Science of the Total Environment 922 (2024) 170990

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Methane emissions from abandoned oil and gas wells in Colorado

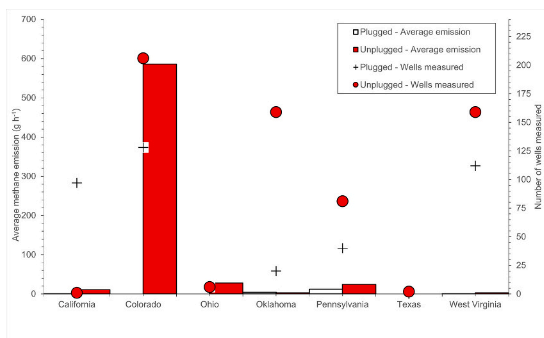
Stuart N. Riddick *, Mercy Mbua, Arthur Santos, Ethan W. Emerson, Fancy Cheptonui, Cade Houlihan, Anna L. Hodshire, Abhinav Anand, Wendy Hartzell, Daniel J. Zimmerle

The Energy Institute, Colorado State University, CO, USA

HIGHLIGHTS

- Average emission from 128 plugged abandoned wells in CO is 0 g CH_4 well^{-1} h^{-1}
- Average emission from 206 unplugged abandoned wells in CO is 586 g CH_4 well^{-1} h^{-1}
- Found the first super-emitting abandoned well (76 kg CH4 well-1 h-1)
- Average emission from unplugged wells is 75 times larger than current US average.
- Suggests that abandoned wells emit 22–49 % of total active oil and gas production

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Pavlos Kassomenos

Keywords:
Methane
Abandoned well
Colorado
Super-emitter
Annual estimate

ABSTRACT

Recent studies indicate emission factors used to generate bottom-up methane inventories may have considerable regional variability. The US's Environmental Protection Agency's emission factors for plugged and unplugged abandoned oil and gas wells are largely based on measurement of historic wells and estimated at 0.4 g and 31 g CH_4 well^{-1} h^{-1} respectively. To investigate if these are representative of wells more recently abandoned, methane emissions were measured from 128 plugged and 206 unplugged abandoned wells in Colorado, finding the first super-emitting abandoned well (76 kg CH_4 well^{-1} h^{-1}) and average emissions of 0 and 586 g CH_4 well^{-1} h^{-1}, respectively. Combining these with other states' measurements, we update the US emission factors to 1 and 198 g CH_4 well^{-1} h^{-1}, respectively. Correspondingly, annual methane emissions from the 3.4 million abandoned wells in the US are estimated at between 2.6 Tg, following current methodology, and 1.1 Tg, where emissions are disaggregated for well-type. In conclusion, this study identifies a new abandoned well-type, recently-producing orphaned, that contributes 74 % to the total abandoned wells methane emissions. Including this new well-type in the bottom-up inventory suggests abandoned well emissions equate to between 22 and 49 % of total emissions from US active oil and gas production operations.

* Corresponding author.
E-mail address: sriddick@princeton.edu (S.N. Riddick).

https://doi.org/10.1016/j.scitotenv.2024.170990
Received 16 November 2023; Received in revised form 29 January 2024; Accepted 13 February 2024
Available online 16 February 2024

1. Introduction

Methane has a greenhouse warming potential 25 times higher than carbon dioxide over a 100-year period and is the largest component of natural gas. Bottom-up approaches estimate the US emits 8.5 Tg of CH_4 per year from the production, processing, and transmission of natural gas (US EPA, 2023). Discrepancies between top-down and bottom-up estimates (Caulton et al., 2014; Schwietzke et al., 2014; Zavala-Araiza et al., 2015) indicate this is an underestimate (Nisbet and Weiss, 2010; Nisbet et al., 2019) and suggest emission sources may be missing from inventories (Zavala-Araiza et al., 2015) or regional variability in emission factors may exist (Lavoie et al., 2017). Recently, abandoned oil and gas wells have been identified as a missing methane inventory source (Kang et al., 2014; Townsend-Small et al., 2016) and have been added to the US Greenhouse Gas (GHG) inventory. The emission factors used in the inventory are taken from measurement studies which were conducted mainly in Eastern US states (Kang et al., 2016; Omara et al., 2016; Pekney et al., 2018; Riddick et al., 2019; Townsend-Small et al., 2016). Following the EPA definition, abandoned describes wells with no recent production, and not plugged (inactive, temporarily abandoned, shut-in, dormant, idle); with no recent production and no responsible operator (orphaned, deserted, long-term idle, abandoned, owners have become bankrupt); and those that have been plugged to prevent migration of gas or fluids (US EPA, 2018).

In Appalachia, where most of the original abandoned well studies were conducted (Kang et al., 2016, 2014; Riddick et al., 2020, 2019; Townsend-Small et al., 2016), plugged and abandoned wells are filled with concrete and typically left with 0.5 m of well casing still exposed. The surface expression of unplugged wells varies from obvious well heads to truncated well casings, and most unplugged wells do not have pump jacks or "Christmas Tree" above-ground piping. The US EPA emission factors for plugged and unplugged abandoned oil and gas wells are largely based on measurement of historic wells and are estimated at 0.4 g CH_4 $well^{-1}$ h^{-1} and 31 g CH_4 $well^{-1}$ h^{-1} (Kang et al., 2016; Riddick et al., 2019; Saint-Vincent et al., 2020; Townsend-Small et al., 2016), respectively.

Across the US, it is estimated there are approximately 3.5 million abandoned oil and gas wells in the U.S. with approximately 39 % of these plugged. Within EPA regional areas, the distribution of US abandoned wells are approximately split as 25 % on the East Coast, 28 % in the Midwest, 30 % in the Gulf Coast, 12 % in the Rocky Mountains and 5 % on the West Coast (Williams et al., 2021). While previous studies have estimated emissions from abandoned wells on the East Coast (Kang et al., 2016; Omara et al., 2016; Pekney et al., 2018; Riddick et al., 2019; Townsend-Small et al., 2016), the Gulf Coast (Townsend-Small and Hoschouer, 2021), the Midwest (Saint-Vincent et al., 2020; Townsend-Small et al., 2016) and the West Coast (Lebel et al., 2020), no study has explicitly studied methane emissions from the Rocky Mountain region.

