Where the Methane Is – New Insights from Novel Airborne LiDAR Measurements combined with Ground Survey Data

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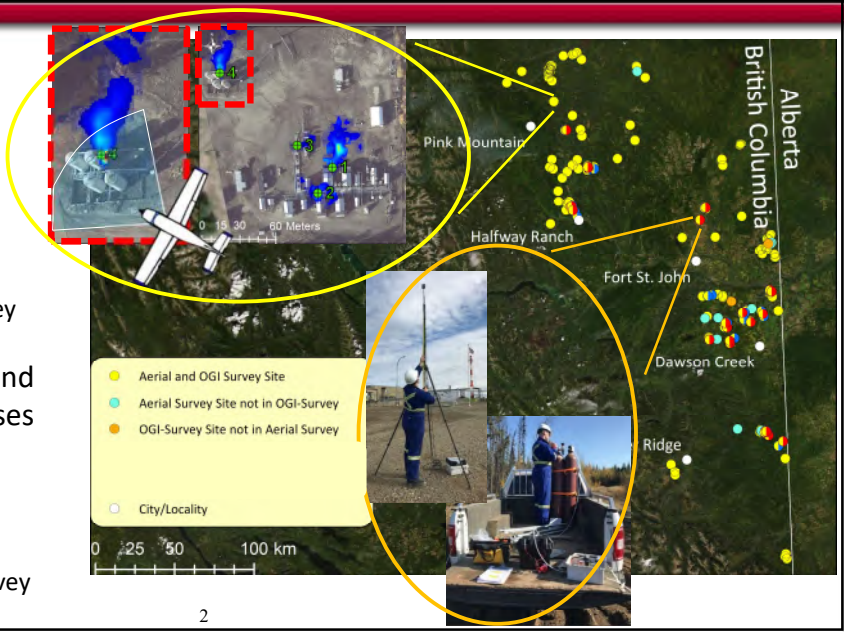
September 2019 British Columbia Aerial Methane Study

- Aerial survey of 167 oil and gas sites in BC in 2019
  - Bridger Photonics Ltd.'s plane mounted Gas Mapping LiDAR
  - Wells, single and multiwell batteries, and gas plants
  - 140 sites in prior 2018 OGI-survey
- EERL deployed wind sensors and **fully-blinded** controlled releases
  - Determine detection limits
  - Identify / quantify sources and emission distributions
  - Comparison with prior OGI-survey



2

Bridger Photonics Gas Mapping LiDAR (GML)

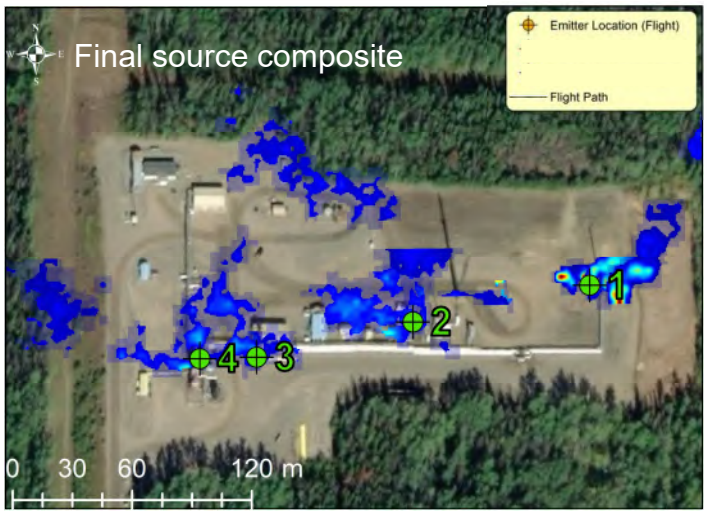
- Aerial methane measurements
  - Bridger Photonics Ltd. Gas Mapping LiDAR™ (GML) technology
  - Patented LiDAR technology developed through ARPA-E program
- Measures a ~128-m wide swath on the ground at resolution of ~2 m
  - A sensor field of view of 31° and nominal flight altitude of 230 m

- Path-integrated methane concentrations within the laser swath are combined to produce 2D imagery of detected plumes
- 3D information of the gas plume location plus with wind speed and other topographic information used to compute methane emission rates in a proprietary method

