

Methane Emissions from Abandoned Oil and Gas Wells in California

Eric D. Lebel,* Harmony S. Lu, Lisa Vielstädt, Mary Kang, Peter Banner, Marc L. Fischer, and Robert B. Jackson



Cite This: *Environ. Sci. Technol.* 2020, 54, 14617–14626



Read Online

ACCESS |



Metrics & More



Article Recommendations



Supporting Information

ABSTRACT: California hosts ~124,000 abandoned and plugged (AP) oil and gas wells, ~38,000 idle wells, and ~63,000 active wells, whose methane (CH_4) emissions remain largely unquantified at levels below $\sim 2 \text{ kg CH}_4 \text{ h}^{-1}$. We sampled 121 wells using two methods: a rapid mobile plume integration method (detection $\sim 0.5 \text{ g CH}_4 \text{ h}^{-1}$) and a more sensitive static flux chamber (detection $\sim 1 \times 10^{-6} \text{ g CH}_4 \text{ h}^{-1}$). We measured small but detectable methane emissions from 34 of 97 AP wells (mean emission: $0.286 \text{ g CH}_4 \text{ h}^{-1}$). In contrast, we found emissions from 11 of 17 idle wells—which are not currently producing (mean: $35.4 \text{ g CH}_4 \text{ h}^{-1}$)—4 of 6 active wells (mean: $189.7 \text{ g CH}_4 \text{ h}^{-1}$), and one unplugged well—an open casing with no infrastructure present ($10.9 \text{ g CH}_4 \text{ h}^{-1}$). Our results support previous findings that emissions from plugged wells are low but are more substantial from idle wells. In addition, our smaller sample of active wells suggests that their reported emissions are consistent with previous studies and deserve further attention. Due to limited access, we could not measure wells in most major active oil and gas fields in California; therefore, we recommend additional data collection from all types of wells but especially active and idle wells.

Abandoned Wells in California

Type	CH_4 Emissions (g h^{-1})
Plugged	0.286
Unplugged	10.9
Idle	35.4

INTRODUCTION

Greenhouse gas (GHG) emissions from hydrocarbon infrastructure are a major source of methane (CH_4) globally,¹ with methane alone contributing nearly one-quarter of the cumulative radiative forcing since 1750.² Methane has a global warming potential 86 times greater than CO_2 over 20 years and 34 times greater over 100 years.³ In addition to climate concerns, methane leakage from wells can pose a potential risk of explosion,⁴ contaminate groundwater,⁵ impact air quality through the formation of ozone,⁶ and be accompanied by the release of benzene, toluene, and other aromatics that affect human health.⁷ Here, we focus primarily on surface methane emissions from various wells across California.

In the United States, methane monitoring regulations for the oil and gas industry on federal lands were substantially rolled back in August 2020; now, monitoring of fugitive emissions at active wells is only required to take place twice per year, with exemptions granted to low-production well sites (<15 barrels of oil equivalent per day).⁸ Upon removal of the production equipment, monitoring is no longer required, potentially leaving millions of idle and abandoned wells unmonitored. However, some states further regulate methane monitoring from these wells; California requires periodic pressure testing for idle wells. Nevertheless, emissions currently reported by the industry and states' GHG inventories likely provide a lower estimate of atmospheric methane emissions because quantitative emission data are incomplete. This conclusion is supported by growing

evidence of methane emissions from abandoned wells in hydrocarbon production areas in the Marcellus shale in Pennsylvania and West Virginia,^{9–12} midwestern United States,^{13,14} United Kingdom,¹⁵ Netherlands,¹⁶ and the North Sea.^{17,18} The majority of methane emissions from abandoned wells investigated in the United States originated from thermogenic sources^{9,10,13}—suggesting a loss of well integrity¹⁹—and the unintended release of deep reservoir gas may also arise via gas migration along the outside of the well as found in the North Sea^{17,18} and in Alberta, Canada.²⁰

Today, there are ~ 1.1 million active wells in the United States and $\sim 800,000$ inactive/idle wells.²¹ The number of abandoned and plugged (AP) wells in the United States is unknown; various sources suggest that this number may fall between 1.6 and 3.2 million wells.^{21–23} Every drilled well has the potential to be a source of methane emissions to the atmosphere through its well casing: the production annulus can serve as a conduit from deep reservoirs to the surface, and typical plugging procedures will not block this pathway.²⁴ Evaluating the emissions from abandoned wells is therefore important to determine if wells are acting as

Received: August 6, 2020

Revised: October 12, 2020

Accepted: October 14, 2020

Published: October 30, 2020



ACS Publications

© 2020 American Chemical Society

14617

<https://dx.doi.org/10.1021/acs.est.0c05279>
Environ. Sci. Technol. 2020, 54, 14617–14626