The Colorado Energy and Carbon Management Commission (ECMC) estimates there are 49,000 plugged and 33,000 unplugged abandoned wells across the state (COGCC, 2023). While the absolute number of unplugged abandoned wells is relatively small, 1.5 % of the US total, Colorado is the fourth largest oil producing state in the county (EIA, 2022). Well abandonment in Colorado is likely caused by operator bankruptcy opposed to reservoir depletion in the historic production areas of the East Coast, Midwest and the West Coast. It is estimated that in Colorado around 0.3 % of operators become bankrupt each year (ShaleXP, 2023), this is in line with the national average of bankruptcies (ShaleXP, 2023) and potentially a reasonable proxy for representing emissions from abandoned wells in higher producing states, e.g. Texas, New Mexico and North Dakota. As there have been only limited studies on wells in the state, it is currently unclear if Colorado abandoned oil and gas wells emit methane and, if they do, how similar the emission profile is to other states in the US.

To address this, the ECMC commissioned a measurement study to better understand the emissions from plugged and unplugged abandoned wells across the state; this report details the findings. Specifically, this study aims to: 1. Review all current literature on US plugged and unplugged abandoned well and generate state-specific emission factors; 2. Measure methane emissions from a statistically significant number of plugged and unplugged abandoned wells in Colorado; and 3. Validate the current EPA emissions inventory estimate for methane emissions from plugged and unplugged abandoned wells in the US (Table 1).

2. Methods

2.1. Literature study of orphaned well emissions in the US

A literature study was completed to generate state average methane emissions from plugged and unplugged abandoned wells across the US. To preserve the credibility, emissions data were only taken from published peer-reviewed journals. Data were collected on lead author, year the study was published, the state the measurements were collected in, the average emission (g CH_4 $well^{-1}$ h^{-1}), the number of wells measured, methods used to identify wells to screen, methods used to screen and methods/instrumentation used to quantify emissions.

2.2. Measuring Colorado abandoned wells' methane emissions

Wells were randomly selected from the ECMC orphaned well list, which is a list of oil and gas wells, locations, and production facilities state-wide for which there are no known responsible parties ("Orphaned Wells or Sites") or for which financial assurance instruments have been claimed. The ECMC orphaned well list mainly contained unplugged wells or newly plugged wells, therefore 29 plugged wells not on the ECMC list were also measured.

Our initial goal was for 300 wells to be measured, with at least 100 plugged and 100 unplugged. For traceability, we required all measured wells to have an API number. The sampling strategy used here selected plugged and unplugged wells from a list of abandoned wells from the ECMC database and defined as follows:

1. Wells were separated in to plugged and unplugged wells

Table 1
Dates of field campaigns conducted across Colorado between August 1st 2022 and March 30th 2023

Campaign	Start date	End date	Counties visited	Number of wells measured
1	8/1/2022	8/5/2022	Jackson	1
			Moffat	10
			Rio Blanco	15
2	9/2/2022	9/7/2022	Adams	15
			Logan	13
			Morgan	3
			Weld	7
3	9/28/2022	10/6/2022	Adams	2
			Fremont	2
			Garfield	3
			La Plata	25
			Mesa	9
			Montezuma	5
			Rio Blanco	12
			Sedgwick	1
4	10/13/2022	3/21/2023	Adams	133
			Arapahoe	6
			Broomfield	5
			Elbert	11
			Larimer	1
			Weld	31
5	3/28/2023	3/30/2023	Adams	7
			Logan	2
			Washington	5
			Weld	10

2. Wells were then separated by county
3. Each well was then assigned a random number using excel
4. Wells were visited in random number order and measured unless there was a land access issue.

Each well site was initially screened using an ABB GLA131 Series Micro-portable Greenhouse Gas Analyser (MGGA; 1-sigma CH_4 precision <0.9 ppb over 1 s; range 0 to 100 ppm). Screening comprised using a 1 m PTFE tubing connected to the MGGA to identify any methane enhancements on the wellhead, wellbore, and any still-attached flow lines. Each plugged well location was identified by the latitude and longitude provided by the ECMC and the MGGA was left on the surface to measure methane concentration for 5 min. Additionally, surface was screened 10 m to the north, south, east and west of the well head location. When a methane enhancement was registered, the methane emission was measured using either the dynamic chamber method or the downwind dispersion method (both are described below).

2.2.1. Dynamic chamber

The dynamic chamber is a 0.12 m^3 plastic container which is placed over the emission source and pressed 5 cm into the soil (Fig. S1). Inside the chamber a propeller is used keep the air in the chamber well mixed. Air is also drawn through the chamber at a fixed rate using a battery powered pump, the rate of air flow is measured using a Cole-Palmer flowmeter. Methane concentrations were measured using an INIR-ME100% sensor (SGX Europe, Katowice, Poland). The methane emission (Q, g s^{-1}) was calculated (Eq. (1)) from the steady state methane concentration inside the chamber (C_{eq}, g m^{-3}), the background methane concentration (C_b, g m^{-3}) and the rate of air flow through the chamber (q, m^3 s^{-1}) (Aneja et al., 2006; Riddick et al., 2019). The uncertainty in the emission calculated using the dynamic chamber is estimated at ±11 % (Riddick et al., 2022).

$$Q = \left(C_{eq} - C_b\right) \bullet q \tag{1}$$

2.2.2. Downwind dispersion method

For any emission source that could not fit inside the chamber (Christmas tree valve, pump jacks), a dispersion approach was applied and downwind methane concentrations were used to quantify emissions. The Gaussian Plume (GP) equation can be used to calculate the expected gas concentration downwind from a point source emission (Seinfeld and Pandis, 2016). The emission rate (Q, g s^{-1}) can be calculated using a methane concentration of the gas (X, μg m^{-3}) measured a distance directly downwind of a source (x, m) and at height above ground level (z, m) using the wind speed (u, m s^{-1}) and the Pasquill-Gifford stability classification (PGSC) as a measure of air stability. The standard deviation of the lateral (σ_y, m) and vertical (σ_z, m) mixing ratio distributions are calculated using the PGSC, x and z in a lookup table (US EPA, 1995). The uncertainties in the emission calculated using the GP equation are estimated at ±9 % when methane concentrations measurements were made as close to the source as possible, at the same height and directly downwind (Riddick et al., 2023).

$$Q = 2\pi u \sigma_y \sigma_z X \tag{2}$$

Methane concentrations were measured the MGGA and meteorological data (wind speed and air temperature), were measured using a Kestrel 5500 weather meter (www.kestrelmeters.com) collocated with the analyser inlet. The distance that the MGGA was placed downwind depended on the emission size, so that the measured mixing ratios were within the linear response of the MGGA, i.e., between 2 and 300 ppm. Methane concentration and meteorological data were averaged over 5 min and the PGSC during was calculated using a lookup table (Table S2).

