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Article

Reported Methane Emissions from Active Oil and Gas Wells in Pennsylvania, 2014–2018

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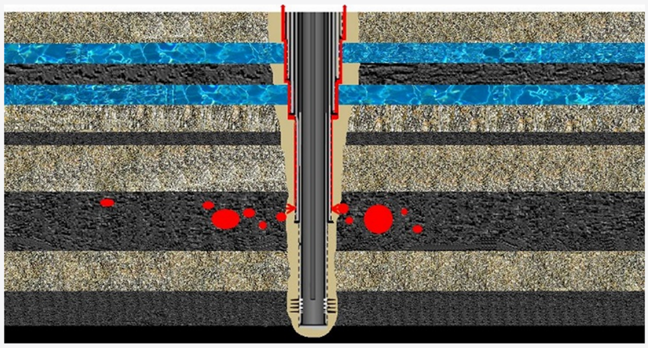
ABSTRACT: Oil/gas well integrity failures are a common but poorly constrained source of methane emissions to the atmosphere. As of 2014, Pennsylvania requires gas and oil well operators to report gas losses, both fugitive and process, from all active and unplugged abandoned gas and oil wells. We analyze 589,175 operator reports and find that lower-bound reported annual methane emissions averaged 22.1 Gg (−16.9, +19.5) between 2014 and 2018 from 62,483 wells, an average of only 47% of the statewide well inventory for those years. Extrapolating to the 2019 oil and gas well inventory yields well average emissions of 55.6 Gg CH_4. These emissions are not currently included in the state's oil and gas emission inventory. We also assess compliance in reporting among operators and note anomalies in reporting and apparent workarounds to reduce reported emissions. Suggestions for improving the accuracy and reliability in reporting and reducing emissions are offered.



1. INTRODUCTION

Oil/gas (O&G) well integrity failures can lead to migration of methane into the atmosphere and contribute to greenhouse gas (GHG) emissions. Recent studies have identified previously ignored sources and undercounting of methane emissions from the O&G sector.[1−5] To date, no study has focused exclusively on methane emissions from leaking active O&G wells themselves. An opportunity to study such emissions presented itself when, in 2011, the Pennsylvania Department of Environmental Protection (PADEP) promulgated new regulations under the Mechanical Integrity Assessment Program (Program) and began to collect extensive data on emissions from active wells statewide. The regulatory language is found in Code Chapter 78, section 78.88 (25 Pa). The Program requires quarterly inspections of all active O&G wells to identify if fluids are currently escaping from various points along the wellbore or at risk of doing so. Active wells include all permitted producing and nonproducing/abandoned wells in the PADEP inventory that are neither plugged nor granted inactive status. Operators of shale gas wells are required to report results quarterly; other operators must report at least once a year. Pennsylvania is currently the only state requiring quarterly mechanical integrity inspections of all active and unplugged abandoned wells. The Program has now amassed 5 years of reported gas emission data. The purpose of this paper is to report for the first time the results of a detailed analysis of this data.

Figure 1 shows a generalized schematic of a modern wellbore and potential pathways to the environment. Wellbores are constructed with redundant barriers of concentric steel casing

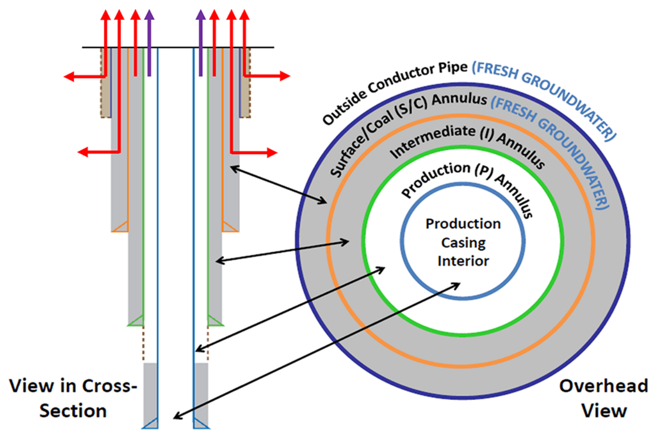


Figure 1. Schematic of casing/cement arrangement for a well with all required and optional casings: colored circles and corresponding vertical lines. Grayed areas indicate required cement sheaths. Purple arrows indicate possible leakage pathways through an open or vented production annulus. Red arrows indicate possible leakage pathways from outer annuli. Adapted from PADEP.[6]

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strings, and the spaces between casings, annuli, may be filled or partially filled with cement.