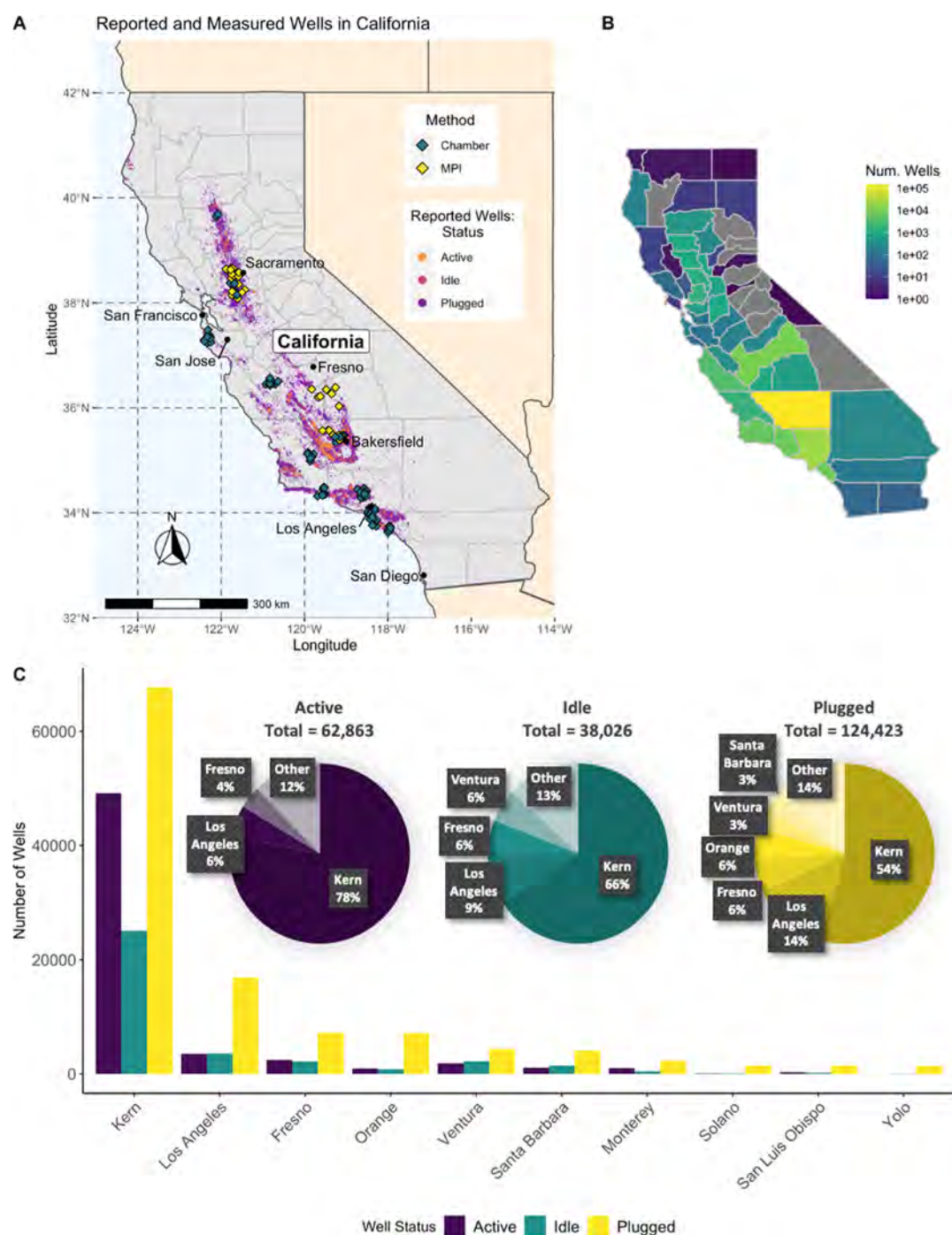


Figure 1. Distribution of wells among counties and sampling sites. (A) Distribution of known wells as reported in the CalGEM database (smallest dots) and their well status designation. Omitted are 1 abeyance well, 7551 canceled wells, 5160 new wells, and 1908 unknown wells. The 203 wells designated “plugged only” were plotted as plugged wells. The larger diamonds indicate our sampling sites in this study, denoting whether the measurement was taken using a chamber-based approach or taken using the mobile plume integrator. (B) California counties are colored based on the total number of active, idle, and plugged wells in each county. Most wells are found in the southern part of the state and in the Central Valley. (C) Total number of wells by type in the top 10 counties and the fractions of each well type in different counties. Kern County by far has the most wells of any county in the state and is home to 78, 66, and 54% of the active, idle, and plugged wells, respectively, of each well category.

conduits for the reservoir gas to reach the atmosphere and mitigate this issue where it may occur. In addition, every region faces different geography and history: well abandonment procedures varied and evolved over the 150 year oil and gas drilling history in 22 states.²⁵ Other geologic or environmental factors may potentially contribute to variations in integrity of long-term well abandonment methods. Thus, California and

other regions should conduct quantitative evaluation efforts, rather than relying on data from other regions.

California has been a major producer of oil and natural gas for more than a century. Today, the Department of Conservation’s Geologic Energy Management Division (CalGEM, formerly DOGGR) oversees operations of the oil and gas industry and maintains the records of wells in the state.²⁶ California currently

Table 1. Summary Statistics^a

status	status in CalGEM	count of measured wells	number [%] of measured wells emitting CH ₄	number [%] of measured wells emitting >1 g CH ₄ h ^{−1}	measurements					total number of wells in CA
					mean (g CH ₄ h ^{−1}) used as emission factor	95% UCI	median (g CH ₄ h ^{−1})	min (g CH ₄ h ^{−1})	max (g CH ₄ h ^{−1})	
abandoned	plugged	97	34 [35%]	1 [1%]	0.286	1.64	0.0	−0.1	26	146,000 ^b
	idle	17	11 [65%]	7 [41%]	35	88.5	0.4	0.0	246	38,026
	unplugged ^c	1	1 [100%]	1 [100%]	11	NA	NA	11	11	NA ^c
active	active	6	4 [67%]	4 [67%]	190	739	1.5	0.0	1100	62,863

^aStatistics (mean, median, min, max, upper 95% confidence interval) of emissions from wells measured in this study. Wells were considered to be leaking if they were emitting at rates higher than 1 g h⁻¹. All emission units are g CH₄ h⁻¹. Not included in the total well count: 1908 unknown wells, 7551 canceled wells, 5160 new wells, and 1 abeyance well (permit pending review). AP wells include 124,423 plugged wells and 203 “plugged only” wells, where the well has been plugged but the surface not reclaimed. Total wells in CA: 233,667. ^bAdjusted in this study from 124,626, assuming a ~17% undocumented rate of AP wells by CalGEM. ^cUnplugged wells are not directly reported by CalGEM.

hosts 124,626 AP wells. Since 1974, California has had relatively strict abandonment procedures to restore the surface and prevent emissions and groundwater contamination from the wells.²⁷ Properly abandoned wells in California are plugged with at least 100 ft of cement at the surface, requiring additional cement plugs depending on the geologic strata that the well penetrates. The casing is cut and capped, so it is buried 5–10 ft below the ground.²⁸ Not all wells were properly abandoned, and although the true number of wells in this category is difficult to estimate, it includes one that we measured in this paper. We consider these wells to be “unplugged” if they have visible well casing without obvious cement plugging.

In addition to these wells, there are 38,026 idle wells in California, which the United States Environmental Protection Agency (USEPA) considers to be abandoned. Idle wells are unplugged but would not have produced oil or gas for 2 or more years.^{28,29} If the owner goes bankrupt, the idle well becomes “orphaned” and the state assumes the responsibility to complete abandonment, which could take decades. In 2018, the cost to the state averaged \$53,329 to abandon a single well,³⁰ but this cost could be offset by factoring in the social cost of the emissions if the well was left unabandoned.³¹

In California, emission inventories from oil and gas production are reported in the California GHG Inventory, prepared by the California Air Resources Board (CARB), but only include estimates of emissions from producing wells.³² Although abandoned wells are not included in the California GHG Inventory, the state has recently passed legislation that requires idle wells to be more rigorously tested and repaired (e.g., Assembly Bill 1328, Assembly Bill 2729).^{33,34} This recent legislation is driven by the state’s regulations and programs (e.g., Senate Bill 32, Assembly Bill 1496) aimed at identifying major sources of methane and reducing these emissions and other GHGs to 40% below 1990 levels by 2030.^{35,36}

Efforts to quantify California’s emissions from wells and other sources recently included the California Methane Survey (Duren et al. 2019). They surveyed 88% of all California’s methane-emitting infrastructure—including abandoned and active oil and gas wells—with a minimum detection limit of ~2 kg CH₄ h⁻¹.³⁷ To adequately measure emissions from wells, a much lower detection limit is needed; for instance, if the ~200,000 active and abandoned wells in California were to emit 1 kg CH₄ h⁻¹, these emissions alone would roughly equal CARB’s estimate for all California methane emissions in 2019.³²

In the following sections, we describe a combination of methods for measuring methane emissions from accessible AP,

idle, and active oil and gas wells and their surrounding soil. We report measurements of methane emissions from abandoned (plugged, unplugged, and idle) wells across 14 counties in California with <1 g CH₄ h⁻¹ sensitivity in order to better capture smaller emitters. We supplement these measurements with additional measurements from a smaller number of active wells, which appear to emit methane at higher rates.

METHODS

Site Selection. We used CalGEM’s Well Finder database to collect information about the wells, including location, well status, drilling depth, spud, and abandonment dates.²⁶ Sites were chosen to promote sampling from as many oil and gas fields and geographic regions as possible; we ultimately sampled wells from 14 different counties (Figure 1A). A prominent consideration when selecting sites was logistical constraints: accessible sites for chamber measurements included sites on a public land or those with permission for access from private landowners and sites where we could feasibly and safely transport sampling equipment to the well. Chamber measurements were mostly taken on public property, with a minority of sites on private land. Sites chosen for the mobile plume integrator were either on public property or were close enough to a public road to allow emission sampling without entering private property.

