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# Methane Emissions from Abandoned Oil and Gas Wells in Canada and the United States

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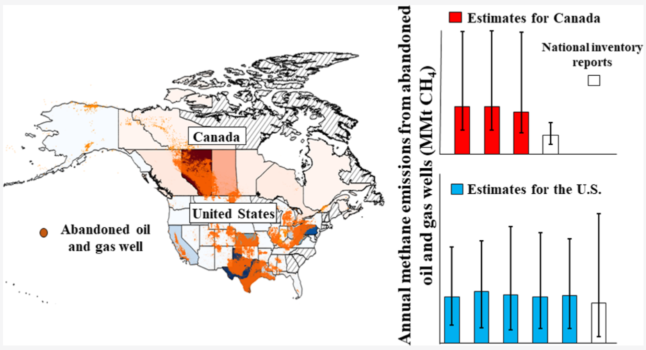


**ABSTRACT:** Abandoned oil and gas wells are one of the most uncertain sources of methane emissions into the atmosphere. To reduce these uncertainties and improve emission estimates, we geospatially and statistically analyze 598 direct methane emission measurements from abandoned oil and gas wells and aggregate well counts from regional databases for the United States (U.S.) and Canada. We estimate the number of abandoned wells to be at least 4,000,000 wells for the U.S. and at least 370,000 for Canada. Methane emission factors range from $1.8 \times 10^{-3}$ g/h to 48 g/h per well depending on the plugging status, well type, and region, with the overall average at 6.0 g/h. We find that annual methane emissions from abandoned wells are underestimated by 150% in Canada and by 20% in the U.S. Even with the inclusion of two to three times more measurement data than used in current inventory estimates, we find that abandoned wells remain the most uncertain methane source in the U.S. and become the most uncertain source in Canada. Understanding methane emissions from abandoned oil and gas wells can provide critical insights into broader environmental impacts of abandoned wells, which are rapidly growing in number around the world.

## ■ INTRODUCTION

In 2019, methane emissions from abandoned oil and gas (AOG) wells were included for the first time in national greenhouse gas (GHG) inventories.[1,2] AOG wells can act as subsurface leakage pathways that connect oil and gas reservoirs to groundwater aquifers and the atmosphere, contributing to water and air quality degradations and climate change.[3] This is particularly true if the AOG well is left unplugged or the integrity of the well and/or plug is compromised. Methane is a potent GHG, with a global warming potential 28−36 times stronger than that of carbon dioxide over a 100 year timeframe and 84−86 times stronger over a 20 year timeframe.[4] Therefore, to curb warming, it is important to quantify and mitigate methane emissions. The U.S. GHG inventory shows that methane emissions from AOG wells represent 0.28 million metric tonnes (MMt) of methane per year and 1−13% of total methane emissions from the oil and natural gas sector.[1] In Canada, the current national inventory estimates that AOG wells represent $1.0 \times 10^{-2}$ MMt of methane emissions in 2018 and less than 1% of total methane emissions from the oil and natural gas sector.[2] Of the top 15 anthropogenic methane emission sources from all sectors, AOG wells are the most uncertain source in the U.S. and the fourth most uncertain in Canada (Table S1). Therefore, a comprehensive analysis of available data and estimation approaches are needed to improve estimates for this new source category.

Measurements of methane emission rates at AOG wells are used to determine emission factors, which are multiplied with the number of AOG wells to estimate total emissions. Emission factors for AOG wells for the U.S. and Canada are calculated using the arithmetic mean of available direct methane measurements and are assumed to be representative of the population of wells that the emission factors are applied to. There have been a total of six published studies that have directly measured methane flow rates from AOG wells in the U.S. and Canada.[5−10] Most of these measurements are focused on the eastern U.S., specifically the Appalachian region[5,6,9] with the exceptions of Townsend-Small et al.[7] who measured wells in Utah (U.S.), Colorado (U.S.), and Wyoming (U.S.) and Williams et al.[8] who measured wells in New Brunswick (Canada). Emission factors based on available measurements vary from region to region, averaging as high as 17 g/h in Pennsylvania (from combining measurements of both Kang et al.[6] and Pekney et al.[10]) to as low as $2.4 \times 10^{-3}$ g/h in Utah.[7] In addition, the flow rates vary depending on the attributes of

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the well such as the plugging status and whether the well produced gas and/or oil.[6−13] In general, it appears that plugged wells emit less methane than unplugged wells.[6,7,9,10] However, there are subcategories of plugged wells such as those that are in coal areas and vented by regulation that emit as much as unplugged wells.[6] In terms of the well type, gas wells have been shown to emit more methane than oil or combined oil and gas wells. Overall, it is important to consider regional variations, the plugging status, and the well type in the development of emission factors for AOG wells.