The innermost production casing houses the tubing carrying hydrocarbon fluids from the reservoir or source rock. Unintentional, or fugitive, flow outside any casing and/or into any of the annuli depicted in Figure 1 can lead to environmental contamination and GHG emissions. Such fugitive flow can occur at any time in the life of the well for many reasons, including construction errors, formation damage, corrosive environments, cyclic temperature and pressure extremes, and material degradation over time. A full explanation of failure mechanisms is beyond the scope of this paper. Numerous seminal and recent studies offer detailed discussion of wellbore failure mechanisms.[7−11] Additional studies are available from the OnePetro online library.[12]

A failure in any wellbore barrier equates to a loss of mechanical integrity and the potential for fugitive flow to the environment. For example, the intrusion of natural gas and/or other fluids into a production annulus sealed at the surface will pressurize that annulus and can lead to migration of fluids to a source of fresh groundwater (Figure 1). Consequently, some wells are equipped with an engineered production annulus vent at the surface, which, if open, prohibits such a pressure buildup but becomes a source of atmospheric methane emissions. Production annulus vent flow then becomes a trade-off between the possibility of fresh groundwater contamination and the certainty of GHG emissions.

The Program requires reporting of flows from all annuli, including engineered vents on the production annulus, and leaks from the wellhead. In this paper, we calculate methane emissions based on reported flows from all annuli and the wellhead. Fugitive flows include all measured flow volumes from production, freshwater, and intermediate annuli as well as wellhead leaks. Fugitive flows are the least constrained emission source and are undercounted or missing from state and national inventories. Engineered vents on the production annulus are considered process flows and are included in national GHG inventories but are often missing in state inventories. The GHG inventory for Pennsylvania does not include well fugitive or process flows.[13]

This paper reports findings of a comprehensive analysis of gas flow over 5 years of Program reporting to answer the following key questions:

(1) How many active wells have reported annular and engineered vent flows? Are different well types more prone to flow?
(2) Can we quantify methane emissions from leaking wells based on Program data, and what is their significance? Are there differences in emission volumes and rates within and among different well types?
(3) What is the rate of compliance with Program requirements, and are there apparent anomalies in self-reporting among the operators? Are operators reporting accurately and consistently?

Recent findings heighten the importance of answering these questions. The Intergovernmental Panel on Climate Change's recent special report emphasizes the increasing importance of controlling non-CO_2 radiative forcing such as that from methane (CH_4).[14] One study reported that, between 2012 and 2015, atmospheric concentrations in Northeastern Pennsylvania had increased by about 100 parts per billion (ppb) over an expected baseline of 1900 ppb.[3] Barkley et al. found that emissions reported to the U.S. Environmental Protection Agency (EPA) from unconventional natural gas development in Southwestern Pennsylvania are underreported by a factor of 5 (±3).[5]

2. MATERIALS AND METHODS

Program operator reports for 2014−2018 were downloaded from the PADEP database as Excel files.[15] Each file contains information organized by well type: conventional gas, oil, oil and gas, coalbed methane, unconventional, and other. For the purposes of data gathering by the Program and this paper, any well producing natural gas or oil from a shale source is classified as an unconventional well.

The Program requires operators to report measured PSIG (pounds per square inch gauge measured pressure in an annulus with no flow) or CFPD (cubic feet per day measured volume rate of flow from an annulus) for the production, freshwater, and intermediate casing annuli (Figure 1) or indicate if such measurements could not or should not be made. Nonmeasurements are reported as either blank entries or one of the three indicators:

(1) NRM (not readily measurable): Flow cannot be constrained for measurement or is too low to estimate with standard equipment. PADEP currently has no protocols or required thresholds and accuracy for the required flow measurements. Operators used equipment ranging from commercial manometers, with relatively high thresholds, to low -flow digital meters with thresholds as low as 0.0283 m^3 per day.
(2) I (inaccessible): The production annulus is inaccessible. Inaccessible does not mean that no gas leak is present.
(3) NA (not applicable): Measurement is inapplicable in this case.

Operators apply these indicators independently to flow or pressure measurements from the production annulus and to flow measurements from outside the freshwater and intermediate casings and the wellhead.