We measured methane emissions from 121 wells in California, directing our focus on abandoned wells (plugged, unplugged, and idle), which receive less mandated emission monitoring. We sampled 115 abandoned wells (97 plugged, 1 unplugged, and 17 idle) and 6 active wells. Wells were measured in campaigns covering all seasons between July 2016 and March 2019. All wells were measured once, except for two to evaluate the persistence of their leaks: one abandoned unplugged well, which was measured on three different occasions and one idle well which was measured twice. Emission factors for each well type were calculated by taking the average methane emission factor from the sampled wells for each category (plugged, unplugged, idle, and active). For each estimate, the confidence interval of the mean was calculated by bootstrapping the data and using the “bias corrected and accelerated” method to calculate the 95% confidence interval (R package “boot”).

Number of Wells in California. Understanding the number of wells in California is essential for scaling our statewide emissions estimate. CalGEM currently reports 124,626 AP wells, 62,863 active wells, and 38,026 idle wells (Figure 1C, Table 1). A majority of wells are found in Kern County (southern San Joaquin Valley, containing the city of

Bakersfield), with Los Angeles, Fresno, and Orange counties being other high concentration areas. While the CalGEM database is the most comprehensive listing of wells in California, it is still subject to gaps and inaccuracies. 1908 wells are described as “unknown” status. “Unplugged” wells are not specifically reported, but it is possible that some wells with the status “unknown” are unplugged. Furthermore, there are some wells that are missing entirely from this database, including some that we measured here. We found a well in the field that was unplugged with no production infrastructure, and thus, we believe that the status of “unplugged” may be important to consider.

We compared 57 wells from old maps from 1944 to 1946 to the CalGEM database to estimate how many wells may be unreported in the CalGEM database, particularly those drilled at the beginning of the 20th century. At random, we selected a well from the United States Geological Survey (USGS) map and searched for a similar well on the CalGEM database, using identifying characteristics such as lease name, American Petroleum Institute number, operator, and spud date. We marked it “reported” if we could, with reasonable certainty, identify the same well with CalGEM; otherwise, we marked it “unreported”. Our USGS maps were sourced from Santa Rosa Hills, North Los Angeles, Sunset-Midway, Puente Hills, and Santa Barbara, representing the various geographic regions where drilling was occurring at this time.

Measurement Protocol. We measured methane emissions from wells using two approaches: (1) a combination of time intensive (~ 1 h) and highly sensitive ($\sim 1 \times 10^{-6}$ g CH_4 h^{-1}) measurements that employ static flux chambers to capture all gases emitted from the enclosed footprint of each well and (2) a comparatively rapid (~ 10 min) but less sensitive (~ 0.5 g CH_4 h^{-1}) mobile plume integration (MPI) measurement of ambient air downwind of the well. These techniques are summarized in the sections below and described in more detail in the [Supporting Information](#). Of the 121 sampled wells, 36 wells were sampled using the MPI method, while the remaining 85 were sampled using static flux chambers.

Static Flux Chamber Measurements. The methodology for the static flux chamber portion of this study is based on Kang et al. (2016),¹⁰ with new methods developed to accommodate California’s abandonment guidelines for AP oil and gas wells. A static flux chamber encompasses the footprint of the leak and is sealed to the surrounding environment. When coupled with a Picarro cavity ring down spectrometer (CRDS; G2210-i) for concentration measurements, the minimum detection limit is $\sim 1 \times 10^{-6}$ g CH_4 h^{-1} .

The flow rate is calculated by measuring the linear increase in methane concentration over time in a known volume, expressed using the following relationship

$$Q = \frac{dC}{dt} \times V \times 1,000,000 \quad (1)$$

where Q is the flow rate (in L CH_4 h^{-1}), dC is the change in methane concentration (in ppm) over the time period, dt (in hours), V is the volume of the chamber (in L), and 1,000,000 is the conversion factor for ppm. Emissions are then converted to mass flow units (g CH_4 h^{-1}) using measured air temperature at ambient pressure.

We used chambers that ranged in size from 33.8 to 32,659 L, depending on the presence and size of the surface infrastructure ([Figure 2A–C](#), [Supporting Information](#)). For wells that were buried with no surface infrastructure, we used a cesium G-860

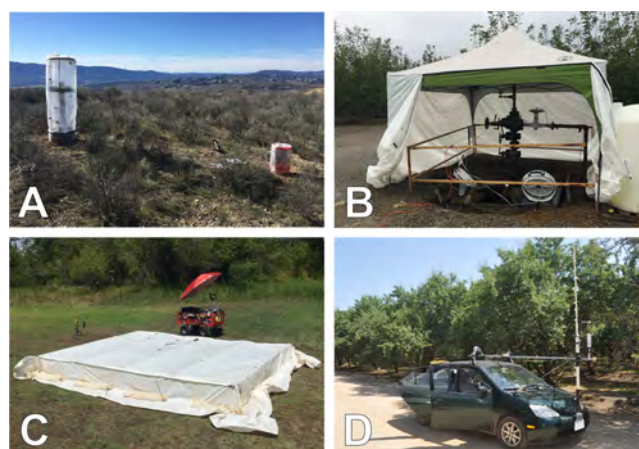


Figure 2. Sampling equipment used in this study. We used chambers of various sizes (A–C) as well as a mobile plume integrator (D) to sample methane emissions from oil and gas wells. (A) Exposed plugged wells were sampled with expandable cylindrical chambers, with the chamber fitting over the above-ground casing. (B) Idle wells required a much larger chamber to enclose all of the associated infrastructure; here, we show a 12' $\times$ 12' Coleman canopy modified with plastic siding. (C) Buried wells were first located within 1 m using a magnetometer ([Supporting Information](#)), and emissions were measured using a large-footprint chamber to cover the full position of the wellhead and tortuous pathways of gas movement through soils. (D) Mobile plume integrator is deployed on a car and is used to measure emissions from wells which are detectable from public roadways. The mast has 12 inlets and three Picarro CRDS analyzers in the car measure concentrations at a rate of ~ 1 Hz. The car is also equipped with a global positioning system (GPS) and sonic anemometer.

cesium-vapor magnetometer (Geometrics) to locate the well within 1 m ([Supporting Information](#)), similar to magnetometry work by Pekney et al. (2018).¹² Gas samples were measured either on the Picarro CRDS for methane, ethane, carbon dioxide, and $\delta^{13}\text{C}$ – CH_4 or on the gas chromatograph (GC) (Agilent 6890N) for methane, ethane, propane, *n*-butane, and isobutane.

In addition to the species listed above, the one unplugged well was also measured for benzene measurements by EAG Laboratories (San Jose, CA) in January 2017. 1.5 L of sample were run across a “coconut shell charcoal” sorbent tube; the total benzene which adhered to the charcoal was measured. Discrete samples were taken over time. Given the chamber size of 204 L used to measure this well, the 30 min testing period, and that the analytical detection limit of benzene concentration using this method was ~ 4.2 ppb (by volume), the minimum benzene flow rate we could detect was 6 μg h^{-1} .

Laboratory testing of the chambers used in this study suggest that they are accurate in determining the flow rate within 20% error when measuring the concentrations on a GC (Agilent 6890N; injections were made using a sampling loop at constant pressure; standards 5 ppm, 10 ppm, 100 ppm, and 1%). Laboratory testing with the Picarro achieved results within 3% ([Supporting Information](#)).

