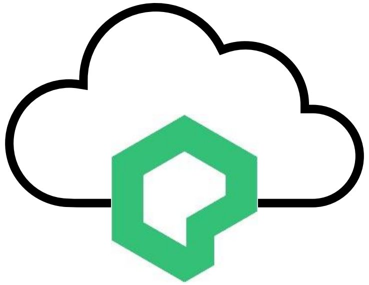
Application of Continuous Monitoring to Landfill SEM

October 29th, 2024

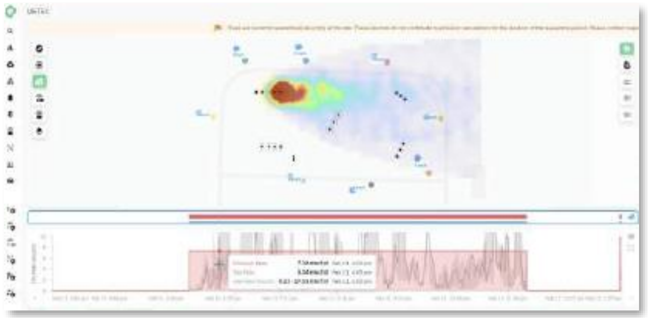
QUBE

Introduction: Continuous monitoring (CM) systems typically consist of three elements

Hardware

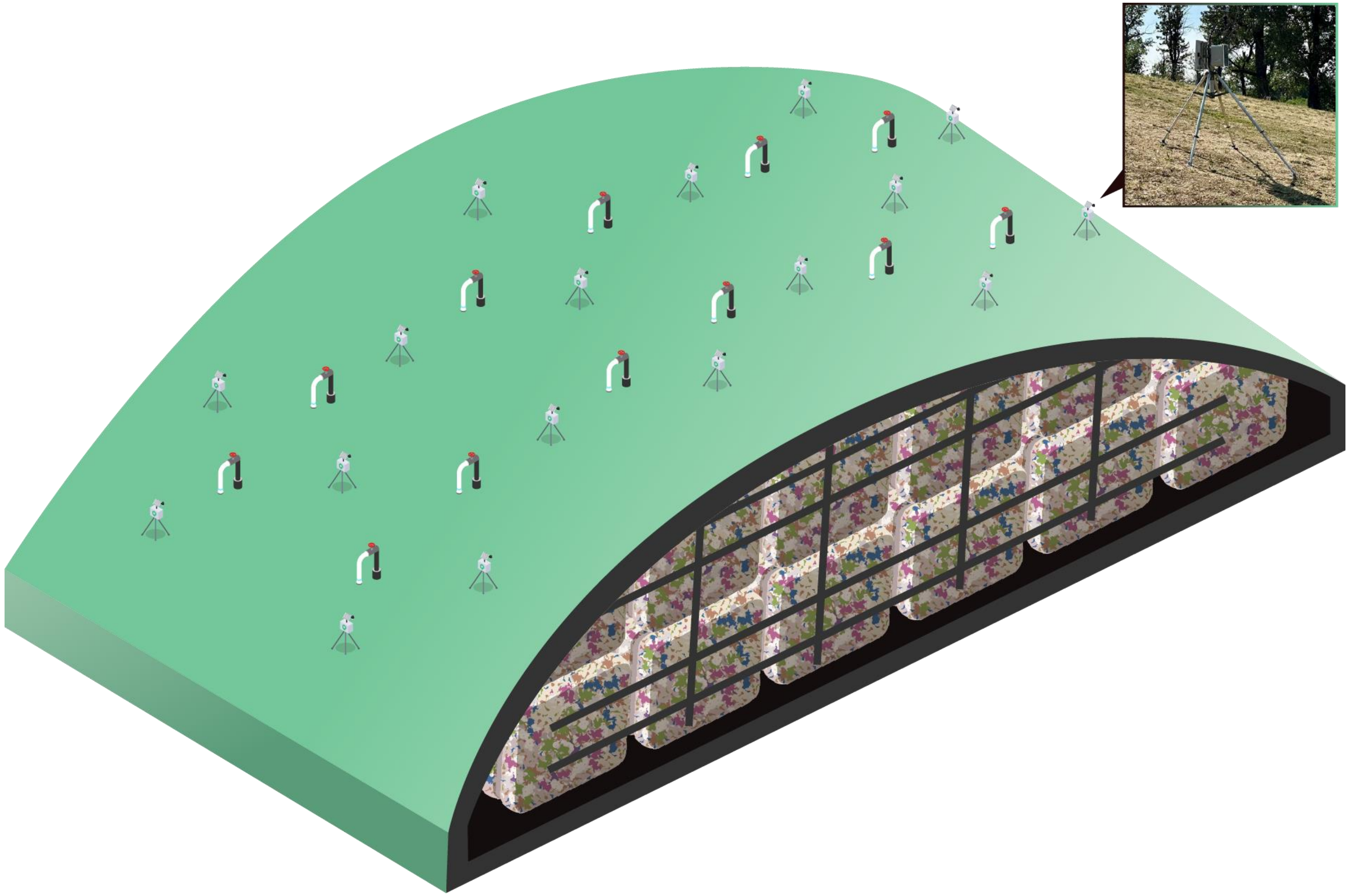


Analytics



Dashboard

Introduction: How do we deploy continuous monitoring (CM) for landfill applications?



High-level view: How does CM fit into the evolving landscape of landfill emissions measurement?

CM **already offers tangible advantages** for reducing landfill emissions relative to current SEM approaches

Internal perspective

External perspective

CM is a **rapidly-evolving technology** with **long-term promise** for managing landfill emissions

Comparison to Method 21: Advantages of CM technology

Time to detection

24/7 monitoring **alerts operators instantly** when leaks are detected, rather than **waiting for quarterly SEM**

Surface coverage

Monitor the entire landfill surface, including the active face and dangerous areas

Environmental resiliency

Devices can last over 7 days without sun and **operate from -40°F to +140°F**

Odor management

Additional sensors (e.g, H_2S, SO_2, etc.) and **device-level wind data assists** with odor detection and mitigation

Volume-based data

Physics-based models go **beyond sensor-level ppm**, using wind and atmospheric conditions to **estimate flow rates and total volume**