3

Flight data: Post-Processing Example

- 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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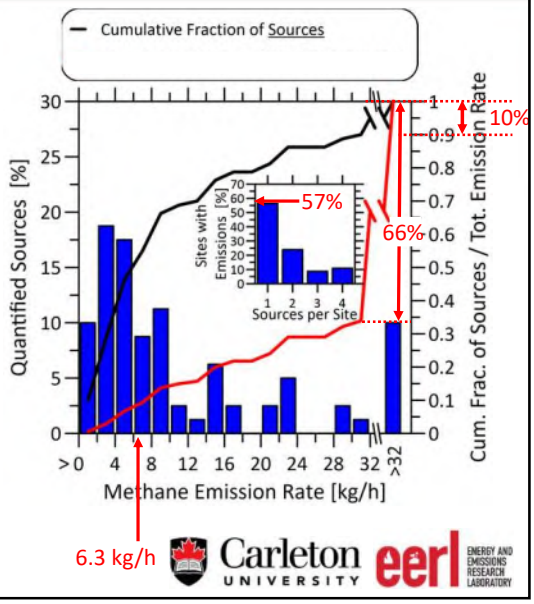
4

Aerial Survey Data: Measured Sources

- 28% of sites had measurable sources
  - 80 sources totaling 1802 kg/h
  - 57% of sites with emissions had a single source
- Skewed/long tailed source distribution
  - Median 6.3 kg/h (Mean 22.3 kg/h)
- 10% of sources > 32 kg/h
  - total 66% of emissions



5

Aerial Survey Data: Measured Sources and Sites

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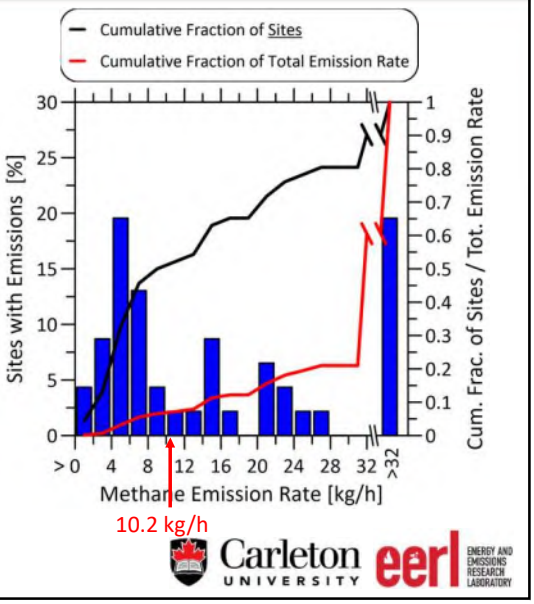
  - 80 sources totaling 1802 kg/h
  - 57% of sites with emissions had a single source
- Skewed/long tailed source distribution
  - Median 6.3 kg/h (Mean 22.3 kg/h)
- 10% of sources > 32 kg/h
  - Total 66% of emissions
- Site emissions similarly skewed
  - 9 sites had rates > 32 kg/h (median 10.2 kg/h)
  - Gini coefficient of 0.76 in the range of other oil and gas emission studies



6

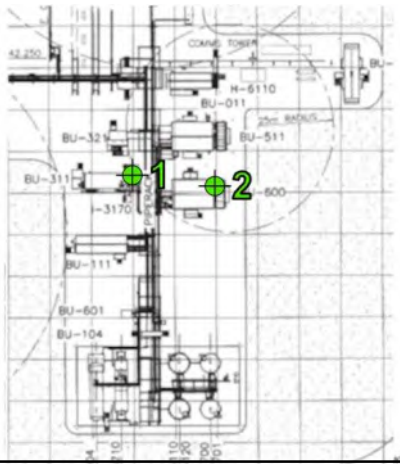
Source Attribution: Geo-locating Aerial Survey Imagery

- Satellite images often dated
- Geo-locate site imagery from Bridger to satellite image