Mobile Plume Integration. For this study, methane emissions from active wells were sampled exclusively using the MPI (Lawrence Berkeley National Lab). This method provides continuous roadway measurements of the vertical distribution of methane plumes, horizontal winds, and other meteorological variables to estimate emissions from localized plumes,³⁸ building on methods pioneered by Rella et al.³⁹ and conceptually similar

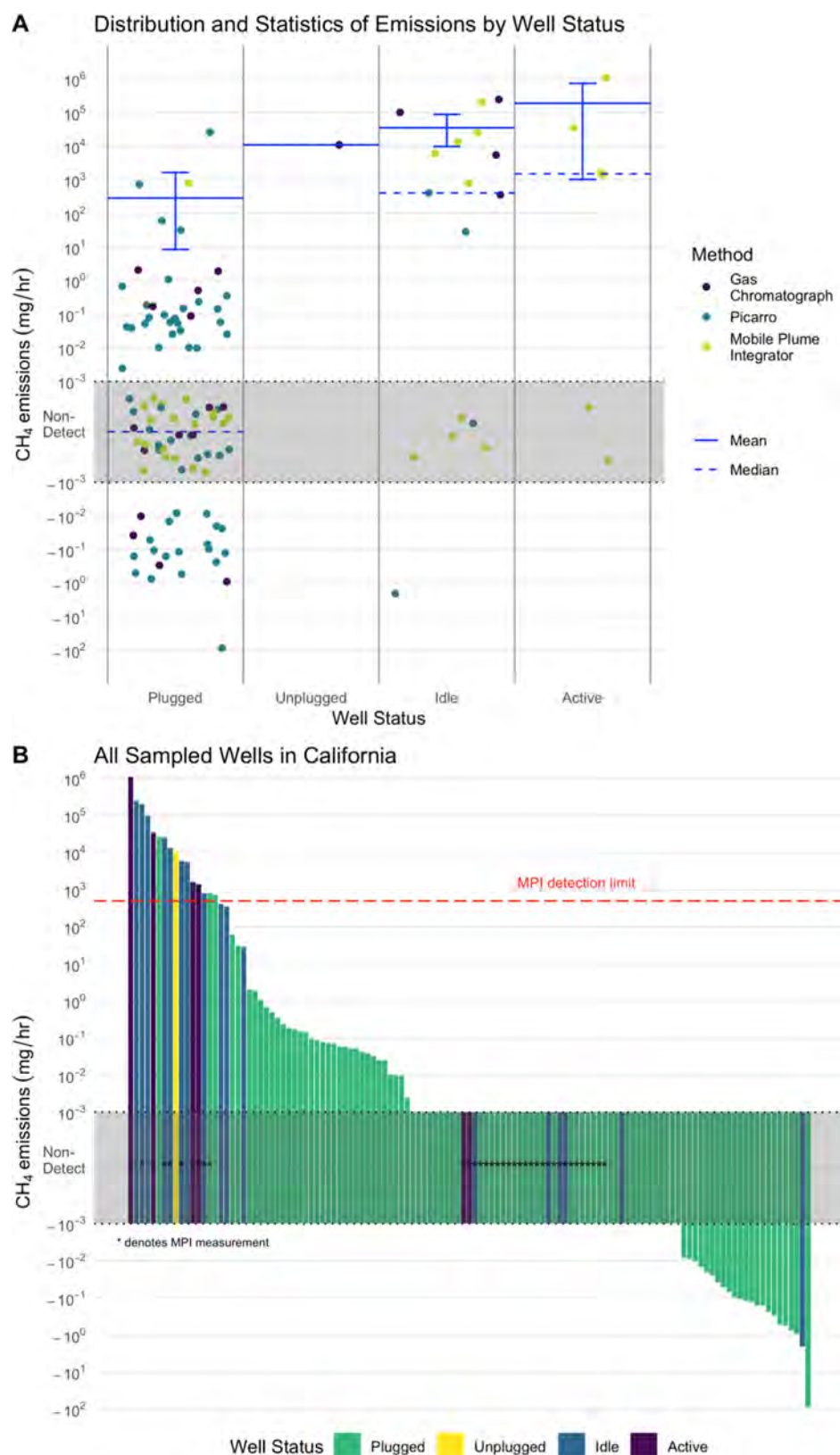


Figure 3. Ranked methane emissions by wells. (A) Each point represents an individual well measurement, colored by the method. The y-axis is in the log scale because emissions encompass multiple orders of magnitude. The solid blue line represents the mean measurement for each category, and the dashed blue line represents the median. The error bars are our 95% confidence interval of the mean, calculated using a bootstrap bias-corrected and accelerated method with 200,000 replicates. (B) Methane emissions from each of the sampled wells ranked by a magnitude of emissions with color-coding showing the well type. Units are $\text{mg CH}_4 \text{ h}^{-1}$, emphasizing the sensitivity of chamber measurements with a detection limit of $10^{-3} \text{ mg CH}_4 \text{ h}^{-1}$, as compared with the $500 \text{ mg CH}_4 \text{ h}^{-1}$ detection limit of the MPI system.

to those of von Fischer et al.⁴⁰ The vehicle is driven through a methane 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, 1.8–2.7, and 3–4 m above the road (Figure 2D).

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), and wind velocity is measured using a sonic anemometer (RM Young 81000), with data synchronized and recorded at 1 Hz on a data logger (Campbell CR1000). More details about the calculations and field evaluation of the MPI are available in the [Supporting Information](#) (Figures S3–S5).

RESULTS AND DISCUSSION

Methane Emissions Summary. Plugged. Observed methane emissions were small relative to other well types for the 97 AP wells we measured across California. We detected methane emissions from 34 wells (35%), ranging from 2×10^{-6} to $26.4 \text{ g CH}_4 \text{ h}^{-1}$. The highest-emitting AP well was located in a tar pit in Los Angeles County (Figure S6) and was leaking more than an order of magnitude higher than the second highest emitter. With our nondetectable measurements assumed to be zero, the average emission factor from AP wells was $0.286 [95\% \text{ CI: } 0.00836, 1.64] \text{ g CH}_4 \text{ h}^{-1}$ (Figure 3A, Table 1).

Idle/Orphaned. We detected emissions from 11 of 17 (65%) idle wells that we sampled. On average, we found that idle wells emitted $35.4 [9.74, 88.3] \text{ g CH}_4 \text{ h}^{-1}$ (Figure 3A, Table 1). The idle wells were sampled from Kern, Solano, Glenn, Yolo, and Sacramento counties, all areas with active oil and gas production. Four idle wells were orphaned wells (idle wells without an owner).

In California, 47% of all reported idle wells has been idle for 8 or more years (classified by CalGEM as “long-term idle”) and 5% of wells has been idle for 50 or more years. The 17 idle wells that we measured had been idle on average for 13.9 years, with a range of 6–39 years. Even though our samples did not capture the wells idled for more than 50 years, our samples suggest that active and idle wells in California could be larger contributors of methane emissions than plugged wells. We also want to note again that these idle wells are considered “abandoned” in the national EPA inventories.

Unplugged. We located and sampled one unplugged well using a chamber, which was leaking at a rate of $10.9 \text{ g CH}_4 \text{ h}^{-1}$ (Figure 3A, Table 1). Unlike an idle well, this well had no production equipment on site and was not reported in the CalGEM database. We sampled this well on three separate occasions in different months (January, March, and August), with emissions varying less than 30% between each measurement (9.8, 10.1, and $12.8 \text{ g CH}_4 \text{ h}^{-1}$, respectively), suggesting that the well's emissions varied relatively little over time. On one occasion, we measured benzene emissions at this well, which were nondetectable (detection limit $6 \mu\text{g h}^{-1}$).

