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FINAL PROJECT REPORT

Quantifying Methane from California's Plugged and Abandoned Oil and Gas Wells

Gavin Newsom, Governor

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Natural Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater natural gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Quantifying Methane from California's Plugged and Abandoned Oil and Gas Wells is the final report for the Quantification of Methane from California's Plugged & Abandoned Oil and Gas Wells: Effects of Land Subsidence and Other Factors project (Contract Number PIR-16-013) conducted by the University of California, Davis. The information from this project contributes to the Energy Research and Development Division's Natural Gas Research and Development Program.

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ABSTRACT

Several studies have examined methane emissions from abandoned oil and gas wells in the United States. California has more than 120,000 documented abandoned oil and gas wells, plus 30,000 idle and 70,000 active wells. To evaluate methane super-emitters in the state, NASA/JPL undertook an aerial survey of methane point sources. The survey included 88 percent of all documented California oil and gas wells and found that 107 wells were leaking methane above the threshold of detection (2 – 10 kilograms per hour). Complementing the aerial survey work, the project team for this study measured emissions from a sample of 121 wells using ground-based instruments. These instruments included a rapid and nonintrusive mobile plume integration instrument and highly sensitive static flux chambers. The measurements provided three to nine orders of magnitude greater sensitivity than the aerial measurements. The researchers adopted an upper limit "leak threshold" of 1 gram of methane per hour. The team measured 97 abandoned and plugged wells, finding only one that exceeded the leak threshold. The researchers also found leaks from 11 of 17 idle wells (mean emissions: 35.6 grams of methane per hour), 4 of 6 active wells (mean emissions: 189.7 grams of methane per hour), and 1 unplugged well (10.9 grams of methane per hour). Acknowledging the small sample size of wells not in the "abandoned and plugged" category, the project team suggests that idle and active wells may account for most emissions from all well status designations. Overall, the sample of wells in this project suggests little evidence for extensive leakage from plugged and abandoned wells in California. However, the researchers acknowledge the sample, obtained from small fields on public and private lands, may not represent most abandoned and plugged wells that are primarily located in active major oil and gas fields.

Keywords: abandoned wells, methane emissions, greenhouse gas

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EXECUTIVE SUMMARY

Introduction

Gas leakage from hydrocarbon infrastructure is a major concern because the primary component of natural gas is methane, a potent greenhouse gas. Concerns arise for all well types, including abandoned wells. Previous work in Pennsylvania found that 470,000-750,000 abandoned wells in the state emit 0.04-0.07 million tons of methane per year, equivalent to 5 percent to 8 percent of Pennsylvania's total annual anthropogenic (caused by human activities) methane emissions.

Regular monitoring of oil and gas wells is only mandatory during the active lifetime of the well, resulting in millions of inactive wells (no longer producing) unmonitored. As such, emissions reported by the industry and state's greenhouse gas (GHG) inventories currently only provide a lower estimate of atmospheric methane emissions because not all leaks are identified and quantitative data on release rates are rare.

Because California has around 120,000 abandoned and plugged wells, there is an interest in quantifying methane emissions from those wells.

Project Purpose

This project measured methane leakage from abandoned oil and gas wells across California to determine the contribution, if any, to California's methane budget, and whether land subsidence (sinking of an area of land) contributed to emission rates from those wells. From a sample of approximately 120 wells, the researchers found no appreciable leaks from any abandoned and plugged wells, leaving the project team unable to conclude whether land subsidence affected emissions. However, the team were unable to gain permission to access any major oil and gas fields in California for measurements and this limited their conclusions to wells in smaller fields located on a mixture of public and private lands.

A 2019 California Methane Survey sampled oil and gas wells using aircraft to identify super-emitting sources (in the context of that study, those with emissions of 2-10 or more kilograms of methane per hour). The researchers in this well study complemented that airborne survey research by providing more sensitive methane emission measurements of abandoned and plugged wells across California in cooperation with the California Department of Conservation and the California Energy Commission (CEC).

Project Approach

The research team, with support from state and federal agencies, worked with private landowners to access a limited number (97) of abandoned and plugged wells and a single unplugged (not properly retired) well. To leverage the low-cost opportunity to collect data on a variety of well types, the team also measured 23 idle and active wells. Collectively, these auxiliary data will help to inform future research, particularly Assembly Bill 1328 (Holden, Chapter 772, Statutes of 2019). This legislation requires the Division of Oil, Gas, and Geothermal Resources, in consultation with the California Air Resources Board, to study a representative sample of idle, idle-deserted, and abandoned wells in California to better understand emissions from these wells and assist with identifying hazardous wells.

The team used two methods to measure methane emissions: a rapid and non-intrusive mobile plume integration method (with a detection limit of approximately 0.5 grams of methane per hour) and a highly sensitive static flux chamber (with a minimum detection of $1x10^{-6}$ grams of methane per hour). A static flux chamber is a closed chamber that encompasses the footprint of the leak, which is sealed to the surrounding environment.

Project Results

The researchers measured 97 abandoned and plugged wells in California, finding only a single well that exceeded the leak detection threshold. The leaking well was located in a field containing active tar pits, which are area sources of methane emissions that complicate interpretation of the measurement as uniquely from the abandoned and plugged well. The mean emissions of all abandoned and plugged wells was 0.286 grams of methane per hour if one includes the measurement at the tar pit, and 0.0173 grams of methane per hour if not. The team also measured several other well types:

- Idle wells: 11 of the 17 wells examined (65 percent) were found to be leaking (mean emission: 5.6 grams of methane per hour).
- Active wells: four of the six wells examined (67 percent) were leaking (mean emission: 189.7 grams of methane per hour).
- Unplugged well: the one well examined was found to be leaking 10.9 grams of methane per hour.

While acknowledging the limited sample size of wells not in the abandoned and plugged category, the researchers found that idle and active wells could account for most emissions from all well-status designations. Taken together, the limited sample of wells suggests there is little evidence for leakage from plugged and abandoned wells in California.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

The methods and results of this work have been prepared for publication in a peer-reviewed journal. Throughout the project, the authors communicated with members of the project technical advisory committee to share results. Additionally, the authors communicated with the Department of Conservation to discuss the results of this study to help inform their approach to Assembly Bill 1328.