2.1. Sorting and Classifying Operator Reports. Annual Program data sets included all counties, municipalities, operators, and well types. The raw data set consists of 589,175 reports, which were sorted and classified as no inspection, noninformative, or inspection.

We identified no inspection reports by a non-null entry in the "Standard No Inspection Comment" field (35,135 reports). Of the remaining reports, we found an additional 3284 associated with wells not subject to the Program mandate due to the change in status or well type. All reports classified as no inspection were from 7364 wells and were omitted from results reported here.

Noninformative reports were identified as those that do not include measurements related to annular flows or wellhead emissions, that is, reports with consistent nonmeasurement indicator (i.e., NRM, NA, or I) or blank entries (222,289 reports). Roughly half of the wells with some reports in this category are associated with informative inspections from the inspected data set, leaving 28,246 active wells that cannot be directly assessed from Program reports. Noninformative reports were not included in results reported for leakage counts and emissions but were assessed as part of the compliance analysis described in Section 3.3.

The remaining 328,647 inspected reports were aggregated to provide a timeline of volumetric flow measurements for each inspected well. The inspected data set reflects Program reporting across 62,483 wells (85.5% conventional; 14.5% unconventional) and 455 operators. These wells account for 47% of the wells in the state 2019 oil and gas well inventory. Our no inspection, noninformative, and inspection data sets are included in the Supporting Information.

2.2. Leaky Well Counts and Methane Emissions. Counts of wells with fugitive leakage were calculated as the sum of unique well permits reporting nonzero flow from any annulus (i.e., production, freshwater, and intermediate annuli) and wellhead leaks. Engineered vents on the production annulus produce process flows and are not included in fugitive leakage but are included in methane emissions.

Volumetric flows from engineered production annulus vents, fugitive leakage from all annuli, and wellhead emissions were averaged across all inspected wells, including those reporting zero flow. In extrapolating flow volumes from the Program wells to the full state oil and gas well inventory, we assumed that the percent of wells leaking from Program reporting holds for wells statewide. All reported volumes were converted to cubic meters by multiplying the reported flow by 0.0283 m^3/cf.

Converting from a flow volume to mass-based emissions across a large well population requires assumptions regarding gas composition and density. The EPA's National Greenhouse Gas Inventory[16] reports a default gas composition of 83.5% CH_4 for general sources in the Northeast oil and gas production sector, although compositions of 90% or higher are common in Pennsylvania's unconventional dry gas wells. Indeed, other studies have used compositions ranging as high as 90 to 100%.[1,17] However, unconventional wells make up only 14.5% of wells reporting, and only a portion of those is likely to be dry gas wells. In extrapolating emissions to the statewide inventory, we use the regional default composition reported by EPA, 83.5% CH_4. Gas density was assumed to be 656 g CH_4 per m^3 at normal conditions.

3. RESULTS

Results presented here reflect measurements from 328,647 inspection reports carried out on 62,483 wells, or 47% of the 2019 PADEP oil and gas well inventory, between 2014 and 2018. Conventional gas and oil wells make up most of the inspected wells (37,442 and 11,498 wells, respectively). Unconventional gas, oil and gas, and oil wells account for a total of 9074 of the inspected wells (8982 gas wells, 91 oil and gas wells, and 1 oil well). The data set also includes 628 coalbed methane wells and 224 wells that are assigned a well type other than oil and/or gas (e.g., injection, storage, and undetermined). Operator reports indicate fugitive leakage from 3482 wells, or 5.6% of inspected wells. Conventional wells account for 1799 of leaking wells, or 3.4% of conventional wells in the inspected data set. Fugitive flows from unconventional wells occur at a much higher frequency (18.5%) according to operator reports. Ingraffea et al. predicted a disparity in impairment rates between conventional (1%) and unconventional (6.2%) wells.[18]

Most of the reported leaks are production annulus fugitive flows, occurring in 3.2% of conventional wells and 17.7% of unconventional wells. Over the 5 year record, 171 conventional wells (0.3%) and 246 unconventional wells (2.7%) report fugitive flow from the intermediate and/or freshwater annuli (Table 1). Surface wellhead emissions are rare in both conventional and unconventional wells (<0.05% of wells, Table 1).