7

Source Attribution: Match Sources to Plot Plans

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



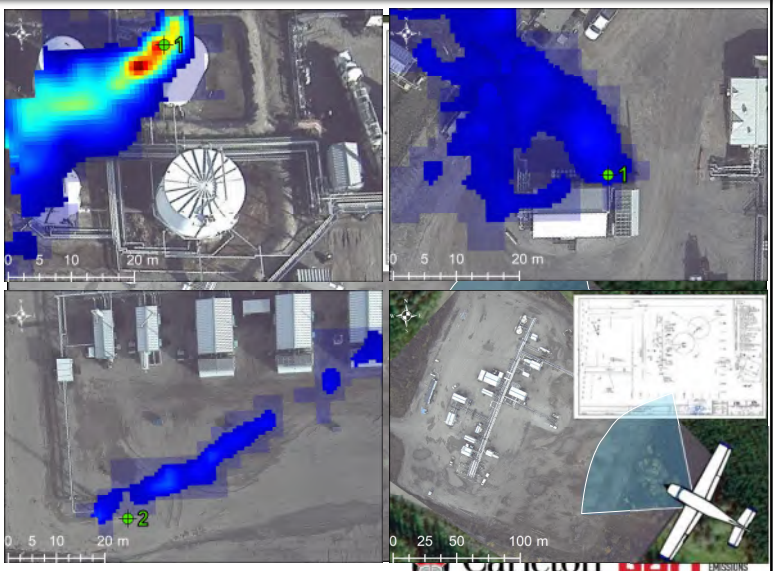
EQUIPMENT/BUILDING LIST AND LOCATION

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

Aerial Survey Data: Largest Identifiable Sources

- 95% of sources (87% of emissions) attributed to specific major equipment types
- 64% of sources (78% of emissions) attributed to tanks, compressor buildings, and unlit flares
- **Tanks**: 13 sources, 2.2-399 kg/h
  - Median 13.7 kg/h
- **Compressors**: 30 sources, 1.5-53 kg/h
  - Median 8.3 kg/h
  - > expected rod packing vent 0.01-3.0 kg/h*
  - Combustion slip
- **Unlit Flares**: 8 sources: 0.5-330 kg/h
  - Median 5.5 kg/h

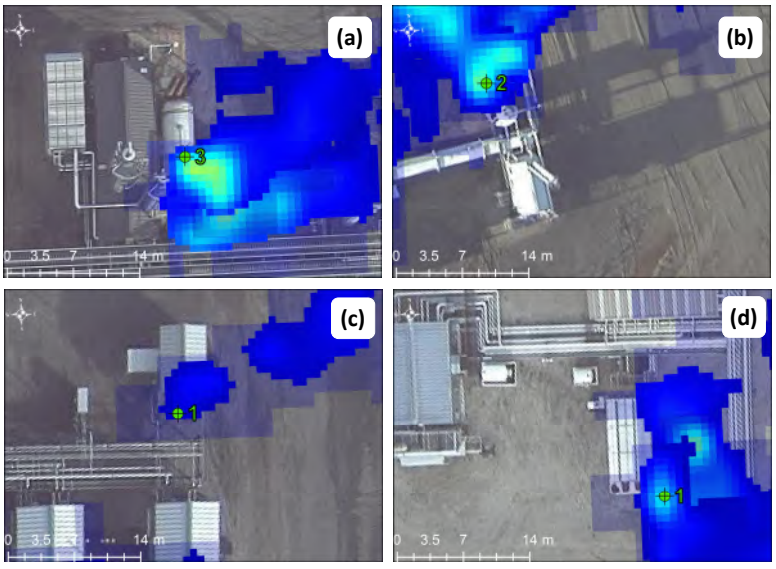
*Prior 2018 OGI-survey with Highflow sampler



9

Aerial Survey Data: Other Identifiable Sources

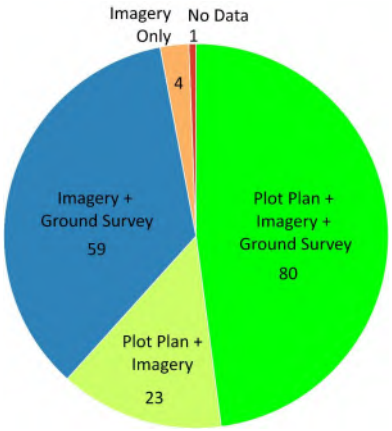
- 31% of sources (9% of emissions) attributed to other sources
  a) Amine boiler unit
  b) Dehydrator
  c) Generator
  d) Cooler
  e) Etc.