2.2.3. Calculating average emission

To ensure that average emission estimates calculated by this study can be compared with previous studies (Kang et al., 2016; Riddick et al., 2019; Saint-Vincent et al., 2020; Townsend-Small et al., 2016), the average emission was calculated as the sum of all emissions measured during the first time a well was visited divided by the total number of wells measured. This average includes the zero-emissions from non-emitting wells.

2.3. Patterns in Colorado unplugged wells' emission

To identify patterns in emission, data were collected on the wells' completion year, total vertical depth of well (ft), time between last production and measurement (years), active production (years), total gas production (Mcf), and total production (BOE). Statistical regressions were conducted between these variables and the measured emission to identify any causal relationships.

3. Results and discussion

3.1. Measured emissions from literature study

Emissions data were collated from 11 measurement studies comprising 412 plugged and 427 unplugged abandoned wells in nine states in the US (Fig. 1A; Table S2). Using these data, the average methane emissions from plugged and abandoned wells in the US is estimated at 1.6 g CH_4 $well^{-1}$ h^{-1}. The states with the largest observed emissions were Pennsylvania (12 g CH_4 $well^{-1}$ h^{-1} from 40 wells) and Oklahoma (4 g CH_4 $well^{-1}$ h^{-1} from 20 wells). Smaller average emissions were observed in California (0.3 g CH_4 $well^{-1}$ h^{-1} from 97 wells), West Virginia (0.1 g CH_4 $well^{-1}$ h^{-1} from 112 wells) and Ohio (0 g CH_4 $well^{-1}$ h^{-1} from 6 wells) (Fig. 1A).

The average emission rate from the 427 unplugged and abandoned wells in the US is 7.5 g CH_4 $well^{-1}$ h^{-1}. The states with the largest average emissions were Ohio (28 g CH_4 $well^{-1}$ h^{-1} from 6 wells) and Pennsylvania (24 g CH_4 $well^{-1}$ h^{-1} from 81 wells). The states with the smallest average methane emissions were Oklahoma (3 g CH_4 $well^{-1}$ h^{-1} from 159 wells) and West Virginia (3 g CH_4 $well^{-1}$ h^{-1} from 159 wells) (Fig. 1B).

In addition to well counts, methods used to identify wells to screen, methods used to screen and methods/instrumentation used to quantify emissions can also be used to quality of emission estimates and how likely the average emission of the study is to be a reasonable estimate for state-wide averages. Studies that use random selection of larger number of wells and emissions calculated using a Hi Flow sampler or dynamic chamber (Riddick et al., 2022, 2023) are likely to give the most precise emission estimates for the state.

3.2. Colorado abandoned wells' methane emissions

Between August 2022 and April 2023, 128 plugged and 206 unplugged abandoned wells were screened and emissions quantified in 18 counties across Colorado (Fig. S2). At most plugged well sites ECMC regulations had been followed: the well head was removed, and the casing cut, capped and buried under three feet (~1 m) of soil. At all plugged well sites, no methane was detected on the surface above the well head or in the adjacent 400 m^2 area. Plugged wells in Appalachia are quite different from plugged wells in Colorado, as they typically have well casing filled with concrete exposed at the surface.

61 % of the 206 unplugged abandoned wells were observed to emit methane. Unplugged wells were easier to find than plugged wells as they were either a hole in the ground (8 % of sites measured), a casing with "Christmas tree" valves on the surface (41 %) or a pump jack (51 %). In addition to methane gas being detected by the methane analyser, liquid could be seen leaking from some of the wells. Gas could be heard escaping from the largest emitting well and the emission from this site was calculated to be 76 kg CH_4 h^{-1} on September 2nd 2022, 65 kg CH_4 h^{-1} on 3rd October 2022, and 20.5 kg CH_4 h^{-1} on 16th March 2023. We suggest the change in emission over time could be caused by water

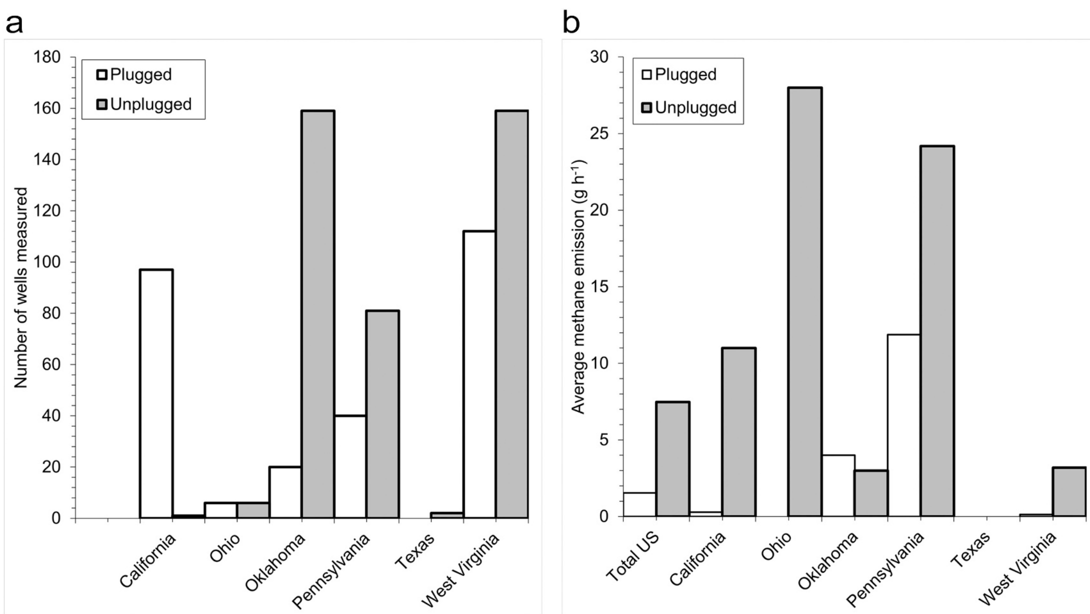


Fig. 1. A. The number of wells measured from plugged and unplugged abandoned wells in the US and in separate states where data exist. Western US data are based on cumulative data for Colorado, Utah and Texas, separate state data were not presented (Townsend-Small et al., 2016). B. Average methane emissions by state.