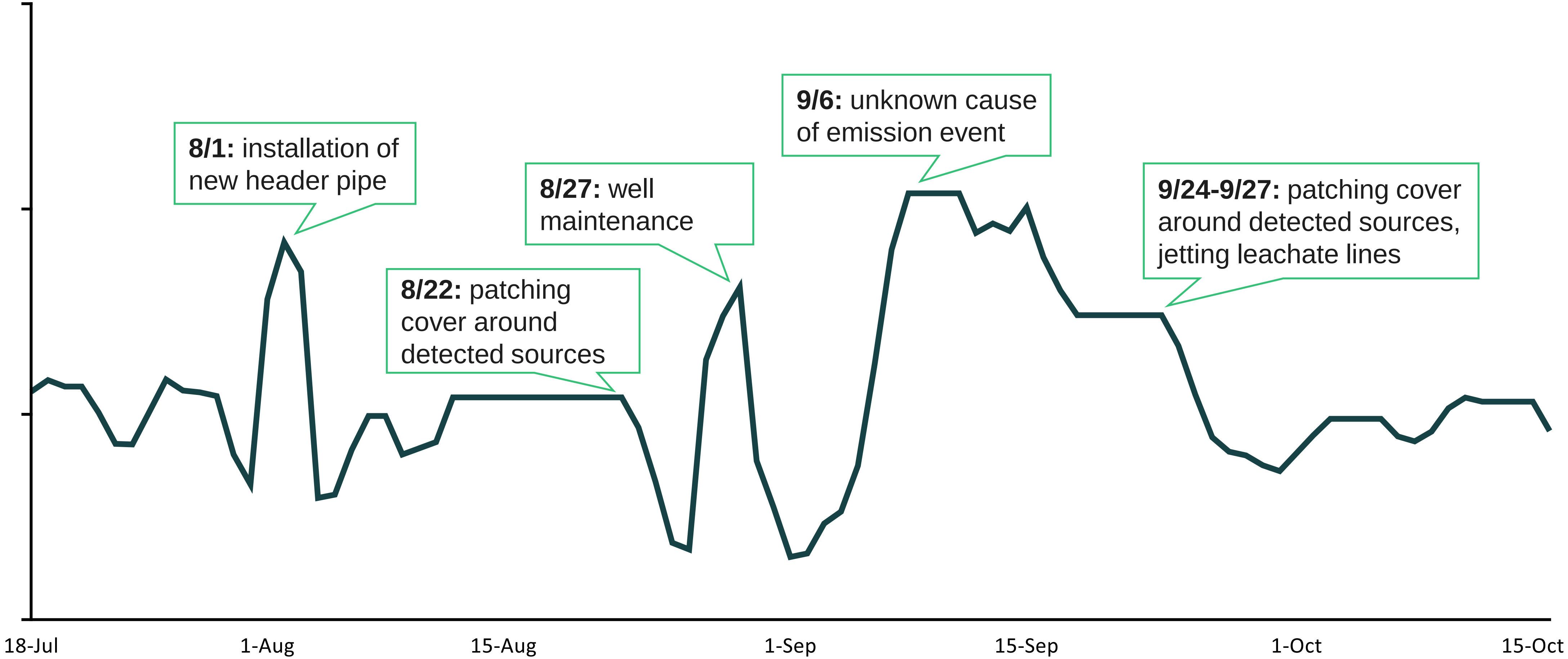
Operational insights

Utilize real-time and rolling-average data to **assess impact of operational practices** (e.g., cover type, effect of repairs and extra collection wells, etc.)