10

Occurrence Rates by Facility Type (above Bridger Sensitivity)

Aerial Survey Site type	Count	Sites with Emissions	Sites with Emissions [%]
Off-Site Well locations	80	3	**4%** *(0-9%)*
Single Well Battery	15	3	**20%** *(0-40%)*
Multi-Well Battery	57	32	**56%** *(44-68%)*
Gas Plant	8	5	**63%**
Compressor Station / Gas Gathering System	4	2	**50%**
Unknown/Liquids hub	2/1	1	**33%**
Total	**167**	**46**	**28%**

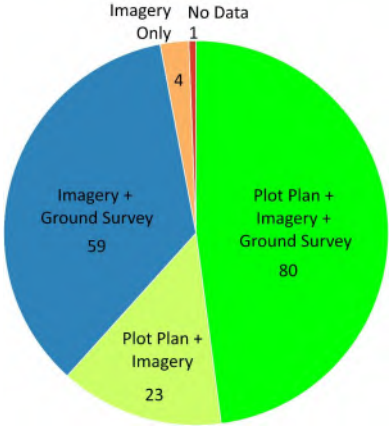


- Excluding off-site wells, half of facilities (C.I. 39-60%) had detectable emissions above the Bridger sensitivity limit of ~1 kg/h

11

Occurrence Rates of Detected Sources (above Bridger Sensitivity)

Source	All 166 sites			80 Overlap Sites with Plot Plans, Imagery, and Ground Survey Counts		
	Emitter Count	Equip. Count	Occurrence Rate	Emitter Count	Equip. Count	Occurrence Rate
Flares	8	71	11% (4-20%)	4	41	10%
Reciprocating Compressors	30	102	29% (21-38%)	11	42	26%
Production Tanks	13	257	5% (3-8%)	4	135	3%



(Credit: Ellen McCole)

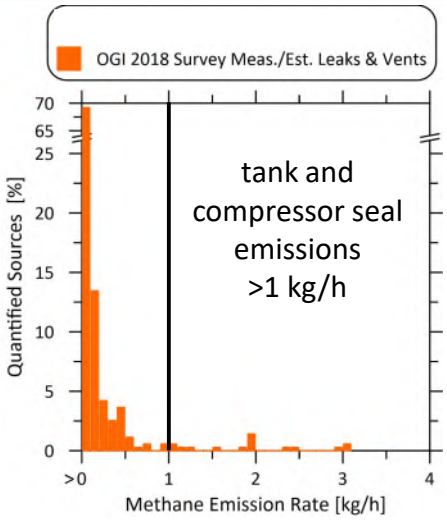
12

2019 Aerial- and 2018 OGI-survey Compared at Common Sites

- Ground Survey (2018) quantified (high flow sampler) or estimated (visual observation) emissions
  - **Fugitive sources**: connectors, values, and other components and controlled tanks (e.g. tied to a flare)
  - **Venting sources**: compressor seals (rod-packing), wellhead surface casing vents, tanks without controls.

	2018 OGI-Survey		
	Meas.	Est.	**Tot.**
Sources [#]	283	74	**357**
Total Emissions [kg/h]	30.8	40.4	**71.2**

- < half of total emissions measured
- 96% of ground survey emissions sources < 1.0 kg/h
  - 4% of sources total 53% of emissions
  - Estimated 21 tank sources (44% of emissions)



13

2019 Aerial- and 2018 OGI-survey Compared at Common Sites

- Ground Survey (2018)
  - 79% of sources and 43% of total emissions measured
  - 96% of ground survey emissions sources < 1.0 kg/h
    - 4% of sources total 53% of emissions
    - Ground survey estimated 21 tank sources (44% of emissions)