Benefits to California

This work provides results on methane emissions from an initial sampling of abandoned and plugged wells in California that suggests emissions are small compared to other oil and gas methane sources and even smaller compared to other sources such as agriculture. These results indicate that current practices for abandoning wells may be adequate with no need for modifications whose costs could be borne by ratepayers. However, given the small sample size and without samples from major oil and gas fields, any conclusions about plugged and abandoned wells across California are limited.

CHAPTER 1: Introduction

Previous Work

Gas leakage from hydrocarbon infrastructure is a major concern because the primary component of natural gas is methane. Methane (CH_4) has a global warming potential (GWP) 86 times greater than carbon dioxide (CO_2) over 20 years and 34 times greater over 100 years (Stocker et al., 2013), which represent updates beyond the GWPs used in California's Short Lived Climate Pollutant Strategy (CARB-SLCP, 2017). In addition to climate concerns, gas leakage can pose multiple risks to the environment and human health, such as the contamination of groundwater (Humez et al., 2016), the reduction of air quality through the formation of ozone (Milich, 1999), and co-release of benzene, a critical pollutant and carcinogen. However, regular monitoring of hydrocarbon infrastructure is only mandatory during the active lifetime of the well, resulting in millions of inactive wells (that is, that are no longer producing) unmonitored. As such, emissions reported by the industry and state's GHG inventories currently only provide a lower estimate of atmospheric CH_4 emissions because not all leakages are identified and quantitative data on release rates are rare. This conclusion is supported by growing evidence for increased CH_4 emissions in hydrocarbon production areas in Pennsylvania (Kang et al., 2014; Kang et al., 2016), the Midwest United States (Townsend-Small et al., 2016), the United Kingdom (Boothroyd et al., 2016), and the North Sea (Vielstädte et al., 2015; Vielstädte et al., 2017), that are attributed to leakage of methane from legacy wells. Whereas the majority of methane emissions from abandoned wells investigated in the United States originated from thermogenic sources (Kang et al., 2014; Kang et al., 2016; Townsend-Small et al., 2016) pointing towards a loss of well integrity and the unintended release of deep reservoir gas, additional emissions may also arise via gas migration along the outside of the well as found in the North Sea (Vielstädte et al., 2015; Vielstädte et al., 2017) and Alberta, Canada (Bachu, 2017).

According to Fractracker, there are almost 1.7 million active wells in the United States (Kelso, 2015). When they stop producing, these wells will add to the three million wells that are already abandoned and will be a potential source for future methane emissions. To date, only a few studies have quantified emissions from abandoned wells. In the Marcellus region of northwestern Pennsylvania, 88 wells were measured and the emissions, when scaled to the state, were estimated to contribute 5 percent to 8 percent of the annual anthropogenic methane emissions in Pennsylvania from the 470,000-750,000 wells in the state (Kang et al., 2014; Kang et al., 2016). In Wyoming, Colorado, Utah, and Ohio, 138 wells were measured, where only nine were found to be leaking, contributing less than 1 percent to the overall anthropogenic methane emissions in these local areas, with higher leak rates found on unplugged wells (Townsend-Small et al., 2016). Internationally, in the United Kingdom, the most important factor in determining leakage rate was the amount of time since decommissioning, particularly whether the well had been decommissioned for more than 10 years, making it more likely to leak at higher rates (Boothroyd et al., 2016). A study in the North Sea found that underwater wells can also be a source of leakage (Vielstädte et al., 2015).

Abandoned Wells in California

In this project, the authors focused on California, which has a long history of oil and natural gas production, and where gas from Southern California is generally produced in association with petroleum, whereas gas from northern California is typically not. California hosts around 120,000 onshore abandoned and plugged (AP) wells and ~30,000 idle wells, as reported by the California Department of Conservation Geologic Energy Management Division (CalGEM, formerly DOGGR) ("DOC CalGEM WellFinder"). Emission inventories from oil and gas production and distribution are reported by the California Air Resources Board (CARB) (California Air Resources Board, 2018). While the abandoned wells are not included in the California Greenhouse Gas Inventory, the state has recently passed legislation that requires idle wells to be more rigorously tested and repaired.

Furthermore, California has also launched efforts to improve estimates of methane emissions to the atmosphere from oil and gas production, which are driven by the state's regulations and programs (such as Assembly Bill 32, the Global Warming Solutions Act of 2006) aimed at reducing greenhouse gas (GHG) emissions, such as methane, to 1990 levels by 2020. The following work was designed to benefit the California public and natural gas ratepayers by assessing the contribution of methane emissions, if any, from properly retired (abandoned and plugged) natural gas and petroleum production wells.

The 2019 California Methane Survey (Duren et al., 2019) measured emissions from more than 272,000 potential sources of methane emissions in California using aircraft sensing, including 88 percent of the ~225,000 oil and gas wells (all statuses) in the state. Although there was a relatively high detection limit (2-10 kilograms per hour [kg/hr]), the researchers were able to identify emissions from 107 wells, including one abandoned and unplugged well. In this project, the authors aimed to complement this work by surveying wells with detection limits 3-9 orders of magnitude smaller than the California Methane Survey.

The following chapters describe a combination of methods for measuring CH_4 leakage from accessible abandoned, idle, and active oil and gas wells and the surrounding soil. The authors then report measurements of methane leakage from AP wells across California to estimate, for the first time, regional contribution to methane. The authors also include measurements of a few idle and active wells, which appear to present a much greater source of leakage, and discuss the findings and need for further work.

CHAPTER 2: Project Approach

The authors performed the measurements of methane emissions from wells using a combination of time-intensive (requiring approximately 1 hour per well) but extremely sensitive (less than 0.001 g CH_4/hr) measurements that employ a variety of static chambers that effectively capture all gas from each well, and a comparatively rapid (requiring approximately 10 minutes per well) but less-sensitive (approximately 0.5 g CH_4/hr) mobile measurement of ambient air downwind of the well. These techniques are described in detail below.

Static Chamber Measurements

This section describes the measurement principle and technical details used to perform static chamber emission measurements.

Measurement Principle

The method for the chamber portion of this study is based on Kang et al. (Kang et al., 2016), with new methods developed to assess larger ground areas to accommodate California's unique collection of AP oil and gas wells. All the methods used a static flux chamber to measure the flow rate. A static flux chamber is a closed chamber that encompasses the footprint of the leak, which is sealed to the surrounding environment. When coupled with the highly sensitive Picarro Cavity Ring Down spectrometer for concentration measurements, the minimum detection limit for the static flux chambers is ~$1\text{x}10^{-6}$ g/hr.