Device connectivity also enables over-the-air updates as advancements in modelling and functionality are made

Case study: Correlation with Ops activities and repairs

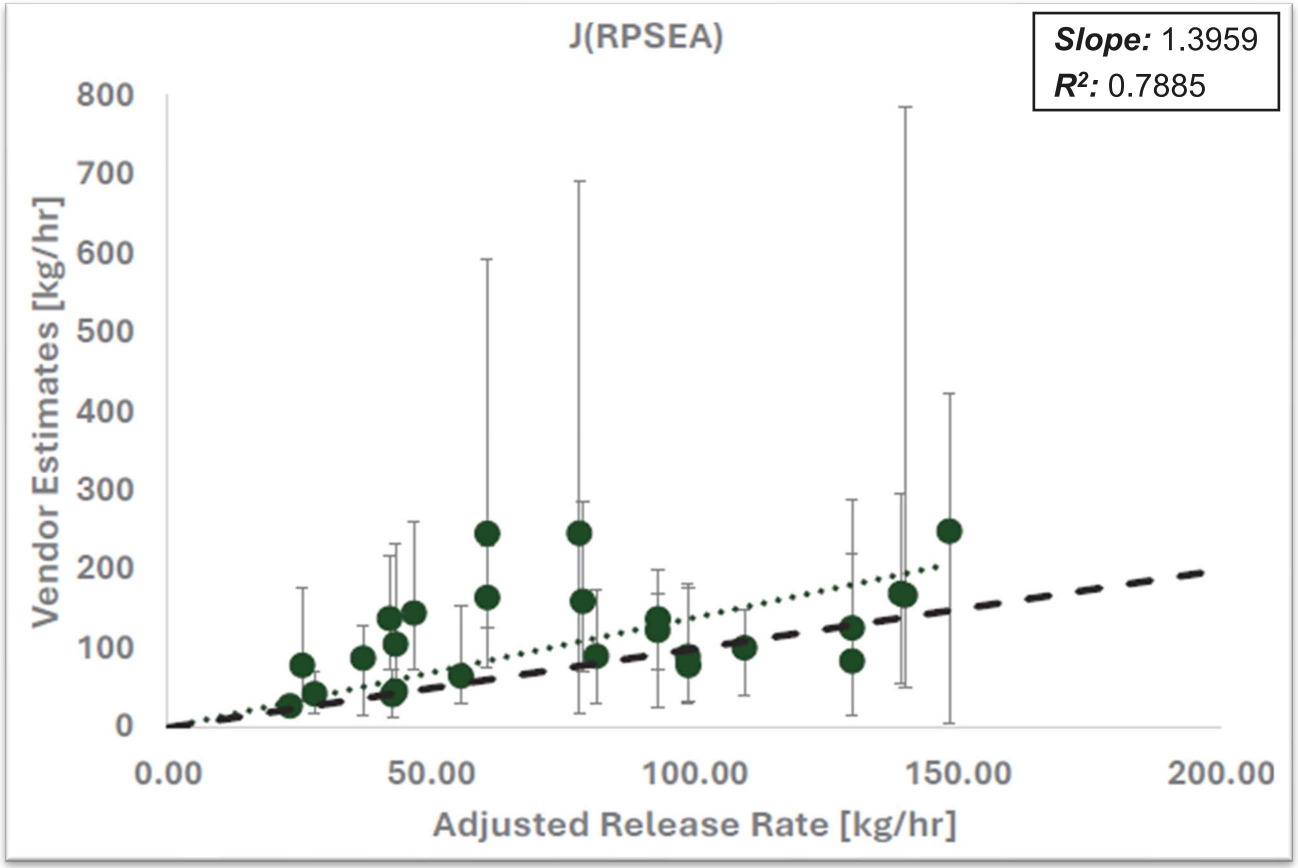
Three-day rolling average of daily emissions volume from section of landfill