filling the wellbore over time, increasing the resistance to gas flow from the reservoir and reducing the emission over time. Overall, the average emission from Colorado unplugged and abandoned wells is estimated at 586 g CH_4 well^{-1} h^{-1} (Fig. 2). Similar to plugged wells, Colorado unplugged wells appear very different to those in West Virginia and Pennsylvania. Approximately 75 % of the 147 wells measured in West Virgina (Riddick et al., 2019) were holes in the ground or had the remains of old oil infrastructure (wooden oil tanks and cast iron well heads) nearby and very few had a date of abandonment recorded (with wells near the town of Volcano, likely to have been abandoned between 1870 and 1920). 92 % of unplugged wells in Colorado had relatively modern production (Christmas tree valves or a pump jack) connected to the well head and, for wells where data was available, the average year of abandonment was 2004.

A random subset of wells, 42 plugged and 25 unplugged wells, were revisited and emissions quantified a second time. Methane emissions were not detected at any of the revisited plugged well sites. For unplugged wells originally not emitting, 10 wells continued to not emit methane and 6 started to emit (Fig. 3). Of the unplugged wells that emitted methane on the first visit, all emissions decreased by an average of 80 % over the 150 days between measurements.

3.3. Patterns in Colorado unplugged wells' emission

The comparison of individual well data (completion year, total vertical depth of well, time between last production and measurement, active years of production, total gas production, and total oil production) to measured emission rate shows that there is no statistically significant correlation between emission rate and any of the variables (Table S3). While the utility in finding physical or environmental drivers of emissions from abandoned wells, this limited analysis suggests the cause of emission is obfuscated by many factors which could include the pressure of reservoir gas, quality of maintenance of the above ground infrastructure, acidity of soils around the well bore, the environmental conditions experienced by the equipment. Other limitations to better understanding why some abandoned wells emit are the dearth of data available and the relatively small number of wells measured.

The Colorado counties with the largest emission rates (Fig. 1) were

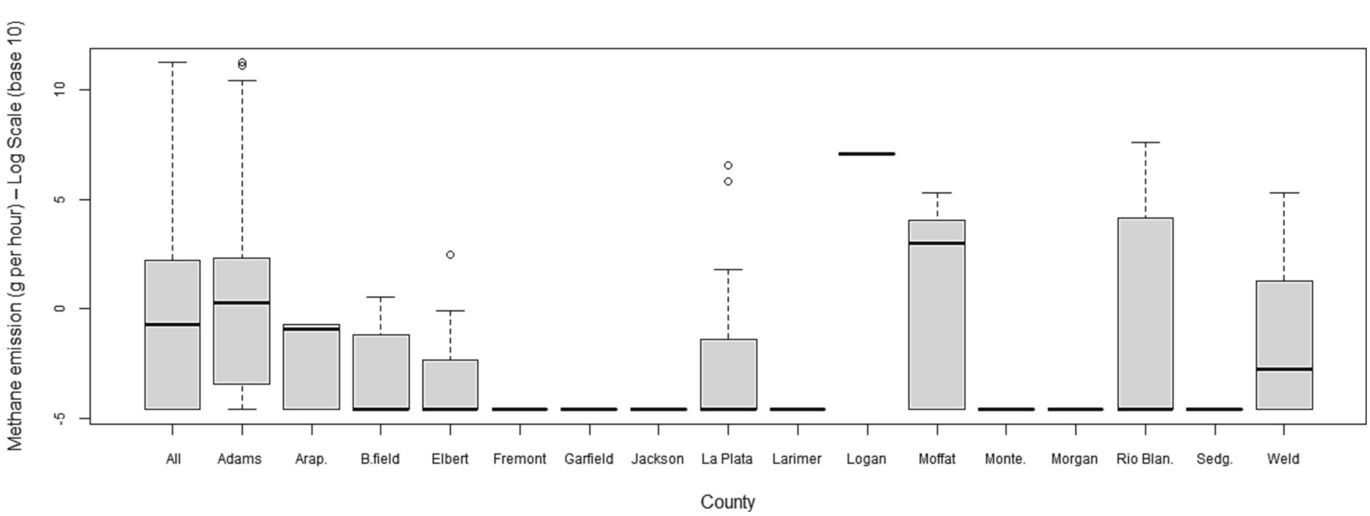


Fig. 2. Emission of the 226 unplugged and abandoned wells total (All) and aggregated by county.