A linear increase in the methane concentration over time in a known chamber volume will allow the calculation of the leak rate. The leak can be represented by the following relationship:

$$Q = dC/dt \ \ V, \text{ where} \qquad (1)$$

Q is the leak rate (in liters per hour [L/hr]), *dC* is the change in methane concentration (in ppm) over time period *dt* (in hours), and V is the volume of the chamber (in L). Emissions are then converted to mass flow units (g CH_4/hr) using measured air temperature and pressure.

The static flux chamber method has a few key assumptions and principles of operation as described below:

1. The air should be well-mixed inside the chamber.
    a. Fans are placed within the chamber to circulate the air. The number and orientation of the fans was considered for each chamber size, and each circulation scheme was tested in the lab to ensure the air in the chamber was well mixed.
2. The pressure inside the chamber should be equilibrated to atmospheric pressure to ensure that the gas leaking into the chamber does not cause the pressure to increase.
    a. Each bucket chamber was equipped with a vent on the top of the chamber to allow pressure equilibration.

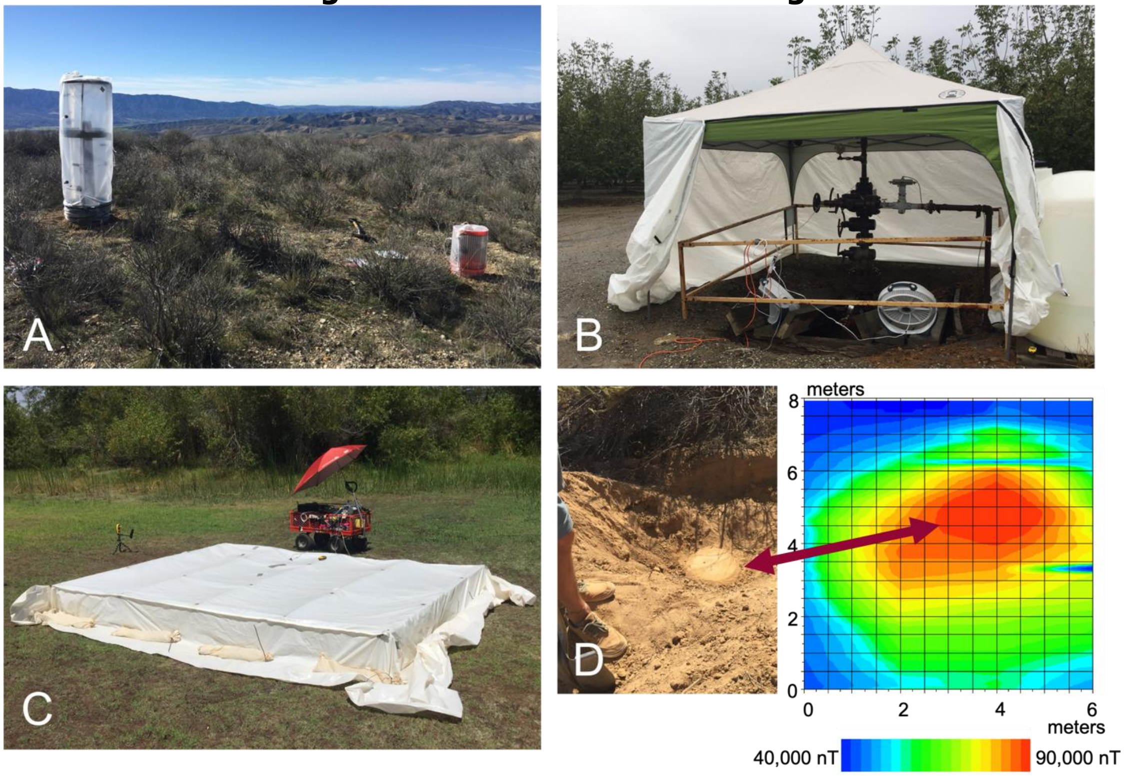
   b. The pop-up and tent chambers were not completely sealed at the bottom with sandbags, allowing for pressure equilibration. Seal of the chambers were tested in the lab using a controlled release; no issues with the seal of the chamber were detected.
   c. Further, soil is porous, so any excess pressure inside the chamber could potentially escape the chamber through the soil.
3. Taking a sample from the chamber does not effectively alter the volume or concentration of air inside the chamber.
   a. Samples to be run on the gas chromatograph were 50 milliliters (mL) every 3-5 minutes; the cumulative volume of 7 samples is only 1 percent of the smallest chamber volume.
   b. When circulating to the Picarro, the flow rate is 1.6 L/min with the air recirculated to the chamber. The Picarro was measured to intake 25 mL/min, and over a 15-minute test in the smallest chamber, this accounts for 1.1 percent of the chamber's volume.

Hardware Design

This work employed and expanded on chamber designs used in Kang et al. (2014, 2016). Each of the chambers used in this study are shown in Figure 1. To summarize, the chambers consist of the following components:

1. Small bucket chamber: 5-gallon bucket (Home Depot) converted into a chamber using plastic and PVC pipe. Volume = 33.8 liters (L).
2. Medium bucket chamber: 32-gallon bucket (Rubbermaid) converted into a chamber using plastic and PVC pipe. Volume = 204 L.
3. Large bucket chamber: 32-gallon bucket (Rubbermaid) converted into a chamber using plastic and PVC pipe. Same diameter as Medium chamber, but taller. Volume = 335 L.
4. For each of these chambers (1-3), the bottom of the chamber was sealed with the soil in a groove dug into the ground, and dirt and rocks were placed on the excess plastic. 1-3 battery-operated fans were placed in each chamber to circulate the air during the measurement.
5. Pop-up chamber: Converted "Pop Up Straight/Flat Trade Show Display Frame" (purchased on eBay) into chamber. The top was covered in plastic and it was sealed with fifteen 7-lb sandbags. Six to eight battery-powered fans (Opolar Clip and Desktop Quiet Fan) were placed inside the chamber to circulate the air. Volume = 2,100 L.
6. Tent chamber: Converted "Coleman 12 x 12 Instant Sun Shelter" into a chamber by wrapping plastic around the sides. Two Lasko 20" 3300 Wind Machine fans were run on high in the chamber, and six battery-powered fans were used to circulate the air in the corners and in the peak. The bottom of the plastic was sealed with fifteen 7-lb sandbags. Volume = 32,659 L.

