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Author (year)	**Title**	**Detection Method**	**Number of Sites Surveyed**	**Key Findings**	**Did Publication Evaluate FEMP Effectiveness Knowledge Gaps?**					
					Did maintenance program repair leaks and confirm [screening] < 500 ppmv?	**What was cost to repair leaks?**	**Did survey method detect 100% of leaks?**	**What was the survey minimum detection limit?**	**What impact does survey frequency have on reducing leak magnitude and frequency?**	**Was abnormal process venting assessed (and distinguished from equipment leaks)?**
Allen et al (2013)	Measurements of methane emissions at natural gas production sites in the United States	OGI and tracer test	150 onshore production sites	Measurements indicate that well completion emissions are overestimated in the EPA national emissions inventory, while emissions from pneumatic controllers and equipment leaks are underestimated. Equipment leak emissions are comparable to the EPA estimates.	Not evaluated	Not evaluated	Dual tracer tests completed by Aerodyne used to validate OGI detection and High-Flow measurement.	Leak detection surveys were conducted by infrared cameras in this study. The leak detection threshold for Infrared cameras is stated to be 30 g/hr (0.026 scf/m). Hi-Flow samplers are used for leak measurements. The smallest non-zero leak rate measured was 0.00048 scf/m which is considered as the detection limit.	Not evaluated	Yes, emissions delineated by category. Conclusions focus on comparison of EPA national inventory estimates versus field observations.
Ravikumar, Wang and Brandt (2017)	Are optical gas imaging techniques effective for methane leak detection?	OGI	8 separate studies	Imaging distance plays the most important role in leak detection, and failing to specify maximum imaging distance will lead to inconsistence reported leak rates.	Not evaluated	Not evaluated	Detection efficiency for a given plume under identical conditions decreases with increasing imaging distance. It is found that about 90% of emissions are detected at 10 m distance while only about 40% are detectable at 200 m. Also, increasing temperature difference between the plume and background increases the detection efficiency by enhancing contrast. Consequently, taking leak images from the ground with the sky as the background scene leads to higher contrasts and leak detection efficiency than aerial images looking down. Other factors that improve detection efficiency are (1) low humidity, (2) gas plumes containing hydrocarbons heavier than methane and (3) backgrounds with low emissivity (e.g., metallic surfaces provide better contrast than soils or forest).	Minimum detectable leak rate (MDLR) ranges from ~1 to 20 g/s depending on imaging distance and temperature difference. Recommended that minimum imaging distance be determined based on a desired MDLR.	Not evaluated	Excluded compressor seal vents (implies that large abnormal process vents are not assessed.)

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Omara et al (2016)	Methane emissions from conventional and unconventional natural gas production sites in the Marcellus Shale Basin	OGI and tracer test	25 sites	(1) The methane emissions distribution was found to be highly skewed. (2) Reported methane emissions for Pennsylvania substantially underestimate measured facility-level CH4 emissions by 10 to 40 times for five UNG sites in this study. (3)Observed methane emissions correlated against production type (conventional vs unconventional), gas production rate, facility age, and maintenance practices. Although some correlation with production is observed, the study does not provide conclusive evidence that methane emissions can be predicted based on a single parameter. It does state facility age is not strong indicator of methane emissions.	Conventional sites that exhibited signs of aging infrastructure and had known maintenance issues were among the highest emitting sites. Well operator practices (e.g., the frequency of well inspection and maintenance) may exert a significant impact on facility-specific CH4 emissions. Component-level screening not completed.	Not evaluated	OGI used to identify methane sources, however, effectiveness of OGI method was not evaluated.	No MDL assertion.	Not evaluated	Yes

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Ravikumar and Brandt (2017)	Designing better methane mitigation policies: the challenge of distributed small sources in the natural gas sector	NA	multiple publicly-available datasets.	(1) variation in the baseline emissions estimate between facilities leads to large variability in mitigation effectiveness (2) highly heterogeneous leak-sizes found in various empirical surveys strongly affect emissions reduction potential; (3) emissions reductions from OGI-based LDAR programs depend on a variety of facility-related and mitigation-related factors and can range from 15% to over 70%; (4) while implementation costs are 27% lower than EPA estimates, mitigation benefits can vary from one-third to three times EPA estimates; (5) a number of policy options will help reduce uncertainty, while providing significant flexibility to allow mitigation informed by local conditions.	Not evaluated	Study relies on EPA methodology for estimating repair costs (2015 Background Technical Support Document for the proposed NSPS).	OGI effectiveness depends on: (1) viewing distance (declines with increasing distance. Max distance of 5 meters recommended), (2) visual acuity and experience of the operator (demonstrated to impact MDL but difficult to relate back to human characteristics), (3) ambient temperature (very poor detection below 0 Celsius), and (4) wind speed (almost linear decline from best detection @ 1 m/s to half of best @ 9 m/s).	OGI MDL not a study objective.	When max viewing distance is 5 meters, FEAST model predicts 40% (annual survey), 60% (semi-annual survey) and 70% (quarterly survey) methane reduction relative to a baseline 'null-repair' scenario (i.e., periodic repairs by operators as part of 'normal maintenance). Modelling advantage is observing behavior over multi-year periods for different survey frequencies at a much lower cost relative to field observations. However, predicted results are only as good as the underlying assumptions programmed into FEAST. The assumption that 100% of detected leaks are repaired is overly optimistic and likely results in an overstatement of methane reductions. To explore the production sector cases in more detail: a semi-annual LDAR survey only reduces emissions by 37%, 41%, and 48% in the facilities modeled using the Allen (2013), ERG [20], and Kuo [21] distributions, respectively. Mitigation potential drops dramatically and survey frequency becomes less important as viewing distance increases beyond 10 meters.	FEAST designed to model equipment leaks not process vents.