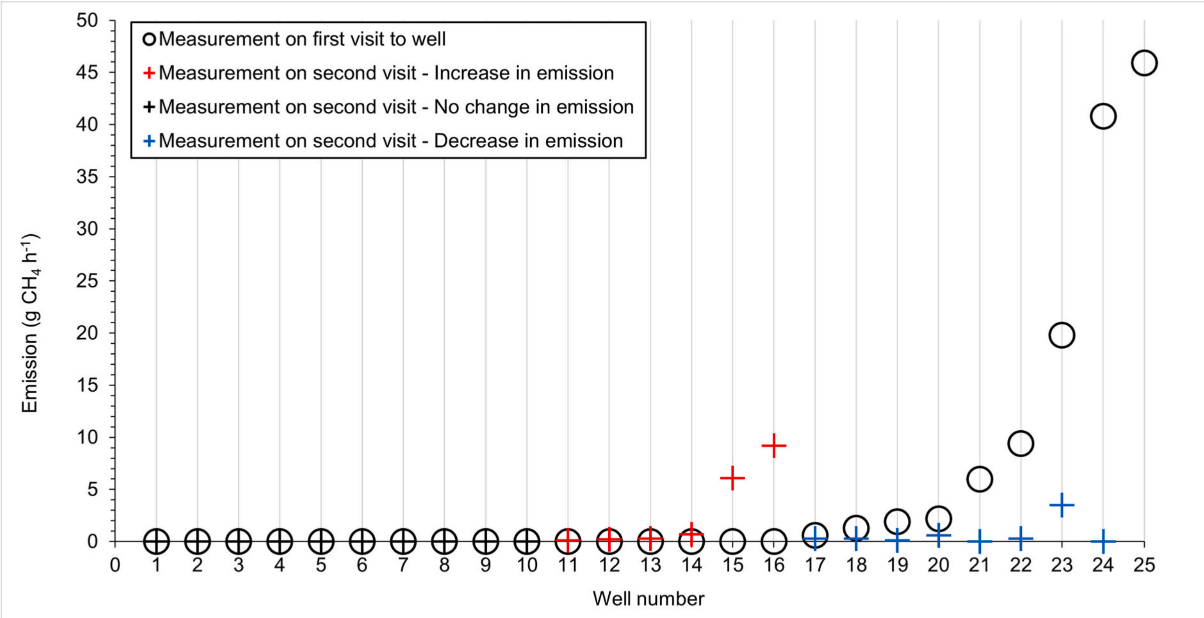


Fig. 3. Methane emission measurements from 25 unplugged and abandoned wells across Colorado. Each well was visited twice: represent emissions measured on the first visit; crosses represent emissions measured on the second visit. Black crosses show well that did not change in emission. Red crosses indicate wells that had zero emission on first visit and higher emission on second visit. Blue crosses indicate wells that had higher emission on the first visit and lower emission on second visit. The largest emitting well emitting 76 kg CH_4 h^{-1} on 2nd September 2022, 65 kg h-1 on 3rd October 2022 and 20.5 kg CH_4 h^{-1} on 16th March 2023 has not been included in this figure as it is off the scale by a factor of 1000.

Adams County (average 1396 g CH_4 $well^{-1}$ h^{-1}) and Logan County (average 290 g CH_4 $well^{-1}$ h^{-1}), with both counties' average emissions skewed by a single large emitter (76 kg CH_4 h^{-1} in Adams Co. and 1.2 kg CH_4 h^{-1} in Logan Co.). Long-tail emission distributions with super emitting sources relative to the median emission rate are common to oil and gas emissions distributions (Vaughn et al., 2017; Yu et al., 2022; Zavala-Araiza et al., 2015; Zimmerle et al., 2015). To date, left-skewed emissions distributions have not been observed while measuring emissions from abandoned wells. We suggest the Colorado emission distribution may be a consequence of the relatively large sample size of this study or because many wells were measured in Adams County. In Adams County many wells were orphaned when the gathering pipeline servicing the wells was removed, stranding the wells' gas production. After stranding, the wells were shut-in, the operator became bankrupt, and the wells were ultimately declared orphaned and adopted by the state.

The findings of this study provide evidence against a common suggestion that marginal wells should be shut-in and abandoned to reduce methane emissions (Townsend-Small, 2023). The US Department of Energy defines a marginal well as producing <15 barrels of oil equivalent per day of combined oil and natural gas. ECMC production records (COGCC, 2023) show that 12 % of the orphaned wells in Adams County measured in this study were considered marginal, i.e. producing <15 barrels of oil equivalent per day (Deighton et al., 2020). On average, we estimate these wells to emit 2724 g CH_4 $well^{-1}$ h^{-1}, while average emissions from marginal wells in the US have been estimated at 128 g CH_4 $well^{-1}$ h^{-1} (Deighton et al., 2020), 138 g CH_4 $well^{-1}$ h^{-1} (Riddick et al., 2019) and 75 g CH_4 $well^{-1}$ h^{-1} (Bowers, 2022). This strongly suggests that shutting-in marginal wells could result in larger emissions than if operators maintain a site, albeit with minimal financial reward. Typically, shutting in a marginal well will deprive smaller operators of revenue, potentially forcing them into bankruptcy which, if it happens, will result in all the operator's productions sites becoming unmaintained, potentially becoming large sources of methane. Maintenance appears to be key in reducing emissions and any attempt at repair is preferable to total neglect.

In Adams County, the stranded wells were initially shut in and were declared orphaned after the operators' bankruptcy even though well bores remain at pressure. We suggest that since being shut in, the integrity of the casing head block valve has degraded over time and gas is initially emitted at significant rate (Fig. S3), with a maximum emission rate of 76 kg CH_4 h^{-1}. Even though over time emission appear to reduce naturally, possibly caused by water entering the well bore, we highlight that unmaintained unplugged abandoned wells can be a major source of emission. These recently-producing but orphaned wells are not currently recognised by the EPA or accounted for separately in GHG inventories. Of the unplugged and abandoned wells measured by this study, all were considered orphaned, 21 % were recently-producing (within the last 10 years) with an average emission of 3640 g CH_4 $well^{-1}$ h^{-1}, and the remaining 79 % non-producers (no production data within the last 10 years) emitted 3.6 g CH_4 $well^{-1}$ h^{-1}, a difference of three orders of magnitude.

This study now suggest that super-emitting abandoned wells exist, i. e. that emit >10 kg of methane per hour (Highwood, 2024), implying that aircraft studies with sufficiently sensitive methods could be used to detect these super-emitters (Bell et al., 2022; Kunkel et al., 2023). Data from this study suggests that 0.9 % of the unplugged abandoned wells in Colorado could be super-emitters, equating to 320 of the 33,000 abandoned wells in the state. Extended further, if the Texas abandoned well emission distribution is more similar to Colorado than Appalachia, there could be thousands of uncontrolled and unknown super-emitting abandoned wells in Texas.

3.4. *Updating the US abandoned well emission factors*

Adding the average emission from the 128 plugged and 206 unplugged abandoned wells measured in Colorado to the data collated in Table S1, changes the average emission from plugged and unplugged abandoned wells from 1.6 and 7.5 g CH_4 $well^{-1}$ h^{-1} to 1.2 and 198 g CH_4 $well^{-1}$ h^{-1}, respectively. Using these updated emission factors to represent the 1.9 million plugged and 1.5 million unplugged wells in the US (EPA, 2023), the total annual emission from unplugged abandoned wells is estimated at 2.6 Tg CH_4 y^{-1}. By contrast, the EPA estimated 2021 CH_4 emissions from active oil and gas production activities at 143 MMT CO_2e or 5.1 Tg CH_4 y^{-1}, assuming a GWP of 28 (US EPA, 2023b, 2023c). This would suggest methane emissions from abandoned wells equates to 49 % of total methane emissions from active production.