Figure 1: Static Chambers Designs



Different chambers are used to measure as follows: (A) Exposed wells were sampled with expandable cylindrical chambers. (B) Idle wells required a much larger chamber to enclose all associated infrastructure. (C) Buried wells were measured using a large footprint chamber because of the inaccuracy of locating the exact position of the wellhead. (D) A cesium-vapor magnetometer was used to locate buried wells, with the results verified by excavating 2 buried wells. Deeper shades of red indicate a higher magnetic field; the well was assumed to be in the center of the region of deepest red.

Source: Fischer, Jackson, Lebel, CEC project 500-16-013

Chamber Operation for Different Well Types

1. Exposed Wells — These wells were sampled using the various bucket chambers, employing the smallest possible bucket chamber that would comfortably fit over the well casing. 50-mL samples were transferred from a sampling port on the chamber to a 20-mL glass vial capped with a butyl rubber stopper using a 60-mL BD plastic syringe for analysis on the gas chromatograph (GC). Ordinarily, samples were taken every five minutes for a 30-minute period, but the number of samples taken varied as needed due to logistic or scientific reasons (for example if the well was known to be leaking). Control chambers were placed at least 10 feet away from each sampled well in a random direction. The samples were analyzed for methane, ethane, propane, iso- and n-butane concentrations on the GC.
2. Buried Wells — Most of California's wells are buried. In California, wells that are properly abandoned must be cut off 5 feet below the ground and filled with cement to 100 feet below the surface. For most older wells, documented GPS coordinates can only locate the well to within 100 meters. To find the wells, a magnetometer survey created a map of the magnetic field in the surrounding area, which will find the wells to <1-meter accuracy, as shown by the sample plot in Figure 1, panel D.

3. Once located, emissions were quantified without excavating the buried well. To account for lateral migration of gas through the soil as it travels to the surface, a large-surface-area method for sampling these buried wells was employed. Here, the authors used the "pop-up chamber" with a ground area of 7.02 m2 (size dictated by purchased frame, described above), to capture all the emissions, even those diffusing laterally. The concentration of the gas was measured using a Picarro Cavity Ring-Down Spectrometer (CRDS) which was running off a nearby car battery. This instrument can measure methane and ethane concentrations to sub-ppb accuracy and can also measure the carbon isotopes of methane (∂13-CH4), CO2, and water vapor. The CRDS provides measurements at 1-Hz frequency, giving many more measurements over a shorter period than the discrete vial samples. In some cases where the car was not close enough to the chamber to use the CRDS, samples were collected in 1-L Tedlar bags to and measured on the Picarro later. In cases where concentrations were too high for the CRDS (>50 ppm), samples were collected in 20-mL vials and analyzed on the GC (see above). As with the exposed wells, control measurements were performed with the pop-up chamber at least 10 feet away from the site of the well.
4. Because the CRDS provides real-time results, it can inform decisions regarding chamber placement. After initially placing the chamber directly over the well, a funnel was attached to the inlet of the CRDS inlet and moved in transects up to 10 m outward from the chamber. If areas of high methane concentration were detected -- indicating gas was likely surfacing from the well, the chamber was moved that location to make quantitative flux reading.
5. Idle Wells — To sample idle wells with infrastructure still present a Tent Chamber, was applied to fit over the entire well. Like with buried wells, the Picarro was used to measure the concentration increase in the chamber. If it was not physically possible to bring the Picarro to the well, or if the concentration inside the chamber quickly exceeded the Picarro's limit, samples were collected in vials and analyzed on the GC. The MPI also was able to measure idle wells if the vehicle was able to safely get close enough (10-20 m) to the idle well infrastructure.
6. Active Wells — Active wells were sampled exclusively by the MPI method, described below.

Laboratory Testing of Chamber Approach

The chamber method was tested extensively in the laboratory. To test the exposed well method, 100 percent or 30 percent methane was released into the chambers of different sizes at known flow rates, and then collecting samples in 20-mL vials for later analysis using a GC. The results from this method testing typically underestimated the actual flow rate by 10 to 20 percent, consistent with the results of other groups for this method due to issues such as pressure change and air leaking from the chamber (Pihlatie et al., 2013).

The pop-up chamber was also extensively tested in the lab, again using 30 percent methane gas and flow rates around 0.2 L/min, using the CRDS to measure concentrations. Here, the pop-up chamber was operated in the lab using the sandbags to seal the bottom as in the field, with gas released at a known rate at different locations inside the chamber. Interestingly, the results showed a 0-10 percent overestimate of the flow, although the gas supply system was operating near its lower limit (0.08 L/min). To confirm this, methane was manually injected into the chamber at very low flow rates (2-10 mL/min) using a 60 mL syringe, obtaining results within 3 percent of the known flow. Here, the measured estimated flow rates were independent of release location, showing that the air was well-mixed by the fans in the chamber.

Mobile Plume Integration

This section describes the system used for mobile measurements of CH_4 leakage.

Measurement Principle and Hardware Design

The Lawrence Berkeley National Laboratory Mobile Plume Integrator (MPI) provides continuous roadway measurements of the vertical distribution of CH_4 plumes, horizontal winds and other meteorological variables to estimate emissions from localized plumes (Fischer et al., 2017), building on methods pioneered by Rella et al. (Rella et al., 2015). The basic concept of the MPI system is shown in Figure 2. The vehicle is driven through a CH_4 plume, continuously drawing air streams from multiple (here 12) inlets spaced at 0.3 m along a 4 m mast, and aggregated into three streams capturing three height intervals at roughly 0.6-1.5 m, 1.8-2.7 m, and 3-4 m above the road.

Air from the three streams is then continuously measured by the three separate gas analyzers (two Picarro 2301 and one 2132), each operated at a flow (~250 sccm) and data acquisition rate (1 Hz) sufficient to provide approximately 0.5 Hz time response. In addition, the vehicle's location, speed and heading data are measured with a GPS (Garmin 18x), while wind velocity is measured with a sonic anemometer (RM Young 81000), with data synchronized and recorded at 1 Hz on a data logger (Campbell CR1000).

