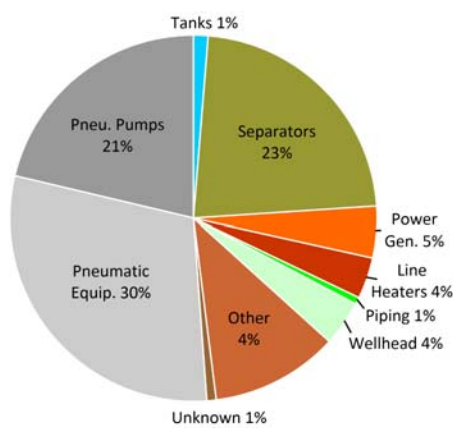
2021 BC Methane Sources By Facility Type



Compressor Stations
(Subtype 601)



Offsite Gas Wells



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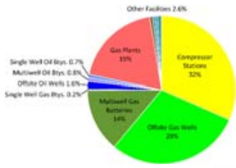
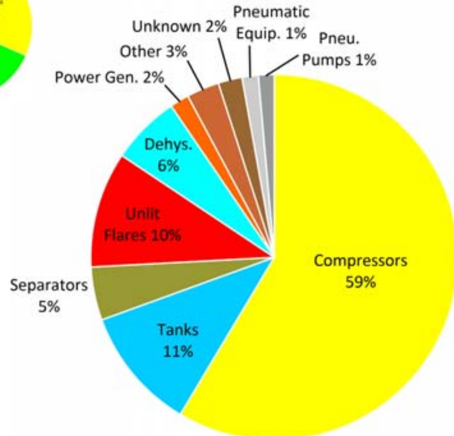
2021 BC Methane Sources By Facility Type



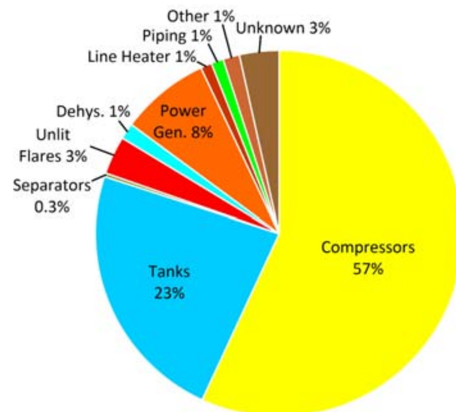
Multiwell Gas Batteries

(Subtype 361 & 362)



Gas Plants

(Subtype 401-407)



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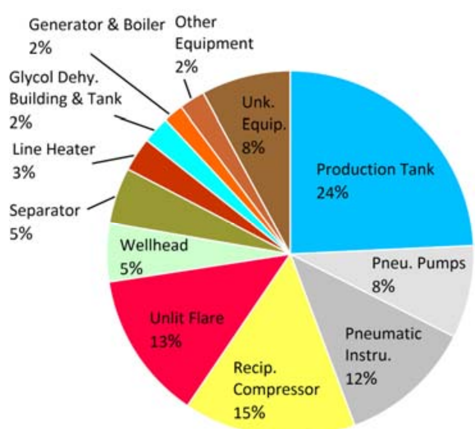
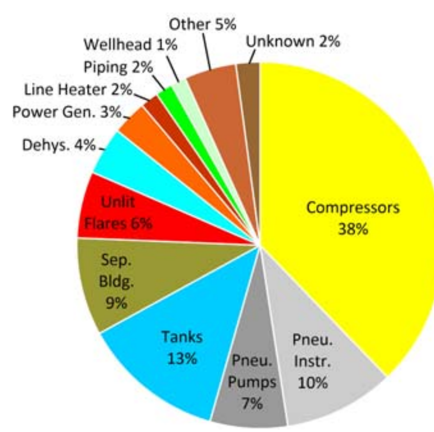
Comparing 2021 with 2019 Methane Contributions