There are many ways in which emission factors can be defined and applied. The latest national inventory reports for Canada and the U.S. estimate methane emissions from AOG wells using emission factors derived from two studies.[6,7] Emission factors for both the U.S. and Canada are grouped according to the plugging status (i.e., unplugged or plugged). In the U.S., emission factors are divided into two regions: the Appalachian region and the rest of the U.S. No spatial division is applied for the Canadian emission factors, which implies that emissions per well are assumed to be similar throughout the country. However, studies such as Watson and Bachu[14] highlight a geographic region as a factor with a major impact on the occurrence of gas migration and/or surface casing vent flow (indicators of well leakage) in wells. Furthermore, oil and gas basins have different properties and current/historical regulatory practices vary among provinces/states/territories.[15] To better estimate emissions and reduce uncertainties, there is a need to understand how the different estimation approaches impact methane emission estimates for AOG wells.

In addition to emission factors, methane emission estimates depend on the well count. Previous studies estimate the number of documented AOG wells in the U.S. at around 3,200,000 for 2018.[1] To the best of our knowledge, there are no published studies that estimate the total number of AOG wells in Canada. In both countries, thousands of wells, especially those drilled prior to the 1950s, are likely to be undocumented.[6,16,17] For example, a study by Kang et al.[6] showed that AOG well counts in Pennsylvania are likely in the range of 470,000 to 750,000, more than ten times higher than the 48,144 recorded by the Pennsylvania Department of Environmental Protection. Similarly, the number of AOG wells in West Virginia is estimated in the range of 60,000 to 760,000 by Riddick et al.,[9] which places the 70,000 reported by the West Virginia Department of Environmental Protection on the low end of this range. Given the large uncertainty in well counts, we consider them in evaluating uncertainties in methane emissions from AOG wells.

In this work, we estimate methane emissions from AOG wells in Canada and the U.S. and evaluate uncertainties considering all available measurement and well count data. We develop five scenarios to attribute emission factors to different regions with corresponding probability density functions to estimate annual emissions and uncertainties using Monte Carlo simulations. For the emission factor development, we include previously unavailable field measurement data from Oklahoma and British Columbia, which partially address the lack of measurements from the southern region of the U.S. and an overall lack of empirical data from Canada. We provide estimates of well counts grouped into the well type and plugging status and explore how AOG well counts have changed over time. Finally, we calculate annual emissions from AOG wells across Canada and the U.S. and discuss how future measurements and data analysis can reduce uncertainties and increase the representativeness of regional methane emission measurements at national scales.

## ■ METHODS

**Methane Flow Rate Measurements and Emission Factors.** We compile and analyze a total of 598 methane flow rate measurements across seven states and two provinces: Ohio,[7] Wyoming,[7] Utah,[7] Colorado,[7] Pennsylvania,[5,6,10] West Virginia,[9] New Brunswick,[8] Oklahoma, and British Columbia. Emission factors are calculated from all six published studies[5−10] and data from 17 unplugged wells that we measured in British Columbia and 53 unplugged wells from Oklahoma. These measurements are grouped according to the plugging status (i.e., unplugged and plugged) and well type (i.e. gas, combined oil and gas, and unknown) and averaged to obtain emission factors. It should be noted that we use the term "well classification" to refer to a combination of the well type and plugging status. We group measurements from oil wells and combined oil and gas (O&G) wells to obtain one emission factor representing both types and hereafter referred them to as O&G wells, as many data sources do not distinguish between these two types. For unknown well types, we develop an emission factor based on all available measurements regardless of the well type. In total, there are 148 measurements from gas wells and 196 from combined oil and gas wells, with the remaining 254 measurements from wells with the unknown well type.

**Number of AOG Wells.** We define AOG wells as wells with no recent production, which follows the definitions used by both the Canadian and U.S. inventories[1,2] that include terms such as suspended, idle, orphaned, plugged, dormant, deserted, inactive, junked, temporarily abandoned, and shut-in.

We use two approaches to determine the number of AOG wells. First, we analyze AOG wells from 47 provincial, territorial, and state repositories. The source of each of these databases are provided in Table S2 of the Supporting Information. Second, we estimate the number of AOG wells from historical documents and national agencies/organizations.[18,19] Using the data from provincial/state/territorial agencies, we categorize AOG wells based on the plugging status and well type depending on the data reported by regional agencies. If no plugging status is reported, we assign the dataset-wide percentage of unplugged and plugged wells based on the total number of unplugged and plugged wells gathered from state/provincial/territorial datasets for that country. If no well type is reported, we use the ratio of currently active well types in 2018 reported by the Canadian Association of Petroleum Producers (CAPP) or the Energy Information Agency (EIA). In Canada, 3% of wells do not report the plugging status and 23% do not report the well type. In the U.S., 23% of wells do not report the plugging status and 7% of wells do not report the well type. Using historical documents and data from the CAPP and EIA, we estimate the total nationwide number of AOG wells based on the number of active wells subtracted from the total number of drilled wells in each country up to 2018,[18,19] similar to the methodology of Brandt et al.[20] for AOG wells. For Canada, we scale the number of AOG wells for each well classification by the total number of AOG wells obtained from the CAPP.[18] For the U.S., we scale the number of AOG wells for each well classification by the total number of AOG wells obtained using data from the EIA and Brandt et al.[20] with the exception of Oklahoma, Pennsylvania, and West Virginia. For Pennsylvania