Comparison to Method 21: Challenges for CM technology

	Description	Mitigation
Complex topography	• Typical dispersion models assume flat ground • Slopes and undulations shape local wind and methane dispersion	• Each device has its own anemometer to capture local wind effects • Delineate “sub-sites” for each major slope, creating more consistent dispersion patterns for the model
Simultaneous emissions	• Typical models focus on identifying the single most likely emission source at a given time • Landfills often have multiple emission sources occurring simultaneously	• **Short term:** sub-site approach reduces the likelihood of simultaneous emissions, while operators “find and fix” one source at a time • **Medium term:** release multi-source model (under development)
Distance from source	• CM devices in other industries have typically been deployed around site perimeters • Perimeter deployment would leave devices too far away from potential sources at large landfills	• New stands designed for landfills allow CM devices to be deployed on steep and uneven terrain

Technology performance: Emission rate



Source: "A Controlled Release Experiment for Investigating Methane Measurement Performance at Landfills", FluxLab and Environmental Research & Education Foundation

FLUX gas detection LAB measurement

Strategic Partner EREF

Technology comparison: What is the annual cost of each?

	Remote Point Sensor	$7-30k
	Satellite Imaging Sensor	$12-26k
	UAV Column/Point Sensor	$20-32k
	Airborne Point Sensor	$56k
	Gas Mapping LiDAR	$56k

**Annual cost for intermittent technologies based on quarterly usage. Daily cost estimates from EREF/FluxLab report*

Source: “A Controlled Release Experiment for Investigating Methane Measurement Performance at Landfills”, FluxLab and Environmental Research & Education Foundation

Strategic Partner

For discussion: Where do we go from here?

What do we still need to learn?

- **Alternative compliance protocol –** what requirements and guardrails should this include (e.g., emission alert levels, response times, reporting exceedances)?
    - Critical to ensure that the protocol **does not punish more frequent monitoring** and data collection
- **Coverage density –** what is the minimum number of devices required to provide adequate coverage for a given landfill size?

How do we get there?

- **Academic studies –** test key questions in landfill settings (e.g., FluxLab SIMFLEX site)
- **Real-world pilots –** gather data and learnings from partnering with on-site operators
- **Regulatory pathways for alt-tech –** approval pathway for products that demonstrate equivalent or superior results to traditional SEM
    - **Example of regulator-led program:** EPA OOOOb Alternative Test Method (ATM)
    - **Example of operator-led program:** Alberta Alternative Fugitive Emission Management Program (alt-FEMP)

Thank you for listening!

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Appendix

Additional seed questions/topics for discussion

Question	Response
How do you manage variable winds and other complex environmental conditions?	• Each device has its own anemometer to continuously record wind speed and direction in addition to recording temperature, humidity, and pressure • Air-dispersion model factors in these varying environmental conditions to estimate source location and emission rate
Is your resolution sufficient to distinguish between allowable emissions (working face) and those that are not allowed?	• Ground-based sensors localize to specific source locations, easily differentiating between sources within the working face and covered areas
Has the technology been tested for any potential chemical interferences from other species present in emissions from landfills, and if so, what were the results?	• Metal-oxide sensors undergo in-house calibration for each combination of temperature and humidity • Methane sensors are not affected by other components of landfill gas. Each device can add sensors to measure up to four other gases directly (e.g., H_2S, SO_2, NO_2, etc.)
What are the required environmental conditions (wind conditions, topography etc.) for your technology to be useful?	• Operating range of -40°F to +140°F, relative humidity of 10-100% • Air-dispersion model requires non-zero wind speed
What are the results of uncertainty analysis of the technology?	• Qube participated in controlled release testing at WM's Petrolia landfill (conducted by FluxLab). Results of quantification accuracy had a slope of 1.3959 and an R^2 of 0.7885