The fundamental assumption made in the inactive unplugged well 198 g CH_4 $well^{-1}$ h^{-1} estimate is the emissions distribution seen in Colorado can be applied to other US states. Our study suggests that the emission rate from orphaned wells is disproportionately high following the financial collapse of the operator. Following the pipeline shutdown in Adams County, 3 of the 318 (ShaleXP, 2023) Colorado oil and gas operators ceased operations. Nationally, around 100 (OGV Energy, 2021) of the 32,000 (ShaleXP, 2023) US oil and gas operators undergo bankruptcy each year. This suggests that the rate of oil and gas operators' financial collapse in Colorado, ~0.3 % $year^{-1}$, is in line with the national average of bankruptcies. For the new US emission factors described above, we aggregated the results of 10 studies together. Most of these studies reported emissions from fewer wells than our Colorado study or were from historic production regions. Consequently, these studies may not have encountered any super-emitting wells as the sample size was too small or the regions sampled did not contain abandoned wells that resulted from recent operator bankruptcies. Therefore, it may be reasonable to consider that the fraction of abandoned wells in the aggregated set could be representative of the national abandoned wells, and our extrapolation to national scale identifies a potential issue not previously encountered.

The major shortcoming of the US abandoned well emission estimate of 2.6 Tg CH_4 y^{-1} presented above is the emissions from recently-producing and orphaned wells in Colorado are unreasonably skewing the national emission estimate. A more realistic approach may be to disaggregate unplugged abandoned well types (including inactive, shut-in, temporarily abandoned, non-producing orphaned, recently producing orphaned and historic pre-1975 abandoned; Fig. S5) and we present an emission estimate based on emission factors/activity data generated for different types of well (Table S5). Using this approach where each abandoned well type is represented by an average emission and activity data are weighted by well type activity data, a more rational US annual emissions from abandoned wells can be estimated at 1.1 Tg CH_4 $year^{-1}$, with 74 % of emissions coming from the newly presented recently-producing orphaned wells. This estimate equates to 22 % of current active production methane emissions.

These findings emphasize the need for future studies to measure enough abandoned wells to account for the left-skewed emission distribution, as this could result in an underestimation of national emission from abandoned wells by not including the rare super-emitting wells. Given that the super-emitting abandoned wells are large enough to be seen during an aerial survey (Kunkel et al., 2023), finding the long tail in emissions may be easier than previously thought. With the ability to quickly detect these large emitting wells, it may also be possible to generate regionally specific emission factors that better describe the emissions distributions in particular production basins, as such, bottom-up emissions estimates could be spatially weighted and more reflective of actual emissions behaviours.

Once detected, large sources can be localized and further measured. In addition to using survey methods which can rapidly screen many wells for super-emitters, assessing abandoned wells for risk factors (i.e. orphaned wells that were recently producing and shut in) would provide efficient target lists for aerial surveys. These aircraft-based survey methods are factors of ten faster than traditional methods and do not have the limitation of land access and by using them regulators could quickly identify the largest sources for plugging.

The non-normal nature of the emission distribution also suggests that the methods used by previous studies to calculate an average emission may not be representative and alternate could be used to derive more descriptive metrics. Other studies (Zavala-Araiza et al., 2015) have used Monte-Carlo approaches to derive more representative emission factors for emissions from the oil and gas industry that show similar emissions distributions. While this could be a future direction form generating abandoned well emission factors, these analyses are out with the scope of this study.

4. Conclusions

This study reports methane emissions from 128 plugged and 206 unplugged abandoned wells across Colorado. Results suggest that plugging strategies (fill, cut, cap and cover) remain successful for over 50 years after plugging. For unplugged wells, the average measured methane emission in Colorado is seventy times higher (586 g CH_4 $well^{-1}$ h^{-1}) than an average US emission rate calculated from current literature (7.5 g CH_4 $well^{-1}$ h^{-1}). The largest emissions observed in Colorado were the result of operator bankruptcies and subsequent neglect of recently producing wells, rather than emissions from historic wells. This is the first time that a measurement study has observed a super-emitting abandoned well or a heavily left-skewed, long-tailed emission distribution of the abandoned well assemblage.

Our observations suggest that recently-producing, orphaned oil and gas wells present a greater environmental and safety risk than historic wells as shut-in wells retain pressure capable of driving at least marginal production but lack of routine maintenance and service of operating marginal wells. Lack of maintenance is associated with methane emissions two-hundred times higher than the largest historic unplugged abandoned well reported in Appalachia. As a result, at-risk areas, i.e. those where abandonment is the result of bankruptcy (instead of non-production) should be considered as a priority for both screening and remediation.

Incorporating the findings of our Colorado study to the literature estimate suggests a US plugged and unplugged abandoned oil and gas wells emission factors of 1 and 198 g CH_4 $well^{-1}$ h^{-1}, respectively, which results in an estimated emission of 2.5 Tg CH_4 y^{-1} from the 3.4 million unplugged abandoned wells in the US. We temper this statement with the caveat that current EPA methods to quantify emissions from abandoned wells may result in an overestimate and a more representative emission could be generated by disaggregating abandoned well types, which results in an annual emission estimate 1.1 Tg CH_4 y^{-1}. Given that the EPA estimates the 2021 total methane loss from oil and gas production at 143 MMT CO_2e (or 5.1 Tg CH_4 y^{-1} at a GWP of 28), this study now provides evidence to suggest that hitherto undiscovered super-emitting wells resulting from operators' financial collapse could make abandoned wells one of the highest emission sources in the energy sector (equivalent of between 22 % and 49 % of methane from active production) and highlights the importance in measuring enough abandoned wells to make the emission factor statistically significant.

Funding information

This work was funded by The Mark Martinez and Joey Irwin Memorial Public Projects Fund.

CRediT authorship contribution statement

Stuart N. Riddick: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Mercy Mbua:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Arthur Santos:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Ethan W. Emerson:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Fancy Cheptonui:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Cade Houlihan:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Anna L. Hodshire:** Writing – review & editing, Writing – original draft. **Abhinav Anand:** Writing – review & editing, Writing – original draft. **Wendy Hartzell:** Writing – review &

editing, Project administration, Funding acquisition. **Daniel J. Zimmerle:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that no financial interest or benefit that has arisen from the direct applications of this research.