Active. We found a similar proportion of emitters in our small sample of active wells (4 of 6, or 67%) to the idle wells that we measured. The active wells that we measured were drilled between 1940 and 2005. These were measured using the MPI, which effectively captured emissions from all infrastructure present on the well pad. The mean emission from these active wells was $190 [1.03, 739] \text{ g CH}_4 \text{ h}^{-1}$ (Figure 3A, Table 1). Active

wells had a mean emission 5.3 times higher than that of idle wells and a median emission 3.7 times higher. However, because of the especially small sample size of active wells, additional sampling is warranted. There is also a potential bias in these measurements; most of the sampling reported here was done at sites that were logistically feasible and accessible, typically on a public land.

Distribution of Emissions. In total, we sampled 121 abandoned, unplugged, idle, and active wells in California and found methane emissions from our set of sampled wells to vary substantially (Figure 3B, Table 1). Including values from the more sensitive static flux chamber, positive emission values were recorded over 9 orders of magnitude, ranging between 10^{-3} and $10^6 \text{ mg CH}_4 \text{ h}^{-1}$.

Similar to most leak studies, we found that methane emissions from wells followed a “long-tail distribution”, where the top few emitters are responsible for most of the emissions.^{22,41} Excluding sites with methane uptake, we found that the top three positively emitting AP wells (4%) were responsible for emitting 99.6% of all emissions from AP wells. Likewise, the top two idle wells (12.5%) emitted 74.1% of all emissions from idle wells. For active wells, the single highest-emitting well (representing 16.7% of active wells sampled) emitted 96.7% of all emissions from active wells. This well was the highest emitter of any well we sampled; in fact, it had 4.5 times more emissions than the second highest emitter, an idle well. The long-tail distribution we observed is also evident by the median measurements being orders of magnitude lower than the means (Figure 3A).

Given the long-tail distribution, here we focus on the highest-emitting wells; for purposes of this analysis, we chose a “high-emitter threshold” of $1 \text{ g CH}_4 \text{ h}^{-1}$ (twice the detection limit of the MPI). If all AP wells in CA were leaking at that rate, it would be a comparable amount of methane emissions as a large dairy; instead, we found that 1 of 97 plugged wells (1%) was at this threshold. Furthermore, 7 of 17 idle wells (41%) and 4 of 6 active wells (67%) were “high-emitters”. Indeed, emission factors from each well type are primarily driven by these largest emitters.

Despite our small number of sampled active and idle wells, the relative dominance of their emissions is important to note. Representatively, our average of the active wells constituted 91.1% of total well emissions measured, emitting an order of magnitude more methane than the idle wells and about 4 orders of magnitude more methane than the AP wells. Similarly, the average emission of 17 idle wells constituted 8.7% of the total measured methane emissions. We found only a small component of emissions (<1%) from plugged wells. Many more samples are necessary in large active oil and gas fields to validate these estimates.

We also measured a broad distribution of methane uptake rates (a negative emission value) from 19% of measured wells (Figure 3B), likely driven by variations in atmospheric methane being consumed by soil methanotrophs.¹⁰ Recent work has found that methane emissions can enhance methanotrophic activity near the emission source.¹⁴ We measured 24 AP wells and 1 idle well with negative emissions. The median uptake of these wells was $0.12 \text{ mg CH}_4 \text{ h}^{-1}$. Given the chamber's $\sim 7 \text{ m}^2$ surface area, the average flux from these uptake areas was $0.15 \text{ g CH}_4 \text{ m}^{-2} \text{ year}^{-1}$. Much of the variation is likely to be natural localized variation in soil fluxes between the well measurement and the nearby control measurement. We found methane-consuming wells in nearly every geographic region that we sampled with chambers.

$\delta^{13}\text{C}$ Isotope Signatures and Other Hydrocarbons. Along with methane emissions, we also measured the isotopic signature of methane ($\delta^{13}\text{C}\text{-CH}_4$) for 56 wells as well as ethane concentrations for 85 wells. For eight wells emitting $>10\text{ mg CH}_4\text{ h}^{-1}$ methane where we collected both isotopic methane and ethane data, we plotted these values to determine if the emissions were of thermogenic or biogenic origin (Figure 4).⁴² We found that most methane was of thermogenic origin; the one point with a higher methane/ethane ratio was leaking very little methane (60 mg h^{-1}).

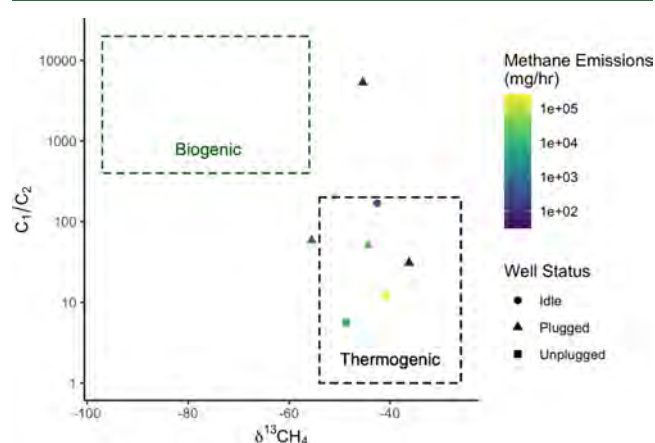


Figure 4. Bernard plot: Isotopic methane vs methane/ethane ratio. We measured eight wells which were emitting methane higher than $10\text{ mg CH}_4\text{ h}^{-1}$ and had collected data for both ethane and $\delta^{13}\text{C}\text{-CH}_4$. One point had a methane/ethane ratio higher than thermogenic gas; however, this well was leaking very little methane ($60\text{ mg CH}_4\text{ h}^{-1}$). The other samples were all classified as thermogenic, providing evidence that the measured gas comes from fossil sources and was not produced biologically through methanogenesis.

California Emissions. In 2019, California reported methane emissions of $39.9\text{ MMT CO}_2\text{e}$ (1.6 Tg CH_4), predominantly from agriculture (54%), landfills (21%), and oil and gas (16%).³² Scientific research has focused on identifying major sources of methane emissions from these sectors. The 2019 California Methane Survey led by Duren et al. (2019) used the next generation airborne visible/infrared imaging spectrometer (AVIRIS-NG) to measure emissions from more than 272,000 potential sources of methane emissions in California and found a comparable distribution from the super-emitting point sources. Focusing on oil and gas, they measured 88% of the $\sim 225,000$ oil and gas wells (all statuses) in the state. Although they had a relatively large detection limit ($2\text{--}10\text{ kg CH}_4\text{ h}^{-1}$), they were able to identify emissions from 107 wells; emissions from wells constituted 8.8% of total emissions from the super-emitters measured in that study.³⁷

Here, we estimate the total emissions from abandoned (plugged, unplugged, and idle) wells using our emission factor and activity factors reported by CalGEM for idle and active wells. For plugged wells, we compared 57 wells selected from old USGS maps and found that 17% of wells were undocumented by CalGEM. Therefore, we estimate the activity factor for AP wells in California to be 146,000, assuming an unreported rate of 17%.