Qube at a glance

Leading CM provider with 5,000+ deployments

Deployed in 10 countries

Work with 90+ operators

Approved by regulators and independently tested

60+ FTEs in Calgary, Houston, Midland, Denver, DFW

Deployed at O&G, Landfills, Mines, Biogas/RNG Facilities

We have measured and recorded:

3,000,477,831 concentration values

22,975,155,009 wind values

Detailed specifications: CH_4 detection and sensor resolutions

PERFORMANCE SPEC	RANGE
CH_4 detection temperature range[1]	-40 to 60°C
CH_4 detection relative humidity range[2]	10 – 100%
CH_4 minimum detection limit[3]	0.1 kg/hr
CH_4 90% probability of detection[3]	1.5 kg/hr
Measurement frequency	3-5 seconds
Transmission frequency[4]	1-20 minutes
Quantification frequency	1 minute
Connectivity	LTE Cat M1: bands: 2, 4, 5, 12, 13
Solar panel	30-45W
Battery[5]	Lithium titanate with 8 days of reserve

SENSOR	UNIT (OUTPUT)	RANGE	RESOLUTION	LIFESPAN (YEARS)
CH_4	ppm	0 – 100, 101 – 1,000	≤1 ppm, >10 ppm	>5
CO	ppm	0 –1,000	0.1 ppm	>5
CO2	ppm	0 – 40,000	40 ppm	>10
SO2	ppb	0 – 20,000	50 ppb	>5
H2S	ppb	0 – 10,000	10 ppb	>5
NO2	ppb	0 – 5,000	20 ppb	>5
VOC	ppm (COe)	0 – 400	100 ppb	>5
PM* 1, 2.5, 4 and 10	µg/m3	1 to 1000 µg/m3	1 µg/m3	8

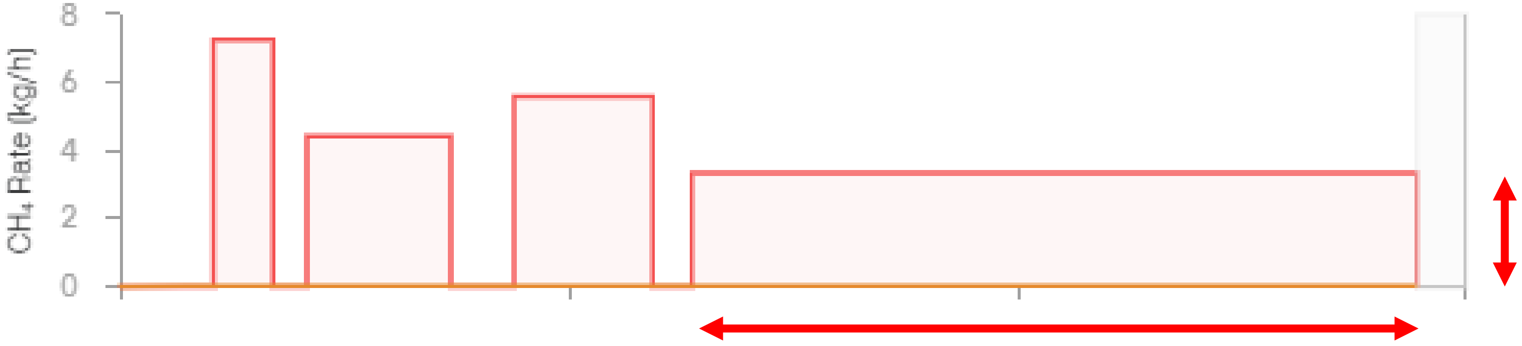
Note:
1. Temperature range varies on the version of CH_4 sensor deployed. Standard range is -40C to +50C, High temp range is -10 to 60C.
2. Relative humidity range varies on ambient temperature and the version of CH_4 sensor deployed. Standard range is 10-90%, High temp range is 10-100%. Range decreases linearly at upper temperature ranges.
3. Minimum detection limit and 90% probability of detection (PoD) verified through blinded 3rd party testing at METEC. Qube's own testing indicated a 90% PoD of 1kg/hr
4. Transmission frequency varies depending on compression at device level (e.g., if no detection the transmission frequency lowers).
5. Battery is capable of discharge at -40 but solar recharge limited at <-20C which is why a reserve of 8 days at 100% is included.