Figure 2: Mobile Plume Integrator Design Schematic

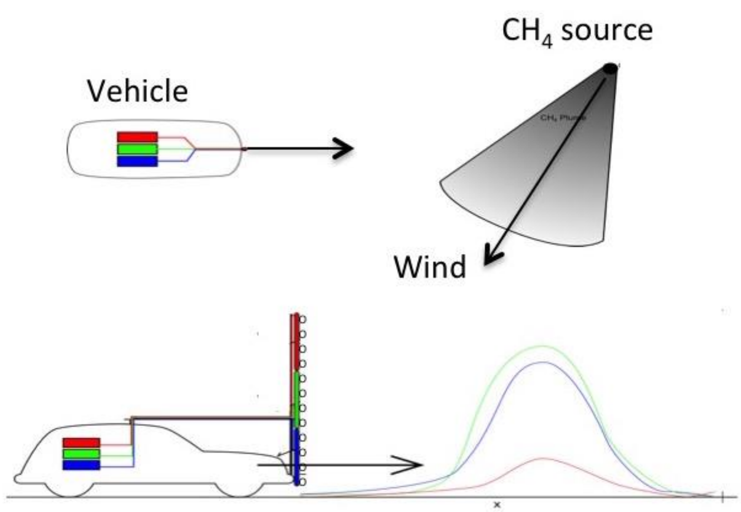


Diagram of MPI system from above showing CH_4 source and plume (top); side view showing vehicle and mast sampling three height intervals and resulting concentration profiles (bottom)

Source: Fischer, Jackson, Lebel, CEC project 500-16-013

The methane flow rate for each plume, Q, is computed as the sum of area integral of methane flux elements defined by the product of the normal component of the wind with respect to the motion of the vehicle and the concentration enhancements above background at each height along the height of the mast as

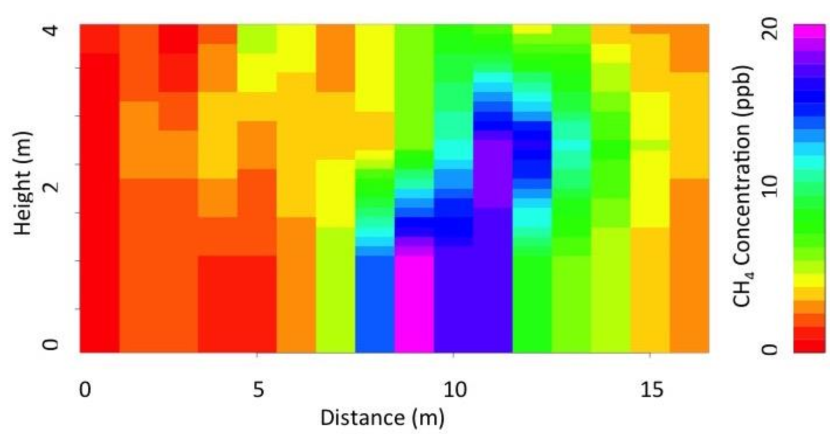
$$Q = \iint v(C_p - C_b)dl\,dz \quad (2)$$

where v (m s^{-1}) is the normal component of the wind velocity, C_p and C_b (kg m^{-3}) are mass densities of CH_4 in the plume and background respectively, the integral is computed over the horizontal δl and vertical δz extent of the plume. Here, plumes are estimated with an iterative peak-detection algorithm and background CH_4 is estimated from the smoothed time series of methane with peaks removed.

Field Evaluation of Mobile Plume Integrator Performance

To estimate the statistical precision and accuracy of the MPI measurements system under typical conditions, the vehicle was driven back and forth downwind of a known source in open level terrain. The source was set back so the minimum distances the vehicle passes was ~8-12 m from the source (depending which side of the road). During these tests the vehicle speed was 2.5 ± 0.6 m/s, while the mean wind speed was 2.2 ± 0.5 m/s with sunny warm (~30ºC) conditions. Methane was released at ground level from a regulator connected to a lecture bottle containing 3.89 percent CH_4 in air. The flow rate was measured using a NIST certified electronic flow meter at a rate of 500 ± 50 sccm (where the uncertainty reflects observed variation during the test), resulting in a mass flow rate was 0.83 ± 0.1 g CH_4/hr. The individual CH_4 enhancements varied in strength and position as expected for instantaneous realizations in turbulent diffusion. An example CH_4 enhancement in Figure 3 shows a plume largely concentrated near the ground with a filament running up and to the right.

Figure 3: Example Map of Measured Methane Plume

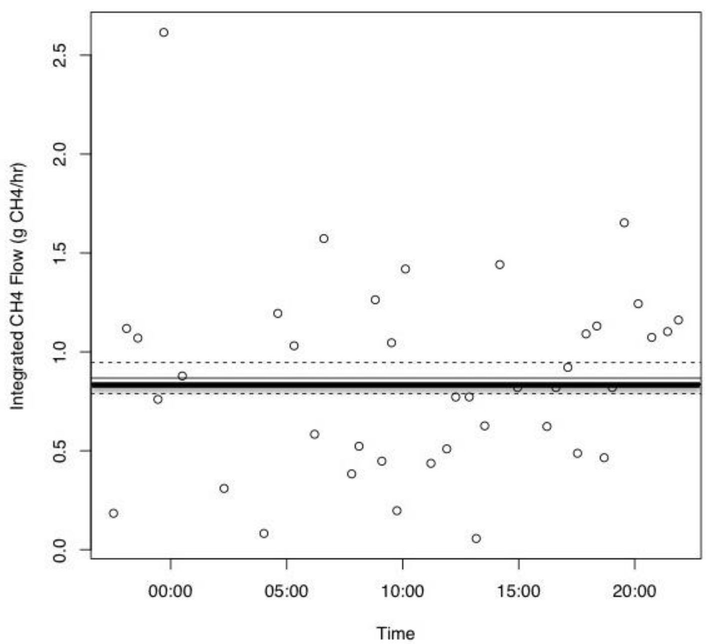


Example map of CH4 enhancement in vertical plane along roadway observed during controlled release experiment with the MPI instrument.