Applying these activity factors, we found that plugged wells emit $0.0004\text{ }[1 \times 10^{-5}, 0.002]\text{ Tg CH}_4\text{ year}^{-1}$ and idle wells emit $0.0117\text{ }[0.0032, 0.0291]\text{ Tg CH}_4\text{ year}^{-1}$. Collectively, abandoned wells emit $0.012\text{ }[0.0032, 0.0311]\text{ Tg CH}_4\text{ year}^{-1}$, predominantly through idle well emissions. In total, our

calculated methane emissions from abandoned wells alone represent 0.8% [0.2%, 1.9%] of California's reported emissions. Regarding the confidence intervals, it should be noted that they were calculated by directly scaling the confidence intervals from our emission factors alone by the activity factors described above. We believe that the relative error of the activity factors is much lower than the relative error of our emission factors—the EPA assumes that bounds of $\pm 10\%$ are reasonable when estimating the number of wells.⁴³

Using a similar procedure, we found from our measurements that active wells emit $0.105\text{ Tg CH}_4\text{ year}^{-1}$; we report this number only as a reference because of our small sample size. Nevertheless, this finding is in line with previous work on active wells specifically in California. Jeong et al. (2014) found that active wells in California emit $0.168\text{ Tg year}^{-1}$, $0.140\text{ Tg year}^{-1}$ from associated production and $0.028\text{ Tg year}^{-1}$ from nonassociated production,⁴⁴ totaling 60% more emissions than we estimate from the few wells we measured. Other recent work found that active wells in Northern California emitted $7.6\text{ kg CH}_4\text{ day}^{-1}$,⁴⁵ comparable to our average finding of $4.6\text{ kg CH}_4\text{ day}^{-1}$.

We apply our emission factors (Figure 3, Table 1) to the geographic distribution of wells in California to identify county-specific emissions, while recognizing our small sample of active wells. By applying our activity factors (Figure 1), we find that Kern County is home to the majority of wells in the California and accounts for 77% of all emissions from wells (91% of these emissions come from active wells). In addition, 6% and 4% of emissions come from wells in Los Angeles and Fresno counties, respectively.

From our measurements, our largest measurement (an active well) was emitting $\sim 1\text{ kg CH}_4\text{ h}^{-1}$, half of the lower detection limit of AVIRIS-NG, which is used in the California Methane Survey. Based on our results, it is likely that most wells are leaking at rates too low to be detected by AVIRIS-NG; nevertheless, the largest of these emitters are leaking enough to make a substantial impact on California's methane budget. If we assume that any random sample of 121 wells of any type contains one well which leaks $\sim 1\text{ kg CH}_4\text{ h}^{-1}$, those wells alone would contribute $0.017\text{ Tg CH}_4\text{ year}^{-1}$ in the total methane emissions from wells, increasing the California Methane Survey's estimate of emissions from wells by 31%,³⁷ suggesting the importance of identifying high-emitting wells that may not be detectable by AVIRIS-NG and other airborne surveys.

Comparing Results to Other Regions. Compared to studies looking at methane emissions from abandoned oil and gas wells in other states, our results suggest that emission factors from California's wells are similar to those in other regions within the United States. For instance, in the Marcellus region of northwestern Pennsylvania, 88 wells were measured. Emission factors were found to be between 22 and $115\text{ g CH}_4\text{ h}^{-1}$, with higher emitting wells generally found from gas wells than from combined oil and gas wells. These emission factors are comparable to those found from idle wells ($36\text{ g CH}_4\text{ h}^{-1}$) in our study. Total emissions in Pennsylvania were estimated to contribute 5–8% of the state's annual anthropogenic methane emissions from the estimated 470,000–750,000 abandoned wells in the state.^{9,10} Compared to California, Pennsylvania has 4–6 times more abandoned wells and less methane emissions from other sectors, resulting in a higher fraction of emissions attributed to abandoned wells than we found in California.

In a separate work, 138 wells were measured in Wyoming, Colorado, Utah, and Ohio, where only 9 were found to be

emitting methane, predominantly from unplugged wells.¹³ Plugged wells were found to emit $0.002 \text{ g CH}_4 \text{ h}^{-1}$, about 2 orders of magnitude less than what we found in California. Unplugged wells emitted $10.02 \text{ g CH}_4 \text{ h}^{-1}$, similar to our findings from idle wells and unplugged wells in this study.

A different study in West Virginia found that plugged wells leaked at an average of $0.1 \text{ g CH}_4 \text{ h}^{-1}$ and unplugged wells leaked $3.2 \text{ g CH}_4 \text{ h}^{-1}$.¹¹ While we did not measure enough unplugged wells to compare directly, the emission factor from the plugged wells Riddick et al.¹¹ sampled was a similar order of magnitude to the plugged wells in our study. This study also measured active wells and reported an average emission rate of $138 \text{ g CH}_4 \text{ h}^{-1}$, also a similar order of magnitude to what we found in the limited number of samples in California.

Future Directions and Recommendations. The data presented here suggest that methane emissions from plugged wells in California are small compared to other well types. We found minimal evidence that AP wells were emitting substantial methane at the surface. In contrast, our small sample of idle wells (considered abandoned by the Environmental Protection Agency) suggests that idle wells contribute almost all emissions from abandoned wells. The handful of active wells that we measured suggests that emissions from these wells may be of greater concern than abandoned wells. We were unable to achieve a truly random sampling of wells across California, especially within the AP category. Most AP wells were sampled on public lands, and we could not obtain access to the large, private oil and natural gas fields in California. Additionally, the total sample of wells is small compared to the total number of wells in the state.

We recommend the following for future research on wells in California:

1. We suggest focusing additional measurements of abandoned wells on private lands, particularly those which are still unplugged and others on active oil and gas fields. A more randomized sampling approach will be able to answer questions we were unable to answer using our dataset; for example, whether or not there were correlations between emissions and well attributes. For these, we recommend a tiered-sampling approach of a truly randomized sample, where the highest emitters are rapidly identified, followed by more precise sampling using one of the methods discussed here or a new method.
2. We recommend further investigation on the contribution of idle and active wells to overall emissions. Additional samples of idle and active wells should be collected with a lower detection limit sufficient to capture the high emitters missed by Duren et al. in the California Methane Survey (the detection limit was 2 kg h^{-1}).³⁷ This work is in line with the proposed legislation in California, particularly Assembly Bill 1328. For idle wells, we recommend finding and sampling some of the 1626 idle wells that have been idle for 50 years or more. Ideally, additional measurements for any well type would utilize new technology, such as drones, to be able to efficiently locate (in the case of buried wells) and quickly measure methane emissions from the wells. Drone technology is now capable of both. If 1% of plugged, idle, and active wells leaked at a rate of $1 \text{ kg CH}_4 \text{ h}^{-1}$ (below the detection limit of AVIRIS-NG), that would account for an additional ~30% more emissions from wells than was found by Duren et al.³⁷ To adequately test this possibility,

we recommend testing ~1000 randomly selected wells at a detection limit of $\sim 10 \text{ g CH}_4 \text{ h}^{-1}$. We recommend this detection limit because the current drone technology can achieve this sensitivity, and we encourage the use of drones for rapid sampling.

3. We recommend additional measurements in zones of subsidence, particularly in the regions in the San Joaquin Valley where high levels of subsidence due to groundwater pumping have been observed. This will likely require hundreds of additional measurements to draw strong conclusions regarding whether subsidence affects methane emissions from oil and gas wells. With enough samples and access to data, effects of well age, plugging date, drill depth, and seismic activity on emissions could also be investigated.
4. We report only on methane emissions to the atmosphere in this study, but there is additional concern that wells leak methane below the ground, which could contaminate groundwater. Especially for wells abandoned prior to 1974 when stricter abandonment regulations were enacted, we recommend a separate campaign to investigate groundwater contamination from subsurface well leakage arising from improper/failed well abandonment.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.0c05279>.