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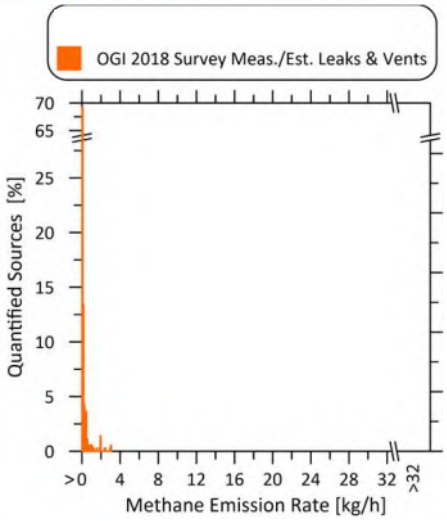

14

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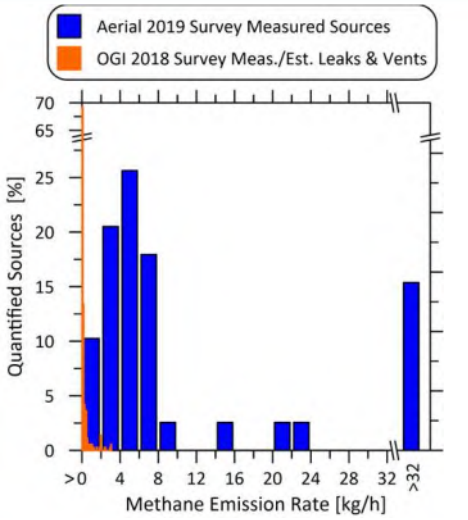
	2018 OGI-Survey			2019 Aerial Survey
	Meas.	Est.	**Tot.**	
Sources [#]	283	74	**357**	39
Total Emissions [kg/h]	30.8	40.4	**71.2**	1296

- Aerial survey (2019) measured 5-18× more emission
  - All sources measured over two days
  - ~60% of sources, 79-84% of emissions, from unlit flares, compressors, and tanks
- **OGI and aerial surveys finding different types/magnitudes of sources at the same sites**



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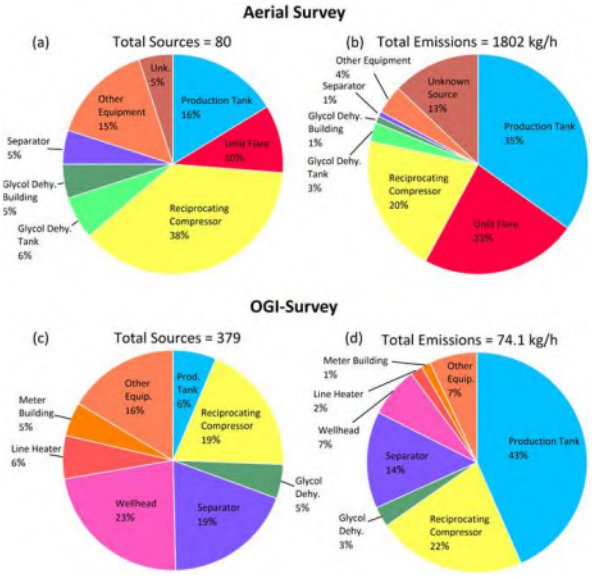
15

2019 Aerial- and 2018 OGI-survey: Sources and Emissions

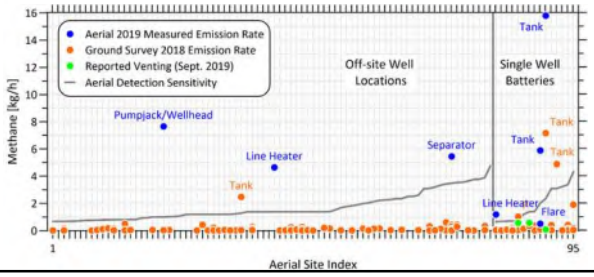
- Most frequent detected sources:
  - Aerial:
    - Compressors, tanks, other equip., unlit flares
  - OGI:
    - Wellheads, separators, compressors, other
    - 73% "fugitives", 27% "Vents"
- Largest emissions contributors:
  - Aerial:
    - Tanks, unlit flares, compressors ~3/4 of total
  - OGI (incl. estimates)
    - Tanks (estimates), compressors, separators