Data availability

Data can be accessed at doi:https://doi.org/10.5061/dryad.sf7m0cgc7

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170990.

References

Aneja, V.P., Blunden, J., Claiborn, C.S., Rogers, H.H., 2006. Dynamic chamber system to measure gaseous compounds emissions and atmospheric-Biospheric interactions. In: Barnes, I., Rudzinski, K.J. (Eds.), Environmental Simulation Chambers: Application to Atmospheric Chemical Processes. Springer, Netherlands, pp. 97–109.

Bell, C., Rutherford, J., Brandt, A., Sherwin, E., Vaughn, T., Zimmerle, D., 2022. Single-blind determination of methane detection limits and quantification accuracy using aircraft-based LiDAR. Elementa: Science of the Anthropocene 10, 00080. https://doi.org/10.1525/elementa.2022.00080.

Bowers, R., 2022. Quantification of methane emissions from marginal (low production rate). Oil and Natural Gas Wells No. DOE-GSI-31702, 1865859. https://doi.org/10.2172/1865859.

Caulton, D.R., Shepson, P.B., Santoro, R.L., Sparks, J.P., Howarth, R.W., Ingraffea, A.R., Cambaliza, M.O.L., Sweeney, C., Karion, A., Davis, K.J., Stirm, B.H., Montzka, S.A., Miller, B.R., 2014. Toward a better understanding and quantification of methane emissions from shale gas development. Proc. Natl. Acad. Sci. 111, 6237–6242. https://doi.org/10.1073/pnas.1316546111.

COGCC, 2023. Colorado Oil and Gas Conservation Commission-COLORADO OIL AND GAS INFORMATION SYSTEM (COGIS). https://cogcc.state.co.us/data.html, Date Accessed 3rd June 2023.

Deighton, J.A., Townsend-Small, A., Sturmer, S.J., Hoschouer, J., Heldman, L., 2020. Measurements show that marginal wells are a disproportionate source of methane relative to production. J. Air Waste Manage. Assoc. 70, 1030–1042. https://doi.org/10.1080/10962247.2020.1808115.

EIA, 2022. U.S. Energy Information Administration. Natural gas. Annu. Rep. 1, 4–5. https://www.eia.gov/naturalgas/annual/ (accessed 13th June 2023).

EPA, 2023. EPA Proposes Updates to Greenhouse Gas Emissions Reporting Requirements for the Oil and Gas Sector. https://www.epa.gov/newsreleases/epa-proposes-updates-greenhouse-gas-emissions-reporting-requirements-oil-and-gas. Last accessed 7th September 2023.

Highwood, 2024. Highwood Emissions Management. Glossary. Super-emitter. Last accessed 26th Januray 2024.

Kang, M., Kanno, C.M., Reid, M.C., Zhang, X., Mauzerall, D.L., Celia, M.A., Chen, Y., Onstott, T.C., 2014. Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania. Proc. Natl. Acad. Sci. 111, 18173–18177. https://doi.org/10.1073/pnas.1408315111.

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., 2016. Identification and characterization of high methane-emitting abandoned oil and gas wells. Proc. Natl. Acad. Sci. 113, 13636–13641. https://doi.org/10.1073/pnas.1605913113.

Kunkel, W.M., Carre-Burritt, A.E., Aivazian, G.S., Snow, N.C., Harris, J.T., Mueller, T.S., Roos, P.A., Thorpe, M.J., 2023. Extension of methane emission rate distribution for Permian Basin oil and gas production infrastructure by aerial LiDAR. Environ. Sci. Technol. 57, 12234–12241. https://doi.org/10.1021/acs.est.3c00229.

Lavoie, T.N., Shepson, P.B., Cambaliza, M.O.L., Stirm, B.H., Conley, S., Mehrotra, S., Faloona, I.C., Lyon, D., 2017. Spatiotemporal variability of methane emissions at oil and Natural gas operations in the eagle Ford Basin. Environ. Sci. Technol. 51, 8001–8009. https://doi.org/10.1021/acs.est.7b00814.

Lebel, E.D., Lu, H.S., Vielstädte, L., Kang, M., Banner, P., Fischer, M.L., Jackson, R.B., 2020. Methane emissions from abandoned oil and gas Wells in California. Environ. Sci. Technol. 54, 14617–14626. https://doi.org/10.1021/acs.est.0c05279.

Nisbet, E., Weiss, R., 2010. Top-down versus bottom-up. Science 328, 1241–1243. https://doi.org/10.1126/science.1189936.

Nisbet, E.G., Manning, M.R., Dlugokencky, E.J., Fisher, R.E., Lowry, D., Michel, S.E., Myhre, C.L., Platt, S.M., Allen, G., Bousquet, P., Brownlow, R., Cain, M., France, J.L., Hermansen, O., Hossaini, R., Jones, A.E., Levin, I., Manning, A.C., Myhre, G., Pyle, J.A., Vaughn, B.H., Warwick, N.J., White, J.W.C., 2019. Very strong atmospheric methane growth in the 4 years 2014–2017: implications for the Paris agreement. Global Biogeochem. Cycles 33, 318–342. https://doi.org/10.1029/2018GB006009.

OGV Energy, 2021. Over 100 oil and gas companies went bankrupt in 2020 [WWW document]. URL https://www.ogv.energy/news-item/over-100-oil-and-gas-companies-went-bankrupt-in-2020#:~:text=The%20107%20oil%20and%20gas,bankruptcy%20report%20published%20this%20month (accessed 8.23.23).

Omara, M., Sullivan, M.R., Li, X., Subramanian, R., Robinson, A.L., Presto, A.A., 2016. Methane emissions from conventional and unconventional natural gas production sites in the Marcellus Shale Basin. Environ. Sci. Technol. 50, 2099–2107. https://doi.org/10.1021/acs.est.5b05503.

Pekney, N.J., Diehl, J.R., Ruehl, D., Sams, J., Veloski, G., Patel, A., Schmidt, C., Card, T., 2018. Measurement of methane emissions from abandoned oil and gas wells in Hillman State Park, Pennsylvania. Carb. Manag. 9, 165–175. https://doi.org/10.1080/17583004.2018.1443642.