Flows from engineered production vents are not included in fugitive leakage counts but are an important emission source. As such, we provide a brief accounting of these flows to provide background in understanding emission trends. In total, 1872 wells report flow from engineered vents on the production annulus, 3.3% of conventional wells and 1.5% of unconventional wells. On average, nonzero vent flow is reported on 690 conventional wells per year, with annual well count ranging from 319 to 1097. Temporal trends in unconventional wells are similarly variable and range from fewer than 10 wells in 2014–2016 to 102 wells in 2017 before dropping to 40 wells in 2018. On average, 132 unconventional wells per year report nonzero flow from engineered vents on the production annulus.

Table 1. Number of Conventional and Unconventional Wells with Fugitive Flows Reported by Leak Location[a]

leak location	conventional		unconventional	
wellhead	19	(<0.05%)	1	(<0.05%)
production annulus	1690	(3.2%)	1605	(17.7%)
intermediate annulus	72	(0.1%)	222	(2.4%)
freshwater annulus	99	(0.2%)	24	(0.3%)

[a]Counts do not include engineered production annulus vent flow or pressure readings from sealed annuli.

3.1. Estimated Methane Emissions from Oil and Gas Wellbores and Temporal Trends. Figure 2 summarizes methane emissions from engineered vents and fugitive flows by reporting year and well type. Average daily flow from all well types is 110.4 thousand m^3 or 22.1 Gg CH_4 (+16.9, −19.5) annually. All well types experienced a dramatic decline in emissions between 2015 and 2016. Reasons for these declines in conventional gas and coalbed methane wells are discussed in Section 3.4.

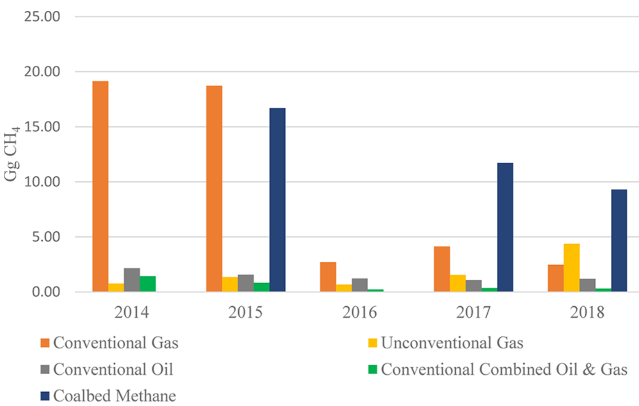

Figure 2. Average annual methane emissions by year and well type.

Conventional gas wells are the largest contributor to average total flow among all well types (45%; 50,000 m^3/day) due to high volumes from engineered production vents and high well counts. Annual emissions range from 2.62 to 20.29 Gg CH_4 with a 5 year average of 10 Gg CH_4. Emissions from conventional gas wells dropped precipitously between 2015 and 2016, while inspected well counts remained steady, averaging 25,770 annually (median = 26,604).

Despite being only 1% of the inspected well population, coalbed methane wells are responsible for a third (40 thousand m^3/year) of the total average flow volume, equivalent to 8 Gg CH_4 (0.02 to 17.69) annually. Flow volumes and emissions dropped to zero between 2015 and 2016 and coincide with a marked decrease in the number of coalbed methane wells

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reported in 2016. In 2014, 2015, 2017, and 2018, an average of 377 (median = 372) coalbed methane wells was inspected; in 2016, just 172 coalbed methane wells were inspected. None of the 2016 inspected wells reported positive engineered vent flows.

Unconventional gas wells contribute only 8% of total average flow (9.2 thousand m^3/day), or 1.85 Gg CH_4 annually. Annual emissions range from 0.7 to 4.64 Gg/year with a 60% decline in emissions between 2015 and 2016. The significant increase in emissions in 2018 is due to a small number of superemitter wells coming into the Program (see Table S11). This is the only type of well that is substantially increasing in number in Pennsylvania. Tens of thousands of additional wells of this type are projected in the next few decades.[19,20] If these forecasts come true, the growth in unconventional wells could have dramatic effects on GHG emissions within the Program.

Oil and combined oil and gas well types are relatively small contributors to total leakage, making up less than 7% of flow volumes over the 5 years of inspected records. Annual CH_4 emissions from these wells average 1.4 and 0.6 Gg CH_4, respectively. Both well types show generally decreasing emissions over the 5 year record.