Technology performance: Considerations for assessing quantification accuracy

Concentration
(ppm)

Momentary rates
(kg/hr or mscf/d)

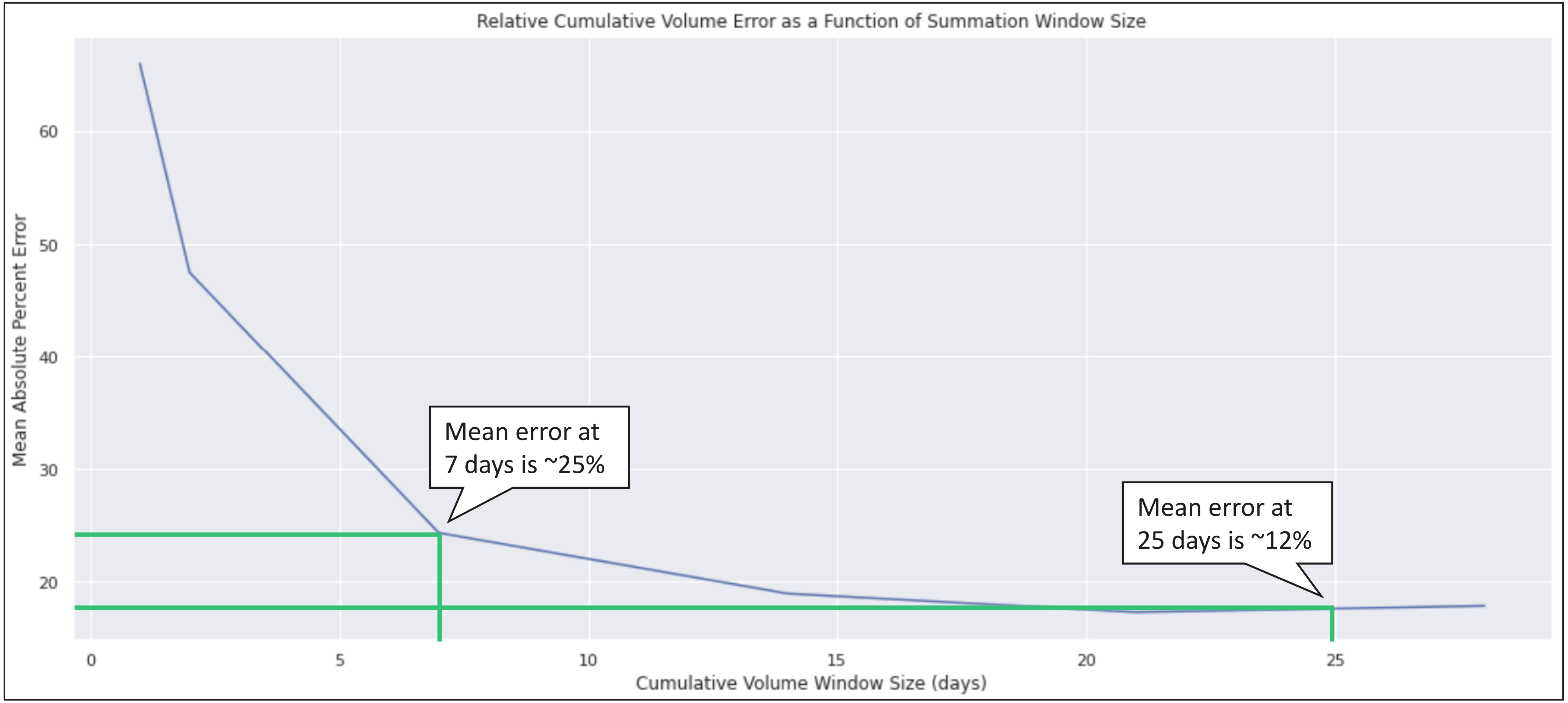
Total emissions
(kg or mscf)



Rate is important,
But it's only half of the equation

Duration & coverage,
Equally important

Technology performance: Cumulative emissions



Source: Internal analysis of 2022 METEC ADED controlled release testing results