Additional details about the methodology, including the geomagnetic surveys, chambers, mobile plume integrator; analyzers used; and description of the tar pit in Los Angeles County (PDF)

Spreadsheet containing specific emissions measurements for individual wells measured in this study (XLSX)

■ AUTHOR INFORMATION

Corresponding Author

Eric D. Lebel – Department of Earth System Science, Stanford University, Stanford 94305, California, United States; orcid.org/0000-0001-5255-6893; Email: elebel@stanford.edu

Authors

Harmony S. Lu – Department of Earth System Science, Stanford University, Stanford 94305, California, United States

Lisa Vielstädte – Department of Earth System Science, Stanford University, Stanford 94305, California, United States

Mary Kang – Department of Earth System Science, Stanford University, Stanford 94305, California, United States; Civil Engineering and Applied Mechanics, McGill University, Montreal H3A 0G4, Quebec, Canada

Peter Banner – Support Resources, Inc., Malibu 90265, California, United States

Marc L. Fischer – Air Quality Research Center, University of California, Davis, Davis 95616, United States; Energy Technology Area, Lawrence Berkeley National Laboratory, Berkeley 94720, California, United States; orcid.org/0000-0001-7956-2361

Robert B. Jackson – Department of Earth System Science and Woods Institute for the Environment and Precourt Institute for

Energy, Stanford University, Stanford 94305, California, United States

Complete contact information is available at:

<https://pubs.acs.org/10.1021/acs.est.0c05279>

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We acknowledge support from the California Energy Commission's Public Interest Environmental Research program under project PIR-16-013. We also acknowledge support from Vulcan Philanthropy and the ReFINE consortium led by Newcastle and Durham Universities, UK. The ReFINE consortium was funded by NERC (NE/N004760/1), Shell, Chevron, GDF Suez, and Centrica between 2013 and 2016, with further funding from INEOS up until 2018. Additionally, work by M.L.F. at the Lawrence Berkeley National Laboratory was conducted under the U.S. Department of Energy contract DE-AC02-05CH11231. We thank Chris Rella and Eric Crosson for inspiration and advice in development of the LBNL mobile plume integrator and Toby Haas Walpert for his effort in constructing an early version of the system used in prior research. We also acknowledge the following people and organizations for their help and support during this project: Gregory Middleton, Patricia Oliver, Dillon Sandidge, the Parris Law Firm, Tracy Drake from Madrona Marsh Preserve, Amy Loseth from the California Geological Survey, the City of Culver City, and the California Open Space Preserve.

REFERENCES

- (1) Jackson, R. B.; Saunio, M.; Bousquet, P.; Canadell, J. G.; Poulter, B.; Stavert, A. R.; Bergamaschi, P.; Niwa, Y.; Segers, A.; Tsuruta, A. Increasing Anthropogenic Methane Emissions Arise Equally from Agricultural and Fossil Fuel Sources. *Environ. Res. Lett.* **2020**, *15*, 071002.
- (2) Etminan, M.; Myhre, G.; Highwood, E. J.; Shine, K. P. Radiative Forcing of Carbon Dioxide, Methane, and Nitrous Oxide: A Significant Revision of the Methane Radiative Forcing. *Geophys. Res. Lett.* **2016**, *43*, 12614–12623.
- (3) Myhre, G.; Shindell, D.; Bréon, F.-M.; Collins, W.; Fuglestad, J.; Huang, J.; Koch, D.; Lamarque, J.-F.; Lee, D.; Mendoza, B.; Nakajima, T.; Robock, A.; Stephens, G.; Takemura, T.; Zhang, H. Anthropogenic and Natural Radiative Forcing. In *Climate Change 2013—The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P. M., Eds.; Cambridge University Press: Cambridge, 2013; pp 659–740.
- (4) Chilingar, G. V.; Endres, B. Environmental Hazards Posed by the Los Angeles Basin Urban Oilfields: An Historical Perspective of Lessons Learned. *Environ. Geol.* **2005**, *47*, 302–317.
- (5) Humez, P.; Mayer, B.; Ing, J.; Nightingale, M.; Becker, V.; Kingston, A.; Akbilgic, O.; Taylor, S. Occurrence and Origin of Methane in Groundwater in Alberta (Canada): Gas Geochemical and Isotopic Approaches. *Sci. Total Environ.* **2016**, *541*, 1253–1268.
- (6) Milich, L. The Role of Methane in Global Warming: Where Might Mitigation Strategies Be Focused? *Glob. Environ. Change* **1999**, *9*, 179–201.
- (7) Gross, S. A.; Avens, H. J.; Banducci, A. M.; Sahmel, J.; Panko, J. M.; Tvermoes, B. E. Analysis of BTEX Groundwater Concentrations from Surface Spills Associated with Hydraulic Fracturing Operations. *J. Air Waste Manage. Assoc.* **2013**, *63*, 424–432.
- (8) Environmental Protection Agency (EPA). *Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources Reconsideration*, 2020.
- (9) Kang, M.; Kanno, C. M.; Reid, M. C.; Zhang, X.; Mauzerall, D. L.; Celia, M. A.; Chen, Y.; Onstott, T. C. Direct Measurements of Methane Emissions from Abandoned Oil and Gas Wells in Pennsylvania. *Proc. Natl. Acad. Sci. U.S.A.* **2014**, *111*, 18173–18177.
- (10) Kang, M.; Christian, S.; Celia, M. A.; Mauzerall, D. L.; Bill, M.; Miller, A. R.; Chen, Y.; Conrad, M. E.; Darrah, T. H.; Jackson, R. B. Identification and Characterization of High Methane-Emitting Abandoned Oil and Gas Wells. *Proc. Natl. Acad. Sci. U.S.A.* **2016**, *113*, 13636.
- (11) Riddick, S. N.; Mauzerall, D. L.; Celia, M. A.; Kang, M.; Bressler, K.; Chu, C.; Gum, C. D. Measuring Methane Emissions from Abandoned and Active Oil and Gas Wells in West Virginia. *Sci. Total Environ.* **2019**, *651*, 1849–1856.
- (12) Pekney, N. J.; Diehl, J. R.; Ruehl, D.; Sams, J.; Veloski, G.; Patel, A.; Schmidt, C.; Card, T. Measurement of Methane Emissions from Abandoned Oil and Gas Wells in Hillman State Park, Pennsylvania. *Carbon Manage.* **2018**, *9*, 165–175.
- (13) Townsend-Small, A.; Ferrara, T. W.; Lyon, D. R.; Fries, A. E.; Lamb, B. K. Emissions of Coalbed and Natural Gas Methane from Abandoned Oil and Gas Wells in the United States. *Geophys. Res. Lett.* **2016**, *43*, 2283–2290.
- (14) Yin, Y.; Mastalerz, M.; Lennon, J. T.; Drobnik, A.; Schimmelmann, A. Characterization and Microbial Mitigation of Fugitive Methane Emissions from Oil and Gas Wells: Example from Indiana, USA. *Appl. Geochem.* **2020**, *118*, 104619.
- (15) Boothroyd, I. M.; Almond, S.; Qassim, S. M.; Worrall, F.; Davies, R. J. Fugitive Emissions of Methane from Abandoned, Decommissioned Oil and Gas Wells. *Sci. Total Environ.* **2016**, *547*, 461–469.
- (16) Schout, G.; Griffioen, J.; Hassanzadeh, S. M.; Cardon de Lichtbuer, G.; Hartog, N. Occurrence and Fate of Methane Leakage from Cut and Buried Abandoned Gas Wells in the Netherlands. *Sci. Total Environ.* **2019**, *659*, 773–782.
- (17) Vielstädte, L.; Karstens, J.; Haeckel, M.; Schmidt, M.; Linke, P.; Reimann, S.; Liebetrau, V.; McGinnis, D. F.; Wallmann, K. Quantification of Methane Emissions at Abandoned Gas Wells in the Central North Sea. *Mar. Pet. Geol.* **2015**, *68*, 848–860.
- (18) Vielstädte, L.; Haeckel, M.; Karstens, J.; Linke, P.; Schmidt, M.; Steinle, L.; Wallmann, K. Shallow Gas Migration along Hydrocarbon Wells—An Unconsidered, Anthropogenic Source of Biogenic Methane in the North Sea. *Environ. Sci. Technol.* **2017**, *51*, 10262–10268.
- (19) Davies, R. J.; Almond, S.; Ward, R. S.; Jackson, R. B.; Adams, C.; Worrall, F.; Herringshaw, L. G.; Gluyas, J. G.; Whitehead, M. A. Oil and Gas Wells and Their Integrity: Implications for Shale and Unconventional Resource Exploitation. *Mar. Pet. Geol.* **2014**, *56*, 239–254.
- (20) Bachu, S. Analysis of Gas Leakage Occurrence along Wells in Alberta, Canada, from a GHG Perspective – Gas Migration Outside Well Casing. *Int. J. Greenhouse Gas Control* **2017**, *61*, 146–154.
- (21) Enverus Drillinginfo Web App. <https://www.enverus.com/products/di-web-app/> (Accessed June 8, 2020).
- (22) Brandt, A. R.; Heath, G. A.; Kort, E. A.; O'Sullivan, F.; Pétron, G.; Jordaan, S. M.; Tans, P.; Wilcox, J.; Gopstein, A. M.; Arent, D.; Wofsy, S.; Brown, N. J.; Bradley, R.; Stucky, G. D.; Eardley, D.; Harriss, R. Methane Leaks from North American Natural Gas Systems. *Science* **2014**, *343*, 733–735.
- (23) Environmental Protection Agency (EPA). *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2016: Updates to Natural Gas and Petroleum Systems Uncertainty Estimates*, 2018; No. March, pp 1–27.
- (24) Ingraffea, A. R.; Wawrzyniak, P. A.; Santoro, R.; Wells, M. Reported Methane Emissions from Active Oil and Gas Wells in Pennsylvania, 2014–2018. *Environ. Sci. Technol.* **2020**, *54*, 5783–5789.
- (25) Ho, J.; Krupnick, A.; McLaughlin, K.; Munnings, C.; Shih, J.-S. *Plugging the Gaps in Inactive Well Policy*; Resources for the Future, 2016; No. May, p 81.