3.2. Relative Contribution to Emission Inventories. The Pennsylvania oil and gas well inventory reports 132,412 active and abandoned but not plugged wells.[21] Applying the average well emissions reported to the Program and the EPA's default gas composition yields an emission rate of 55.6 Gg CH_4 annually (Table 2). These emissions are in addition to routine site emissions from unconventional well sites (62.3 Gg CH_4) reported to the PADEP Air Quality Bureau in 2018.[22]

Table 2. Extrapolated Statewide Fugitive and Engineered Vent Emissions for April 2019 Well Inventory

well type		avg. flow (m^3/year)	PADEP 2019 well inventory count	Gg CH_4/year
conventional	gas	828.8	62,834	28.5
unconventional	gas	588.0	11,514	3.7
conventional	oil	366.3	48,229	9.7
unconventional	oil	0.00	1	0.0
conventional	comb. O&G	540.0	9070	2.7
unconventional	comb. O&G	638.3	79	0.03
coalbed methane		29,137.4	685	10.9
			132,412	55.6

Combined with our estimate of fugitive and engineered vent flows from unconventional wells (3.74 Gg/year), the AQB estimate yields total site-level emissions of 66 Gg/year for this subset of wells of which fugitive and engineered vent flows make up 6%. Site-level measurements indicate that actual emissions from active unconventional sites are more than 6 times larger than this estimate (452 Gg/year).[2] This measurement would reduce the contribution of emissions reported to the Program to just 1% of total well site emissions. However, the large discrepancy between operator reported emissions and site-level measurements is likely to encompass flow measurements from the Program as well as routine emissions from production equipment (see Section 3.4). Complete and consistent reporting by well operators may reduce the gap in traditional, component-based, and top-down site-level inventories.

Conventional well types are not required to report emissions and are omitted from the AQB inventory.[23] Omara et al. estimate 350.4 Gg CH_4 annually from active conventional sites.[2] Our estimate of 51.82 Gg/year accounts for roughly 15% of these emissions. In total, our estimate of well emissions (55.6 Gg CH_4/year) is 7.3% of total active site emissions reported by Omara et al.[2] As with unconventional wells, several studies have reported field-level emissions 5 times that of component-based emission estimates, indicating, again, that estimates based on Program reporting may be too low.[2,5]

Our calculations do not include plugged wells. Kang et al.[1] estimated total site emissions of 28 Gg CH_4 from abandoned plugged wells based on a sampling of direct measurements and a revised estimate of abandoned plugged well counts across Pennsylvania. Combining these two estimates yields a total of 83.6 Gg CH_4 annually from all wells, operating and abandoned, in Pennsylvania.

It is important to note that active well emissions and their impact on total oil and gas production sector emissions, as calculated from Program data, are underestimated. The large number of noninformative inspections, noninspections, and wells that did not file reports (see Section 3.4) could omit an unknowable range of emissions. Moreover, the dominance of relatively few superemitters in the existing Program data could impact averaging over populations of each well type. Gas emissions from wells under the Program, as with other emission sources in the oil and gas sector, are dominated by relatively few superemitters.[24−26] For all well types other than coalbed methane wells, fewer than 10% of the wells produced at least 50% of reported emissions. Sensitivity varies across well types, with unconventional gas and conventional oil wells, showing the greatest impact from superemitters. For these well types, just 2.5% of inspected wells are responsible for 67.3 and 62% of emissions, respectively. Unconventional combined oil and gas and coalbed methane well types are less impacted, with 25% of wells accounting for 59 and 69%, respectively. Alvarez et al.[4] summarize multiple ground-level measurement and flight studies to compile a national emission inventory for the oil and gas supply chain. The authors of that study found that the federal emission inventory underestimates methane emissions from oil and gas production sites by at least 4 Tg CH_4 annually. The authors attribute this discrepancy to high emissions (superemitters) associated with mechanical upsets and equipment malfunctions not accounted for in component-based emission inventories. Given the distribution of fugitive and engineered vent flow volumes in the Program data, we propose that part of the difference in component-based and site-level inventories is attributed to superemitting wellbore emissions that are not fully accounted for in current inventories.