Source: Fischer, Jackson, Lebel, CEC project 500-16-013

The integrated flow rates, computed using Equation 1 for all (41) passes downwind of the source, are shown as a time series in Figure 4. The actual flow rate (thick line) and the mean of and standard error of the mean (thin line and dashed lines) are also shown. The statistical uncertainty in estimated mean leak rate was estimated from the standard deviation of the measurements and the number of passes by the source. Here, the standard deviation of estimated flow rates is 0.49 g CH_4/hr, equivalent to 57 percent of the actual release rate. This suggests that near-surface releases of CH_4 in the near 1 g CH_4/hr can be estimated to within roughly 0.3 g CH_4/hr (~ 33 percent) if one averages data for at least three passes. In terms of accuracy, the ratio of mean to actual release flow rate is 1.04 ± 0.09, suggesting that near-surface emissions can be accurately estimated by the MPI system under conditions similar to this test.

Figure 4: Emission Rates Estimated Using Mobile Plume Integrator During Controlled Release Experiment



Integrated CH_4 flows estimated using the MPI instrument during controlled release experiment. Actual release rate (thick line), mean estimated rate (thin line), and 68 percent confidence standard error of mean estimate (dashed lines) also shown.

Source: Fischer, Jackson, Lebel, CEC project 500-16-013

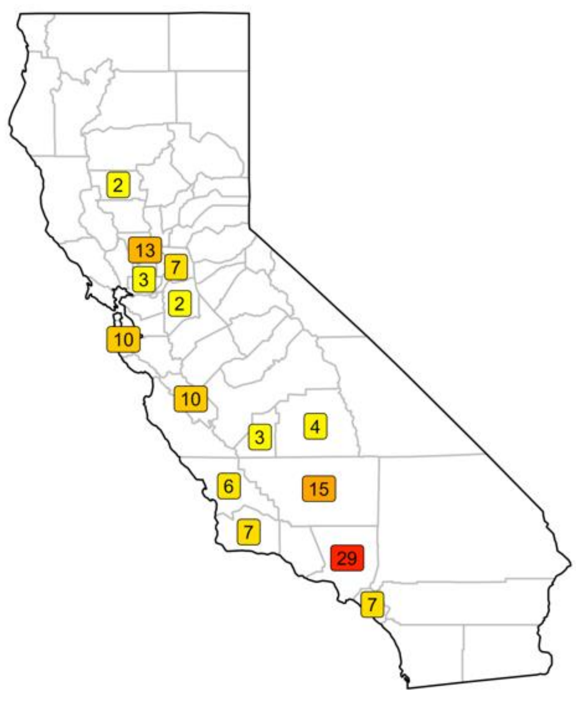
CHAPTER 3: Project Results

Measured Emissions

The authors measured 121 wells, including a sample of 97 abandoned and plugged wells, 1 abandoned unplugged well, and 23 idle or active wells. The measurements were made in several seasons between July 2016 and March 2019. The one unplugged well (identified to be leaking) was measured on three occasions to evaluate the persistence of the leak.

Of the 121 wells, 36 wells were sampled using the MPI method while the remaining 85 were sampled using the static flux chambers. Wells were sampled in 14 different counties, with the distribution of measurements shown in Figure 5. Of the sampled wells, 97 were plugged and abandoned, 17 were idle, 6 were active, and 1 well was unplugged. General statistics of the sampled wells are presented in Table 1. Henceforth, wells are identified as "leaking" when the emissions are greater than 1 g CH_4/hr so as to be significantly (approximately 95 percent confidence) detected by the MPI and chamber systems. Here, it is worth noting that even if all AP wells were leaking at this level, the total leakage from the roughly 120,000 AP wells in California would be 120 kg CH_4/hr (1.1 Gg CH_4/yr), which is comparable to emissions from individual large emitters (refineries, oil and gas production fields, or large dairies) but less than 1 percent of total estimated natural gas CH_4 emissions (approximately 200 Gg CH_4/yr).

Figure 5: Map Showing Counties with Well Measurements



Map of number of samples and their distribution across counties of California.

Source: Fischer, Jackson, Lebel, CEC project 500-16-013

Table 1: Statistics of Well Leakage by Well Status

Status	Count	Number leaking	Fraction leaking	Mean	Median	Min	Max
Abandoned/ Plugged	92	0	0	0.0	0.0	0.0	0.8
Abandoned/ Plugged – tar pit	5	1	0.20	5.2	0.0	-0.1	26
Active	6	4	0.67	190	1.5	0.0	1100
Idle	17	7	0.41	36	0.4	0.0	246
Unplugged	1	1	1.00	11	NA	11	11

Statistics (mean, median, min, max, shown in g CH_4/hr) of emissions from wells measured in this study. Abandoned wells from the tar pit are shown separately from the other measurements of abandoned and plugged wells. All emission units are g CH_4/hr.

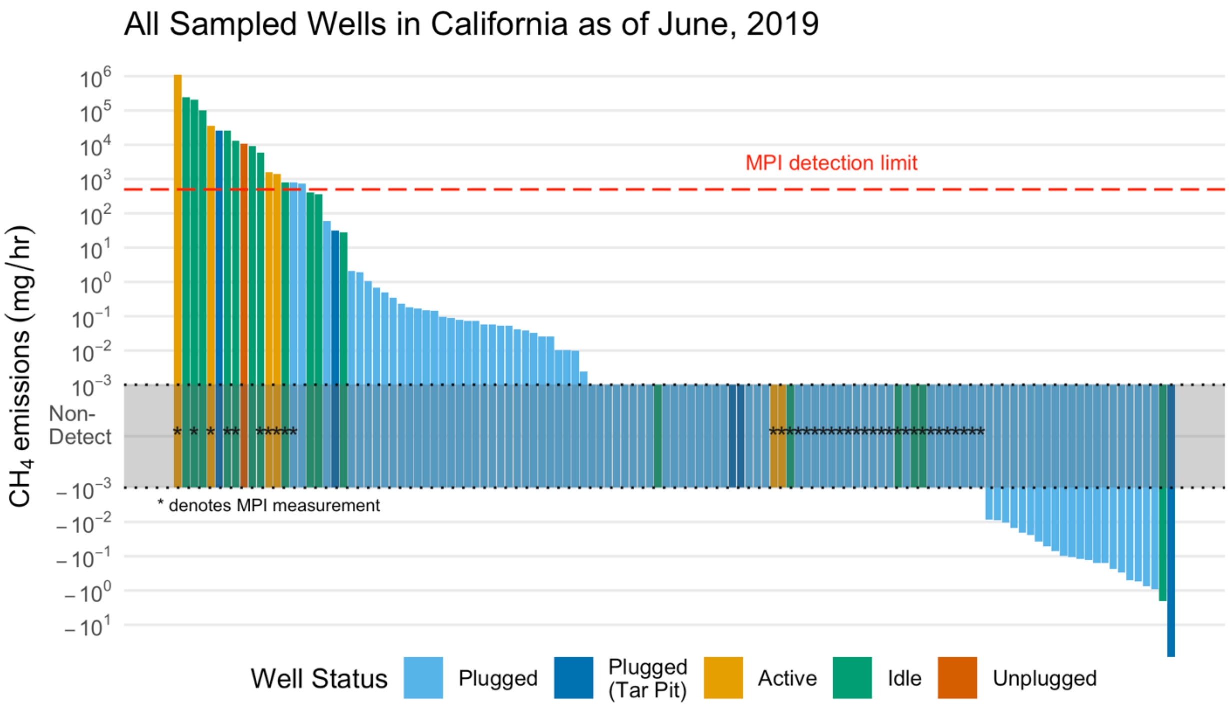
Source: Fischer, Jackson, Lebel, CEC project 500-16-013