Riddick, S., Ancona, R., Bell, C., Duggan, A., Vaughn, T., Bennett, K., Zimmerle, D., 2022. Quantitative comparison of methods used to estimate methane emissions from small point sources (preprint). Gases/In Situ Measurement/Validation and Intercomparisons. https://doi.org/10.5194/amt-2022-9.

Riddick, S.N., Mauzerall, D.L., Celia, M.A., Kang, M., Bressler, K., Chu, C., Gum, C.D., 2019. Measuring methane emissions from abandoned and active oil and gas wells in West Virginia. Sci. Total Environ. 651, 1849–1856. https://doi.org/10.1016/j.scitotenv.2018.10.082.

Riddick, S.N., Mauzerall, D.L., Celia, M.A., Kang, M., Bandilla, K., 2020. Variability observed over time in methane emissions from abandoned oil and gas wells. Int. J. Greenh. Gas Control 100, 103116. https://doi.org/10.1016/j.ijggc.2020.103116.

Riddick, S.N., Mbua, M., Riddick, J.C., Houlihan, C., Hodshire, A.L., Zimmerle, D.J., 2023. Uncertainty quantification of methods used to measure methane emissions of 1 g CH4 h−1. Sensors 23, 9246. https://doi.org/10.3390/s23229246.

Saint-Vincent, P.M.B., Reeder, M.D., Sams, J.I., Pekney, N.J., 2020. An analysis of abandoned oil well characteristics affecting methane emissions estimates in the Cherokee platform in eastern Oklahoma. Geophys. Res. Lett. 47 https://doi.org/10.1029/2020GL089663.

Schwietzke, S., Griffin, W.M., Matthews, H.S., Bruhwiler, L.M.P., 2014. Natural gas fugitive emissions rates constrained by global atmospheric methane and ethane. Environ. Sci. Technol. 48, 7714–7722. https://doi.org/10.1021/es501204c.

Seinfeld, J.H., Pandis, S.N., 2016. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, Third edition. ed. John Wiley & Sons, Inc, Hoboken, New Jersey.

ShaleXP, 2023. Oil & Gas Companies [WWW Document]. URL https://www.shalexp.com/companies?page=322 (accessed 8.23.23).

Townsend-Small, A., 2023. An immediate, very low-cost method for reducing methane emissions from the US oil and gas supply chain. PLOS Clim. 2, e0000151 https://doi.org/10.1371/journal.pclm.0000151.

Townsend-Small, A., Hoschouer, J., 2021. Direct measurements from shut-in and other abandoned wells in the Permian Basin of Texas indicate some wells are a major source of methane emissions and produced water. Environ. Res. Lett. 16, 054081 https://doi.org/10.1088/1748-9326/abf06f.

Townsend-Small, A., Ferrara, T.W., Lyon, D.R., Fries, A.E., Lamb, B.K., 2016. Emissions of coalbed and natural gas methane from abandoned oil and gas wells in the United States. Geophys. Res. Lett. 43, 2283–2290. https://doi.org/10.1002/2015GL067623.

US EPA, 1995. Industrial Source Complex (ISC3) Dispersion Model, Research Triangle Park. U.S. Environmental Protection Agency, NC. User's Guide. EPA 454/B 95 003a (vol. I) and EPA 454/B 95 003b (vol. II).

US EPA, 2018. United States Environmental Protection Agency. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Oil and Gas Wells. [WWW Document]. URL https://www.epa.gov/sites/default/files/2018-04/documents/ghgemissions_abandoned_wells.pdf (accessed 8.23.23).

US EPA, 2023. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2021. U.S. Environmental Protection Agency, EPA 430-R-23-002. [WWW document]. URL https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021 (accessed 8.23.23).

US EPA, 2023b. United States Environmental Protection Agency. Estimates of Methane Emissions by Segment in the United States. [WWW Document]. URL https://www.epa.gov/natural-gas-star-program/estimates-methane-emissions-segment-united-states (accessed 8.23.23).

US EPA, 2023c. United States Environmental Protection Agency. US GHG Inventory 2023 Executive Summary. [WWW Document]. URL https://www.epa.gov/system/files/documents/2023-04/US-GHG-Inventory-2023-Chapter-Executive-Summary.pdf (accessed 8.23.23).

Vaughn, T.L., Bell, C.S., Yacovitch, T.I., Roscioli, J.R., Herndon, S.C., Conley, S., Schwietzke, S., Heath, G.A., Pétron, G., Zimmerle, D., 2017. Comparing facility-level methane emission rate estimates at natural gas gathering and boosting stations. Elem. Sci. Anth. 5, 71. https://doi.org/10.1525/elementa.257.

Williams, J.P., Regehr, A., Kang, M., 2021. Methane emissions from abandoned oil and gas Wells in Canada and the United States. Environ. Sci. Technol. 55, 563–570. https://doi.org/10.1021/acs.est.0c04265.

Yu, J., Hmiel, B., Lyon, D.R., Warren, J., Cusworth, D.H., Duren, R.M., Chen, Y., Murphy, E.C., Brandt, A.R., 2022. Methane emissions from natural gas gathering pipelines in the Permian Basin. Environ. Sci. Technol. Lett. 9, 969–974. https://doi.org/10.1021/acs.estlett.2c00380.

Zavala-Araiza, D., Lyon, D.R., Alvarez, R.A., Davis, K.J., Harriss, R., Herndon, S.C., Karion, A., Kort, E.A., Lamb, B.K., Lan, X., Marchese, A.J., Pacala, S.W., Robinson, A.L., Shepson, P.B., Sweeney, C., Talbot, R., Townsend-Small, A., Yacovitch, T.I., Zimmerle, D.J., Hamburg, S.P., 2015. Reconciling divergent estimates of oil and gas methane emissions. Proc. Natl. Acad. Sci. 201522126 https://doi.org/10.1073/pnas.1522126112.

Zimmerle, D.J., Williams, L.L., Vaughn, T.L., Quinn, C., Subramanian, R., Duggan, G.P., Willson, B., Opsomer, J.D., Marchese, A.J., Martinez, D.M., Robinson, A.L., 2015. Methane emissions from the natural gas transmission and storage system in the United States. Environ. Sci. Technol. 49, 9374–9383. https://doi.org/10.1021/acs.est.5b01669.