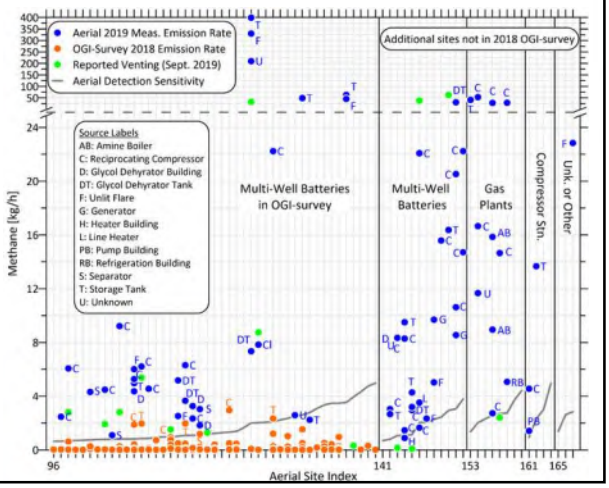


16

Site Level Emissions (excluding pneumatic device emissions)

- Attributed sources at different facility types
- Site-by-site source comparisons further highlight differences with ground survey
- Reported venting (Petrinex, green dots) not a factor at most sites
- Sensitivity function demarcates aerial and ground survey data remarkably well
  - Can combine to estimate total emissions





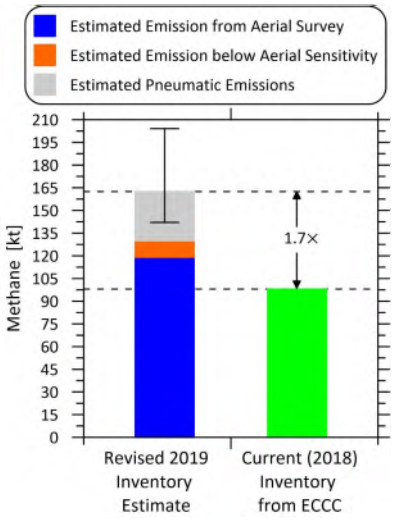
Site Level Emissions (excluding pneumatic device emissions)

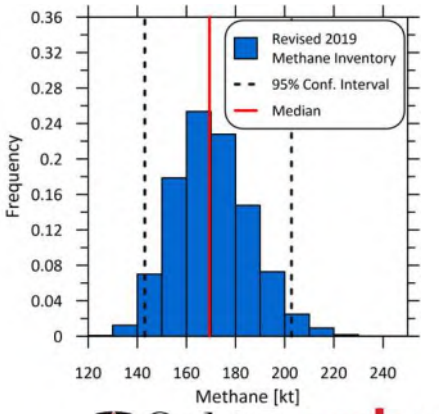
- Measurement-based emission estimates by site type (excluding pneumatics)
  - Combines direct aerial measurement data and ***portion*** of ground survey data below the aerial sensitivity limit
  - First-ever direct measurement based methane estimates by facility type
- 95% confidence limits represent Monte Carlo derived uncertainties in Bridger measurement data
  - Uses uncertainty data from blinded controlled releases (Paper 1)

Aerial Survey Site type	Count	Total Aerial Emissions [kg/h]	Total OGI Emissions below Aerial Sensitivity [kg/h]	Estimated Emission Rate [kg/h/site][b]
Wells at Off-Site Well locations	105	17.8	9.5	0.26 (0.21,0.35)
Single Well Battery	15	23.4	9.2	2.2 (1.6,3.2)
Multi-Well Battery	57	1491.7	31.3[a]	26.7 (19.1,38.1)
Gas Plant	8	227.0	4.4[a]	28.9 (27.3,38.4)
Compressor Station/Gas Gathering System	4	19.6	2.2[a]	5.5 (4.9,7.8)
Unknown/Liquids hub	2/1	0/22.8	NA	NA

New (First-ever) Measurement-Based Methane Inventory

- Comparison with ECCC Inventory
  - Measured sources by Bridger
  - Measured/estimated sources below sensitivity from OGI
  - Pneumatics based on actual count & manufacturer data
  - Uncertainty in Bridger measurements from Monte Carlo analysis
- 1.5-2.1× higher is consistent with other recent Western Canada Studies (ECCC≈2×)