Sites were selected mainly to comply with logistical constraints; logistically accessible sites included sites on public land or those with permission from private landowners, and sites where the authors could feasibly and safely transport the necessary sampling equipment to the site. Many sites were on public property or were nearby a public road in which the MPI could sample the emissions. The majority, but not all of the chamber measurements were wells on public property.

Figure 6 shows the distribution of emissions for each of the 121 wells that were sampled in the course of this project. In general, the distribution of emissions is long-tailed, with emission rates per well ranging over 10 orders of magnitude. Additionally, some sites were methane sinks spanning 4 orders of magnitude. The sinks were recorded when methane concentrations decreased over time in the chambers, perhaps caused by methanotrophs in the soil as observed at other sites by Kang et al. (2016).

The wells labeled “Plugged (Tar Pit)” were a set of wells sampled using the Pop-Up chamber in Towsley Canyon (Los Angeles County). The area was once a lucrative drilling site with dozens of wells, but is now an abandoned field with minimal surface infrastructure present. It was clear that there were pockets of natural methane fluxes from the soil, and there were tar pits spotted around the site. Here, control measurements were averaged and applied to estimate the control flux for all measurements at the site of the well.

Figure 6: Ranked Emissions from Wells

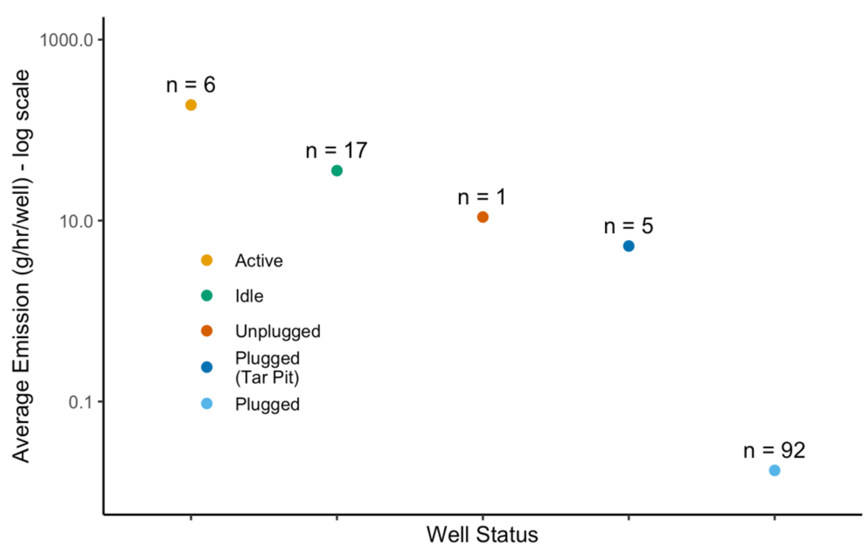


Methane emissions from each of the sampled wells ranked by magnitude of emissions with color-coding showing well type. Note units are mg CH_4/hr, emphasizing the sensitivity of chamber measurements with a detection limit of 10^{-3} mg CH_4/hr, as compared with the 500 mg CH_4/hr detection limit of the MPI system.

Source: Fischer, Jackson, Lebel, CEC project 500-16-013

When grouped by well status (that is Plugged, Idle, Active, Unplugged), drastic differences in the average emission rate are observed, as illustrated in Figure 7.

Figure 7: Average Emissions by Well Type



Average emission factors from each well type. The y-axis is in log scale to show how the average emissions encompass multiple orders of magnitude.

Source: Fischer, Jackson, Lebel, CEC project 500-16-013

In particular, properly plugged and abandoned wells do not show appreciable leakage in this sample of wells. There are some emissions from the plugged wells in the tar pit, but it is not possible to determine whether those emissions are a result of the natural geology in the local area or a consequence of the drilling that took place on this site. In particular, the one unplugged well measured showed emissions of about 10 g CH_4/hr on three separate occasions in different months (January, March, and August), with emissions varying less than 30 percent (9.8, 10.1, 12.8 g/hr), suggesting that the well's emissions had little variation over time.

Active wells were only sampled by the MPI, so no values were reported below the MPI detection limit. For the six measured active wells, total CH_4 emissions were 190 g/hr. Of particular interest is that the highest measured emitter was an active well; in fact, it had 4.5x more emissions than the second highest emitter, an idle well. Averaged over the 17 measured idle wells, CH_4 emissions were 35.7 g/hr. Indeed, six of the top 10 emitters were idle wells, and so while limited the measurements suggest that idle wells may play a significant role in CH_4 leakage from oil and gas wells overall.

CHAPTER 4: Knowledge Transfer

The methods and results of this work have been prepared for publication in a peer-reviewed journal. Throughout the project, the authors communicated with members of the project technical advisory committee to share results. Additionally, the authors communicated with the Department of Conservation to discuss the results of this study to help inform their approach to Assembly Bill 1328, (Holden, Chapter 772, Statutes of 2019) which requires the Division of Oil, Gas, and Geothermal Resources, in consultation with the California Air Resources Board, to study a representative sample of idle, idle-deserted, and abandoned wells in California to better understand emissions from these wells and assist with identifying hazardous wells.