3.3. Compliance in Reporting. There are various metrics for assessing operator compliance with Program directives. The first of these is how many of the active wells in the state inventory, 132,412 in 2019, have been reporting to the Program (62,483). This is a compliance rate of only 47%. Another metric is the accuracy with which operators abide by Program directives in completing their reports. In a preliminary report on the Program results, the PADEP summarized results from what it called a verification study of the accuracy and completeness of reports concerning directives about which indicator should be used for each possible flow or pressure measurement.[27] For both conventional and unconventional well reports, 75% of a small sample ($N = 95$) of randomly selected reports from 1 year were found to be error free, that is, compliant with Program directives.

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We performed an analysis of 163,030 reports for unconventional gas wells for this metric of compliance. The basis for this analysis was to compare the instructions given to operators for completing their reports to the contents of the reports. This analysis was based on a logic tree for correct indicator use according to Program definitions of the indicators. The complete logic flow is described in the Supporting Information, and only a summary of the analysis is reported here. Table 3 shows that compliance ranged from 62% in 2014 to 71% in 2018, essentially consistent with the results from the PADEP's smaller sample.

Table 3. History of Compliance with Program Directives for Unconventional Wells

year	reports	% with faults
2014	26,418	37.6
2015	30,159	25
2016	32,390	24.4
2017	35,273	28.7
2018	38,790	29

Yet another metric assesses whether all wells were reporting annually as required, at least once for conventional wells and quarterly for unconventional wells. In total, a third of conventional wells and more than half of unconventional wells submitting inspections reported at least once per year across all years since the well was drilled (Table 4).

Table 4. Number of Wells Reporting at Least Once per Year in All Years Since Well Was Drilled[a]

well type	conventional		unconventional	
gas	12,029	(32.1%)	5070	(56.4%)
oil	4610	(40.1%)	1	(100.0%)
comb. oil and gas	720	(19.9%)	41	(45.1%)
coalbed methane	13	(2.1%)		
other	71	(31.7%)		
sum	17,443	(32.7%)	5112	(56.3%)

[a]Values in parentheses indicate the percent of total wells reported in each well category.

3.4. Apparent Anomalies in Reporting. There were apparently anomalous reports in all reporting years and for each type of well. Some examples are described next. Each example discussed below is an example of "missing data" that precludes an accurate assessment of emissions from Pennsylvania's well inventory. These anomalies highlight the lower-bound nature of the total emission estimate given in Table 2 and extrapolations therefrom.

Some operators report an improbably low or high rate of leaking wells across their holdings. For example, in 2014 and 2015, operator Onexxx reported on 102 conventional gas wells and measured production annulus flow from 94 of these wells, a leaking well frequency of about 92%. In contrast, in 2015, operator Range reported on 3493 conventional gas wells and reported making measurements on production annulus flow on 3481 of those wells, finding that only two wells were emitting gas. In 2014, operator Seneca reported on 2209 conventional gas wells and reported making measurements on production annulus flow on 2121 of those wells, finding that no wells were emitting gas. The average conventional well leakage rate in 2014–2018 for all operators was 3.4%, with a 95% confidence interval of (3.24%, 3.56%). This confidence interval does not include the emitting gas reporting rate of both operators. More missing data: an operator of a large number of wells, Atlas, reported NRM on a large percentage of its wells, 2409 of 2575, in 2014.

An obvious anomaly is the abrupt decrease in reported emissions across all well types in 2016. Most of the declines can be explained by either high-emitting wells inexplicably being omitted from the database or wells reporting abrupt and substantial decreases in flow. An example of the former is found in the dramatic decrease in emissions from coalbed methane wells between 2015 and 2016. Ninety-nine percent of coalbed methane emissions are reported by a single operator in 2014, 2015, 2017, and 2018; in 2016, none of the wells owned by this operator reported to the Program (see the Supporting Information for detailed discussion; Table S9). Actions by only two operators are an example of the latter reason. In 2014, 300 wells were responsible for 94% of all emissions from conventional gas wells. EXCO operated 218 and Alliance operated 6 of these wells, and these wells were responsible for 81% of all emissions from conventional gas wells. Figure 3 depicts the interactions of these two operators over the following 3 years. This figure shows that Alliance acquired all the EXCO wells among their top 300 emitters by 2016; additional Alliance wells reported zero emissions in 2016 and 2017; the net effect of these actions was to reduce the combined emission rate from these two operators in 2015 by 87% in 2016. None of these EXCO and Alliance wells were plugged during this reporting period.