19

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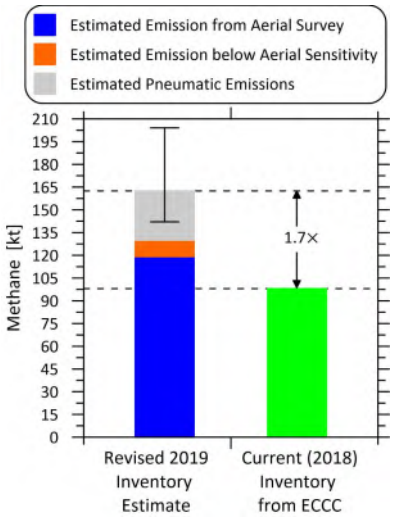
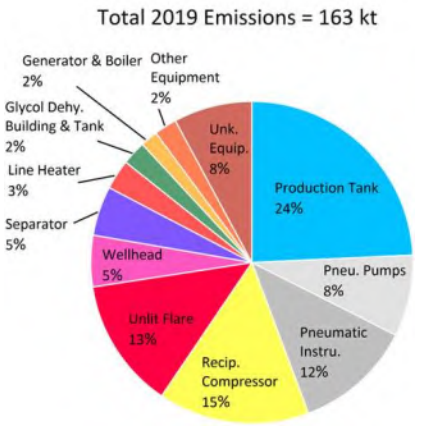
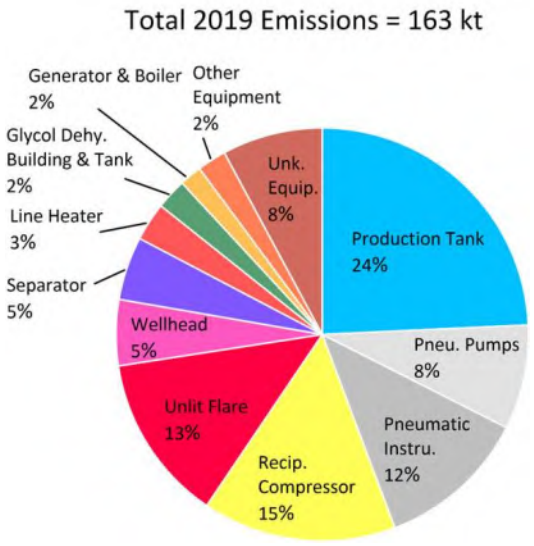




20

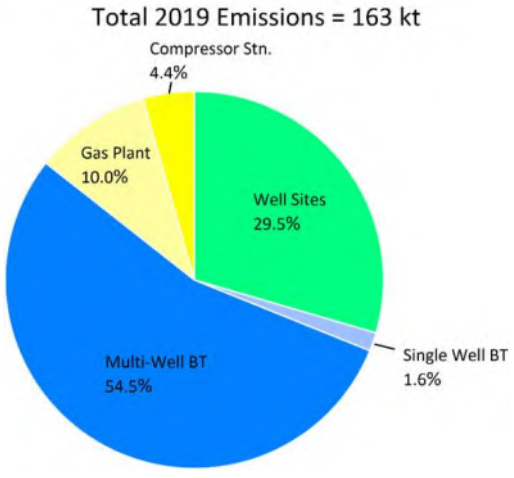
"Where the Methane Is"

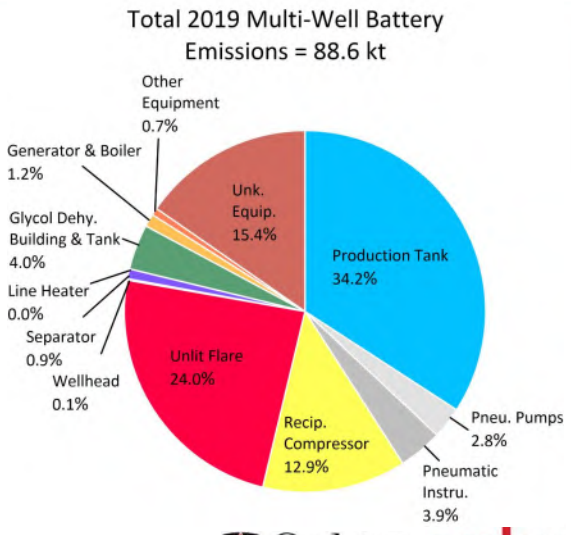
- Best estimate breakdown of upstream methane sources in BC
  - Likely the first-ever comprehensive, measurement-based source distribution at this scale
- Some implications:
  - Pneumatics appear less of a concern than thought
  - Compressors and tanks are more important than thought
  - Unlit flares are a possible wild card but should be easily addressed with quick benefit