- (26) California Department of Conservation. Well Finder. <https://www.conservation.ca.gov/calgem/Pages/WellFinder.aspx> (accessed June 5, 2020).
- (27) State Division of Oil and Gas. *Oil and Gas Well Regulations*, 1974.
- (28) California Department of Conservation: Geologic Energy Management. *Statutes & Regulations*, 2020; No. January.
- (29) California Department of Conservation. Idle Well Program. https://www.conservation.ca.gov/calgem/idle_well (accessed June 9, 2020).
- (30) Interstate Oil and Gas Compact Commission. *Idle and Orphan Oil and Gas Wells: State and Provincial Regulatory Strategies*, 2019.
- (31) Kang, M.; Mauzerall, D. L.; Ma, D. Z.; Celia, M. A. Reducing Methane Emissions from Abandoned Oil and Gas Wells: Strategies and Costs. *Energy Policy* **2019**, *132*, 594–601.
- (32) California Air Resources Board. California Greenhouse Gas Emissions for 2000 to 2017. *2019 Edition, California Greenhouse Gas Emission Inventory 2000–2017*, 2019; pp 1–24.
- (33) Bill Text—AB-1328 Oil and Gas: Notice of Intention to Abandon Well: Study of Fugitive Emissions from Idle, Idle-Deserted, and Abandoned Wells. https://leginfo.ca.gov/faces/billTextClient.xhtml?bill_id=201920200AB1328 (accessed June 8, 2020).
- (34) Bill Text—AB-2729 Oil and Gas: Operations. https://leginfo.ca.gov/faces/billNavClient.xhtml?bill_id=201520160AB2729 (accessed July 17, 2020).
- (35) Bill Text—SB-32 California Global Warming Solutions Act of 2006: Emissions Limit. https://leginfo.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB32 (accessed July 17, 2020).
- (36) Bill Text—AB-1496 Methane Emissions. http://leginfo.ca.gov/faces/billTextClient.xhtml?bill_id=201520160AB1496 (accessed June 8, 2020).
- (37) Duren, R. M.; Thorpe, A. K.; Foster, K. T.; Rafiq, T.; Hopkins, F. M.; Yadav, V.; Bue, B. D.; Thompson, D. R.; Conley, S.; Colombi, N. K.; Frankenberg, C.; McCubbin, I. B.; Eastwood, M. L.; Falk, M.; Herner, J. D.; Croes, B. E.; Green, R. O.; Miller, C. E. California's Methane Super-Emitters. *Nature* **2019**, *575*, 180–184.
- (38) Fischer, M. L.; Jeong, S.; Faloon, I.; Mehrota, S. A Survey of Methane Emissions from the California Natural Gas System, 2017; No. October, p 151.
- (39) Rella, C. W.; Tsai, T. R.; Botkin, C. G.; Crosson, E. R.; Steele, D. Measuring Emissions from Oil and Natural Gas Well Pads Using the Mobile Flux Plane Technique. *Environ. Sci. Technol.* **2015**, *49*, 4742–4748.
- (40) von Fischer, J. C.; Cooley, D.; Chamberlain, S.; Gaylord, A.; Griebenow, C. J.; Hamburg, S. P.; Salo, J.; Schumacher, R.; Theobald, D.; Ham, J. Rapid, Vehicle-Based Identification of Location and Magnitude of Urban Natural Gas Pipeline Leaks. *Environ. Sci. Technol.* **2017**, *51*, 4091–4099.
- (41) Alvarez, R. A.; Zavala-Araiza, D.; Lyon, D. R.; Allen, D. T.; Barkley, Z. R.; Brandt, A. R.; Davis, K. J.; Herndon, S. C.; Jacob, D. J.; Karion, A.; Kort, E. A.; Lamb, B. K.; Lauvaux, T.; Maasakkers, J. D.; Marchese, A. J.; Omara, M.; Pacala, S. W.; Peischl, J.; Robinson, A. L.; Shepson, P. B.; Sweeney, C.; Townsend-Small, A.; Wofsy, S. C.; Hamburg, S. P. Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain. *Science* **2018**, *361*, 186–188.
- (42) Bernard, B. B.; Brooks, J. M.; Sackett, W. M. Light Hydrocarbons in Recent Texas Continental Shelf and Slope Sediments. *J. Geophys. Res.* **1978**, *83*, 4053.
- (43) *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2017*; Environmental Protection Agency, 2019.
- (44) Jeong, S.; Millstein, D.; Fischer, M. L. Spatially Explicit Methane Emissions from Petroleum Production and the Natural Gas System in California. *Environ. Sci. Technol.* **2014**, *48*, 5982–5990.
- (45) Zhou, X.; Yoon, S.; Mara, S.; Falk, M.; Kuwayama, T.; Tran, T.; Cheadle, L.; Nyarady, J.; Croes, B.; Scheehle, E.; Herner, J. D.; Vijayan, A. Mobile Sampling of Methane Emissions from Natural Gas Well Pads in California. *Atmos. Environ.* **2021**, *244*, 117930.