2019



2021



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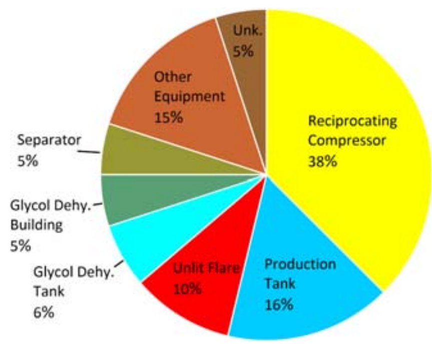
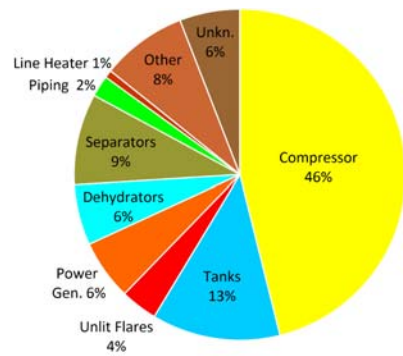
Comparison of ***Measured*** Source Frequencies 2019 vs. 2021

Measured Sources ONLY

2019 Source Fraction



2021 Source Fraction



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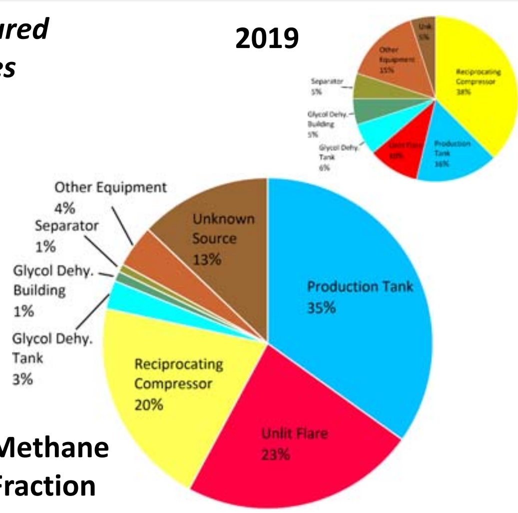
Comparison of ***Measured*** Source Frequencies 2019 vs. 2021

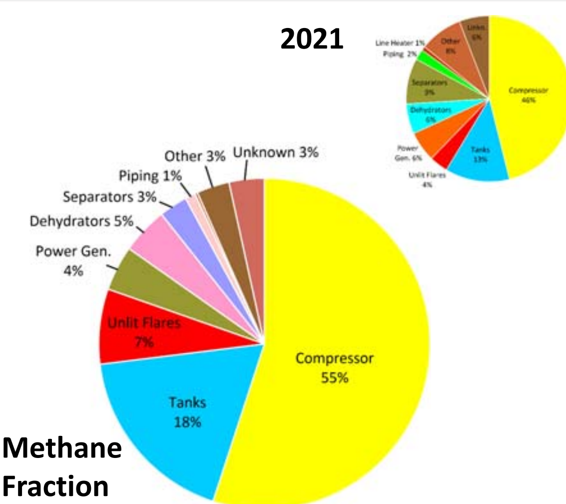
Measured Sources ONLY

2019



Methane Fraction

2021



Methane Fraction

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Conclusions

- A robust measurement-based 2021 methane inventory for BC
  - Likely the first-ever inventory, in any jurisdiction, with direct consideration of both measurement error and finite sample size effects for non-normally distributed data
  - Stark contrast from current ECCC inventory based on scaled estimates from 2011, estimated counts in aggregate, and no direct measurement data
- Measurable source magnitudes consistent between 2019 and 2021 within uncertainties
  - Nominal 1.4% decrease well within uncertainties
- Uncertainties in emissions factors for normally operating pneumatic emissions is a key knowledge gap
  - Same issue for ECCC inventory
  - Future need for field work to better constrain these sources

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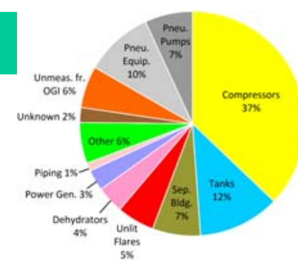
Conclusions

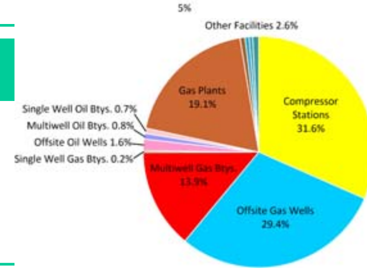
Key sources of methane emissions are:

- Compressors
- Tanks
- Pneumatic instruments and pumps
- Separator buildings
- Unlit flares and vent stacks



Most important facility types:

- Compressor stations
- Offsite gas wells (majority of pneumatics)
- Multiwell gas batteries
- Gas plants



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Acknowledgements

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BC Oil and Gas Research and Innovation Society

BC Oil & Gas COMMISSION

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