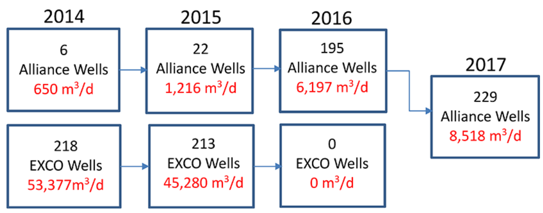

Figure 3. Timeline mapping of actions of two conventional well operators, leading to the marked reduction in reported emissions between 2015 and 2016 shown in Table 2. Each box in this figure shows the number of wells for each operator reported under the Program that were in the list of top-emitting 300 wells in that year and their daily emission rate from all flow sources. Numbers in red are before/after measures of emissions from these actions.

No commentary from these two operators was offered to the public through the Program reporting requirements to explain why many of the highest emitting wells could, within one reporting period and with a change in ownership, cease to emit gases. Figure S2 shows that similar actions of the same operators were responsible for the marked decrease in emissions from conventional combined oil and gas wells. Similar actions by the same two operators were responsible for 15% of the decrease in emissions from unconventional wells between 2015 and 2016. Actions by only two other operators account for an additional 55% of that decrease. In 2015, MDS and Vantage operated 24 of the highest emitting wells of this type. In 2016, they operated only eight such wells with much lower emissions from the same wells, and the interannual emission decrease from these two operators was 0.9 million m^3/year (see Table S11).

Another contributor to the large decrease in reported emissions between 2015 and 2016 is the marked increase in the percentage of wells with an "I" indicator among all operators

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between 2015 (3%) and 2016 (10%). The production annulus on many wells was accessible in 2014 and 2015, but those same wells were curiously inaccessible in 2016 and 2017.

4. DISCUSSION

Self-reported operator data collected through the PADEP's Mechanical Integrity Assessment Program have begun to answer the key questions posed in this paper. However, some serious shortcomings in compliance, accuracy of reporting, failure to respond to Program mandates, and anomalous activities lead to an unknown, but possibly, large underestimate of total emissions from active wells in the state and to unquantifiable uncertainties in their measurement. These problems need to be addressed for the Program to produce an accurate measure of methane emissions. Nevertheless, the emissions as reported from 62,483 wells are significant in Pennsylvania, and they suggest that a similar nationwide assessment of the 3 million[28] operating wells in North America would be significant at the continental scale.

There are recommendations to the PADEP to improve the Program. The PADEP has recently published a strategy for reducing methane emissions from the oil and gas sector.[29] A clearly effective approach for reducing emissions based on results from the Program would be to require the repair or plugging of the relatively small number of superemitting wells, especially coalbed methane wells. Consistency and completeness in reporting of emissions from wells in the Program also need improvement to eliminate the large number of wells (28,246 of 62,483) for which no measurements were recorded either because they were not (NA) or could not (NRM or I) be made and to establish criteria for thresholds and resolution in measurements. It is not feasible to establish confidence limits on the Program data without such improvements. The Program offers the opportunity to operators to comment in writing for each well and for each reporting period. Some operators are diligent in offering comments that would be helpful to the PADEP and the public to understand why a well is emitting. Unfortunately, no comments are offered to the public to assist in understanding why, for example, many wells with the highest leak rates can change ownership and within one reporting period have emissions go to zero and cause strong oscillations in reported total emissions for the entire state.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c00863.

Number of operators reporting on each type of well, summary of well and well indicator counts for conventional gas wells, conventional oil wells, conventional combined oil/gas wells, coalbed methane wells, and unconventional gas wells; operators of 10 conventional gas wells, 10 conventional oil wells, 10 conventional combined oil/gas wells, 10 coalbed methane wells, and 10 unconventional gas wells with the highest total annular flows; summary of reported incidents of consistent flows outside intermediate and freshwater casings; example logic tree to determine operator compliance with Program directives; and timeline mapping of actions of two conventional oil and gas well operators (PDF)

Not inspected well datasheet (XLSX)

Noninformative report datasheet (XLSX)

Inspected well datasheet (XLSX)

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Author Contributions

A.R.I. designed the study. P.A.W performed data analysis. R.S. retrieved data and performed data analysis. M.W. performed statistical analyses.

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Notes

The authors declare no competing financial interest.

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