21

Where the Methane Is – Estimated Methane Source Breakdowns by Facility Type





22

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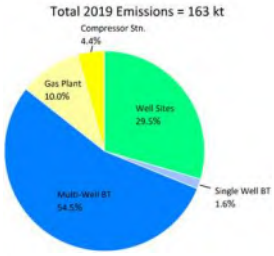

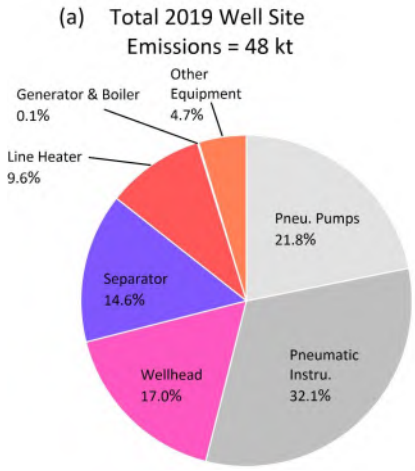

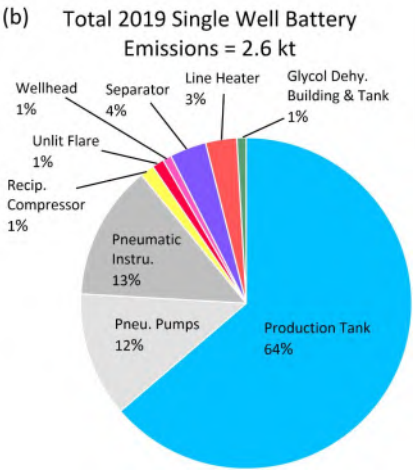

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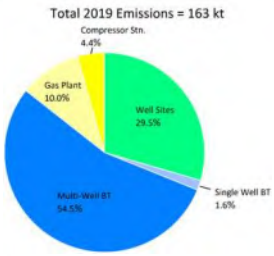

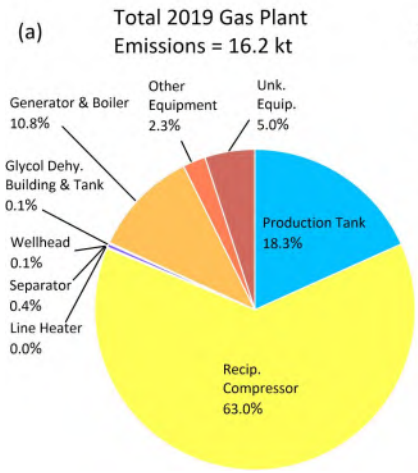

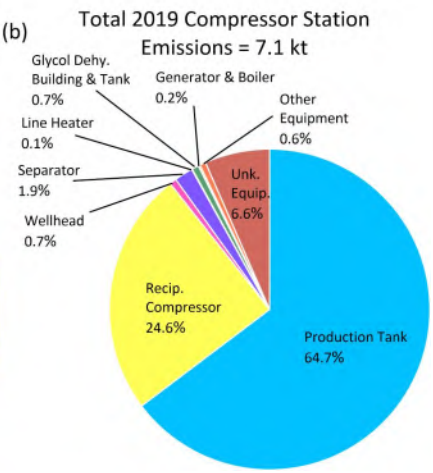

Comments and Recommendations

- Tanks are a critical source as seen in both surveys
  - Character of tank emissions is largely unknown and poorly quantified
    - Variability in flux (both methane and total gas flow)? Implications for mitigation?
    - A study to characterize the transient nature of tank emissions through direct connection on-site measurements as we have proposed would be very valuable
- Recommend a second survey with larger sample size (under more efficient routing), planned based on what we have learned
  - Tracking mitigation progress since Jan. 2020
  - Would support new inventories, gas certification, policy review, and equivalency renewal
- Analysis shows power of this approach in better understanding source breakdown of emissions and doing what was not even possible just 5 years ago
  - Many ways to extend!

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25

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