CHAPTER 5: Conclusions

The limited data presented here suggest that methane emissions from abandoned/plugged (AP) wells in California are negligible, at least for wells located primarily outside large active oil and gas fields. Excluding measurements from wells in the tar pit (which may have their own natural sources), the authors found no AP wells to be leaking above 1 g/hr.

In 2019, California emitted 39.9 million tonnes CO_2 equivalent of CH_4 (1.6 Tg CH_4) predominantly from agriculture (54 percent), landfills (21 percent), and oil and gas (16 percent) (California Air Resources Board, 2019). The California Methane Survey complements these statistics by showing that super-emitting point-sources emit substantial amounts of methane from these same sectors. Although the detection limit of the AVIRIS-NG instrument was high (2-10 kg/hr), after surveying 88 percent of all documented wells in the state, the California Methane Survey found emissions from only one AP well. In this study, the authors found the highest emitter (an active well) was emitting 1 kg/hr, below the detection limit of AVIRIS. If the authors assume that any random sample of 121 wells would include one well that leaked ~1 kg/hr, that would add 0.017 Tg CH_4/yr from wells, increasing the estimate of leakage from wells from the California Methane Survey by 31 percent. To better understand this, a larger sample size needs to be collected with lower detection threshold than the California Methane Survey, especially including idle and active wells in addition to AP wells in large oil and gas fields.

Table 2 shows each of the well categories and the number of currently reported wells in California, as reported by CalGEM. For the purposes of this analysis, the "Canceled" and "Idle" categories are grouped into the "Idle" category, since canceled wells are essentially idle wells in which the owner is unable to be contacted. "Unknown" wells were considered to be "Unplugged", since unplugged wells are typically holes in the ground and CalGEM is unaware of their existence. The one unplugged well was not listed on the CalGeM database. "New" wells were excluded from this analysis. However, because of the small number of samples, it is not possible to estimate expected levels of emissions from active, idle, and unplugged wells. There is also potential bias in these measurements, since most of the sampling reported here was done at sites that were logistically feasible and did not include measurements in currently active large O&G fields.

While the number of active wells measured is small, it is important to note the dominance of their emissions. If representative, the average of the active wells is 91.1 percent of total well emissions measured, emitting an order of magnitude more CH_4 than the idle wells, and about four orders of magnitude more CH_4 than all the plugged and abandoned wells. The 17 idle wells sampled constituted 8.7 percent of well total measured CH_4 emissions. Only a small component of emissions (less than 1 percent) was found to be emitted by plugged and unplugged wells, which seem to be a negligible component of overall emissions, despite the large number of abandoned wells in the state. However, many more samples are required in large active oil and gas fields before such a claim can be made with more certainty.

Table 2: Number of California Wells by Status

Status	Count
Abandoned/Plugged (AP)	122,685
Active	72,328
Idle	29,242
Cancelled	7,447
Unknown	1,965
Total	**233,667**

List of California number of wells in each well status in CalGEM database (accessed 6/5/2019).

Source: Fischer, Jackson, Lebel, CEC project 500-16-013

This study was not able to achieve a truly random sampling of wells across California, even within the AP category. Most AP wells were sampled on public lands. It might be expected that these sampling limitations could result in underestimation of the overall emissions from a given well type if wells on public lands are more likely to be monitored for leakage. Additionally, the total sample of wells is quite small compared to the total number of wells in the state. In particular, it would be valuable to sample more idle and active wells, as these data suggest that idle and active wells are responsible for almost all CH_4 emissions.

Future Directions

Based on the work thus far, future research might be valuable in fields with active oil and gas production and zones with high subsidence, particularly in the regions in the San Joaquin Valley. In the case of oil and gas fields, there is a possibility that emissions from AP wells are different from those in areas where oil or gas or both have been depleted. In the case of subsidence, it will likely require hundreds of additional measurements to draw strong conclusions regarding whether subsidence affects CH_4 emissions from oil and gas wells. Additionally, a more detailed campaign measuring additional active and idle/canceled wells would be beneficial, as these wells appear to have the greatest potential to contribute to California's methane emissions. Measuring additional AP wells could potentially unveil unaccounted for emissions from this study; specifically, a more random sampling of wells, including wells from major oil and gas operators. If 1 percent of AP wells leaked at a rate of 1 kg/hr (below the detection limit of AVIRIS), that would account for an additional 20 percent more emissions from wells than was found by Duren et al. To adequately test this, approximately 1,000 wells would need to be tested at a detection limit of approximately 100 grams/hr. This, along with additional testing for subsidence influencing leaks, would be suitable for research in support the legislation of Assembly Bill 1328. This legislation is allocating state funds to future work in the state, specifically creating a larger sample set of abandoned idle, idle-deserted, and abandoned wells in large active oil and gas fields.

CHAPTER 6: Benefits to Ratepayers

This work provides results on CH_4 emissions from an initial sampling of AP wells in California that suggests emissions are small compared to other oil and gas CH_4 sources and tiny compared to other (for example, agricultural) sources. If these results are representative, this in turn suggests that current practices for abandoning wells may be adequate and that modifications to those procedures may not be necessary, hence limiting additional costs that might be borne by ratepayers. However, more data are needed from plugged and abandoned wells in large oil and natural gas fields across California.

LIST OF ACRONYMS

Term	Definition
AP	Abandoned and plugged
C	Centigrade
CalGEM	California Department of Conservation Geologic Energy Management Division, formerly California Department of Oil and Gas and Geothermal Resources (DOGGR)
CalGEM	California Geologic Energy Management Division (formerly DOGGR)
CARB	California Air Resources Board
CEC	California Energy Commission
CH_4	Methane
CO_2	Carbon dioxide
CRDS	Cavity Ring-Down Spectrometer
DOGGR	Former California Department of oil and Gas and Geothermal Resources, now California Department of Conservation Geologic Energy Management Division (CalGEM)
g CH_4/hr	Grams of methane per hour
GC	Gas chromatograph
GHG	Greenhouse gas
GPS	Global Positioning System
Hz	Hertz
Kg/hr	Kilograms per hour
L	Liters
L/hr	Liters per hour
lb	Pound
mL	Milliliters
MPI	Mobile plume integrator
O&G	Oil and gas
PVC	Polyvinyl chloride
Tg	Teragram

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