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Ravikumar A P, Wang J, McGuire M, Bell C S, Zimmerle D and Brandt A. (2018)	"Good versus Good Enough?" Empirical Tests of Methane Leak Detection Sensitivity of a Commercial Infrared Camera.	OGI	5 days of testing at METEC	The study provides empirical evidence regarding the probability of leak detection with respect to imaging distance and leak magnitude. It indicates a 90 percent probability of detecting a leak at the EPA minimum detection limit of 30 g CH4/h if the imaging distance is 4 meters. The probability decreases as the OGI camera operator moves away from the source . Moreover, it is predicted that the fraction of leaks detected saturates at median detection limit of ≤ 100 g CH4/h, and any improvement in sensitivity beyond this limit does not improve leak detection. This is because leak-size distribution is highly skewed in natural gas production facilities, where a small number superemitters account for the large fraction of total emissions. These superemitters are easily detectable at lower sensitivities, and increasing sensitivity only results in detecting small leaks that do not contribute significantly in total emissions. The authors conclude that current OGI technology is good enough for detecting leaks as a detection limit of 20 g CH4/h is obtained from an imaging distance of 3 m.	Not evaluated	Not evaluated	The study indicates a 90 percent probability of detecting a leak at the EPA minimum detection limit of 30 g CH4/h if the imaging distance is 4 meters. The probability decreases as the OGI camera operator moves away from the source .	Controlled single blind leak detection tests show that the median detection limit (50% detection likelihood) for FLIR-camera based OGI technology is about 20 g CH4/h at an imaging distance of 6 m, an order of magnitude higher than previously reported estimates of 1.4 g CH4/h.	Not evaluated	Not evaluated
Zavala-Araiza D, Herndon SC, Roscioli JR, Yacovitch TI, Johnson MR, Tyner DR (2017)	Methane emissions from oil and gas production sites in Alberta, Canada	Tracer Dilution and Inverse Plume dispersion	60 sites (25 sites with tracer; 35 with inverse dispersion)	20% of sites responsible for 75% of emissions; Trends similar to other production regions in North America; Statistics analysis suggests superemitters are influencing overall emissions (where emissions at sites are stochastic and therefore not predictable); Loss rates in Red Deer are among the highest of any region measured.	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated
Johnson, M.R., Tyner, D.R., Conley, S., Schwietzke, S, and Zavala-Araiza, D. (2017)	Comparisons of Airborne Measurements and Inventory Estimates of Methane Emissions in the Alberta Upstream Oil and Gas Sector	Aircraft flux (box) method with C2/C1 ratio combined with EDGAR data	Two regions (50x50km and 60x60km) each with ~2700 sites	Actual emissions in Lloydminster 3-5x higher than inventory and 5+ times higher than reported. Casing gas venting (bad GOR measurements) likely the cause. In Red Deer region, 94% of emissions are from sources not currently captured in Petrinex reporting.	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated

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Lyon, D. R., Alvarez, R. A., Zavala-Araiza, D., Brandt, A. R., Jackson, R. B., & Hamburg, S. P. (2016)	Aerial Surveys of Elevated Hydrocarbon Emissions from Oil and Gas Production Sites	FLIR via helicopter	8220 well pads in 7 U.S. Basins	Overall, 4.0% of sites had large leaks. As many as 14.9% of sites in Bakken had large leaks; Detected leaks were more likely at oil sites than gas sites and more likely at low GOR sites than high GOR sites; Tanks are by far the most common source for large emissions (92% of all leaks were tanks or thief hatches); Newer sites more likely to leak than older sites (contrasts with Atherton et al.); Detailed statistical modelling cannot predict emissions with operating parameters such that sources are stochastic and unpredictable (requiring monitoring to detect)	Not evaluated	Not evaluated	Interesting side note: Test of 19 sites revealed NO CORRELATION between IR camera operator estimates of leaks size and actual leak size; IR camera detection limit (from helicopter) estimated to be 1g/s for wet gas (tanks) and 3 g/s for dry gas (mostly methane) -- this was worse at higher wind speeds	Not evaluated	Not evaluated	Not evaluated
Atherton et al. (2017)	Mobile measurement of methane emissions from natural gas developments in northeastern British Columbia, Canada	Drive-by vehicle survey	~1600 sites	~47% of sites emit above minimum detectable limit (MDL), crudely estimated at 0.59 g/s; Indication of increased emissions at older sites (incl. abandoned wells); extrapolations based on MDL suggest emissions in BC are much higher than government estimates;	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated
Rosciolli et al. (2018)	Characterization of Methane Emissions from Five Cold Heavy Oil Production with Sands (CHOPS) Facilities	Tracer Dilution	5 CHOPS sites	Higher than reported emissions. Dual tracer measurement implicates casing gas venting as main source, but emissions through tanks also important	Not evaluated	Not evaluated	Tracer dilution is the best site quantification method available today	MDL not discussed, but uncertainty of~35% in quantification suggested	Not evaluated	Not evaluated
GreenPath (2017)	Historical Canadian Fugitive Emission Management Program Assessment	OGI	1252 sites	Inconsistent data Inconsistent results in repeat frequencies	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Oscillating leak counts and rates observed for facilities subject to annual OGI inspections	Not evaluated
GreenPath for the AER (2017)	GreenPath 2016 Alberta Fugitive and Vented Emissions Inventory Study	OGI	676 sites	Low leak rate and frequency at well sites and small facilities	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Yes but in-accessible vents not quantified.
US EPA CTG (2016)	Control Techniques Guidelines for the Oil and Natural Gas Industry	OGI/FID	n/a	Assertion on changes in inspection frequency40-60-80. Synthesis of available data. Strongly relies on Carbon Limits 2013	40-60-80 and 46 to 97% effective - relies on model facilities. Overly reliant on CL 2013. 80, 60, 40 not based on previous data. Recommends repair confirmation with days.	estimated	Not evaluated	NSPS defines a leak as 10,000 PPM, NESHAP defines a leak as 500PPM for valves and 1,000 PPM for other sources	Not evaluated	Not evaluated
CCAC - TGD (2017)	Quantification methodology for fugitive emissions	OGI FID Other	n/a	Summary of best practice. Recommends annual surveys. Includes scrubber dump valve leakage as emissions type.	Provides leak common causes. No repair costs. Provides cost estimates for LDAR that are low. Economic decision on	Not evaluated	Not evaluated	10,000 PPM and 100,000 PPM overage	Not evaluated	Not evaluated

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					repairs					
Carbon Limits (2013)	Quantifying Cost-effectiveness of Canadian LDAR	OGI	4293 sites	Provides survey costs that are referenced in other regulatory development pieces. Provides aggregate abatement costs for LDAR by Facility type.	Assumes all leaks fixed. Repair data not verified – likely from CAPP 2007 BMP. Only two LDAR providers. Data set not analyzable. Sites with multiple inspections showed increasing leak rates.	Relies on CAPP BMP values adjusted by service providers	No basis to confirm OGI method detected 100% of leaks.	OGI MDL not a study objective.	Emission reductions of 40 percent are expected for annual survey frequency while further emission reductions of 60 percent can be achieved by surveying two times per year, 70 percent by surveying three times per year, and 80 percent by surveying four times per year. However, these emission reductions are inferred from simple assumptions that leak rate magnitude increases linearly with time and that 100 percent of leaks are detected and repaired.	Not evaluated
Carbon Limits (2017)	Statistical Analysis of leak detection and repair in Canada	OGI	3913 sites	Focuses 2013 data on only Canadian data. Canadian data equivalent to US data for most component types	Same as CL2013	Relies on CAPP BMP values adjusted by service providers	No basis to confirm OGI method detected 100% of leaks.	OGI MDL not a study objective.	Yes, based on sites with more than 1 data point	Not evaluated
Carbon Limits (2018)	Statistical Analysis of Leak Detection And Repair Programs in Europe	FID	415 sites	Time series data on multiple method 21 engagements in T&D	In the data set only 2,000 records have Multiple measurements. Of those 2,000 records, only 60% show that an effective repair was executed.	Not evaluated	FID Based -minimum of 10ppm Maximum of 100,000ppm	<10ppm = background methane	Yes, based on components where concentrations recorded after measurement.	Not evaluated

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Clearstone (2018)	Update of Alberta Upstream Oil and Natural Gas Equipment, Component and Fugitive Emission Factors	OGI	333 sites	The following factors are developed for emission inventory purposes. o Process equipment count per facility subtype or well status code. o Component count per process equipment unit. o Emission control type per process equipment unit. o Natural gas driven pneumatic device count per facility subtype or well status code. o Leak rate per component and service type considering the entire component population surveyed (i.e., 'average population' factor). o Leak rate per component and service type considering leaking components only (i.e., 'leaker' factor).	Not evaluated	Not evaluated	No basis to confirm OGI method detected 100% of leaks. Uncertainty assessment considers that every 3 of 4 leaks were detected.	OGI MDL not a study objective.	Not evaluated	Yes, qualitative estimates indicate the majority of methane emissions observed during the 2017 field campaign is from venting sources (pneumatics, production tanks, casing vents and unlit flares).