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**Table 1. Emission Factor Spatial Attribution Scenarios in the U.S. And Canada as Described in the Methods Section.**[a]

| | | U.S. | | | | | |
|---|---|---|---|---|---|---|---|
| | | emission factors (g/h) | | | | | |
| | | unplugged | | | plugged | | |
| scenario | regions | O&G | gas | all unplugged | O&G | gas | all plugged |
| 1 | U.S. | 13 (101) | 23 (60) | 11 (293) | $5.1 \times 10^{-2}$ (80) | 4.8 (84) | 1.6 (276) |
| 2 | Oklahoma | 14 (34) | 22 (19) | 17(53) | $5.1 \times 10^{-2}$ (80) | 4.8 (84) | 1.6 (276) |
| | Pennsylvania | 12 (56) | 48 (19) | 21 (75) | 0.17 (22) | 18 (22) | 9.6 (44) |
| | Utah | 13 (101) | 23 (60) | 11 (293) | $5.1 \times 10^{-2}$[b] (80) | $4.1 \times 10^{-3}$ (51) | $2.4 \times 10^{-3}$ (88) |
| | West Virginia | 13 (101) | 23 (60) | 3.2 (147) | $5.1 \times 10^{-2}$ (80) | 4.8 (84) | 0.10 (112) |
| | Colorado | 13 (101) | 23 (60) | 11 (293) | $5.1 \times 10^{-2}$ (80) | 4.8 (84) | 1.6[b] (276) |
| | Remainder | 13 (101) | 23 (60) | 11 (293) | $5.1 \times 10^{-2}$ (80) | 4.8 (84) | 1.6 (276) |
| 3 | East | 14 (62) | 28 (34) | 9.6 (228) | 0.13 (28) | 18 (22) | 2.8 (162) |
| | West | 13 (39) | 17 (26) | 15 (65) | $5.1 \times 10^{-2}$ (80) | 4.8 (84) | $1.8 \times 10^{-3}$ (114) |
| 4 | North | 12 (56) | 24 (41) | 8.8 (257) | $6.2 \times 10^{-2}$ (59) | 4.8 (84) | 1.6 (276) |
| | South | 14 (34) | 22 (19) | 17 (53) | $5.1 \times 10^{-2}$ (80) | 4.8 (84) | 1.6 (276) |
| 5 | Appalachian | 14 (62) | 28 (34) | 9.6 (228) | 0.13 (28) | 18 (22) | 2.8 (162) |
| | Anadarko | 13 (101) | 22 (19) | 16 (26) | $5.1 \times 10^{-2}$ (80) | 4.8 (84) | 1.6 (276) |
| | Uintah | 13 (101) | 23 (60) | 11 (293) | $5.1 \times 10^{-2}$[b] (80) | $4.1 \times 10^{-3}$ (51) | $2.4 \times 10^{-3}$ (88) |
| | Denver | 13 (101) | 23 (60) | 11 (293) | $5.1 \times 10^{-2}$ (80) | 4.8 (84) | 1.6[b] (276) |
| | Powder River/Denver | 13 (101) | 23 (60) | 11 (293) | $5.1 \times 10^{-2}$[b] (80) | 4.8 (84) | 1.6[b] (276) |
| | Anadarko/Uintah/Denver | 13 (101) | 17 (25) | 12 (38) | $5.1 \times 10^{-2}$[b] (80) | $3.7 \times 10^{-3}$ (57) | $2.0 \times 10^{-3}$ (104) |
| | Remainder | 13 (101) | 23 (60) | 11 (293) | $5.1 \times 10^{-2}$ (80) | 4.8 (84) | 1.6 (276) |
| | | Canada | | | | | |
| scenario | regions | O&G | gas | all unplugged | O&G | gas | all plugged |
| 1 | Canada | 12 (113) | 22 (65) | 10 (310) | $4.6 \times 10^{-2}$ (92) | 4.8 (84) | 1.5 (288) |
| 2 | British Columbia | 12 (113) | 22 (65) | 0.15 (17) | $4.6 \times 10^{-2}$ (92) | 4.8 (84) | 1.5 (288) |
| | Remainder | 12 (113) | 22 (65) | 10 (310) | $4.6 \times 10^{-2}$ (92) | 4.8 (84) | 1.5 (288) |
| 3 | East | 14 (62) | 28 (34) | 9.6 (228) | 0.12 (40) | 18 (22) | 2.5 (174) |
| | West | 14 (51) | 15 (31) | 12 (82) | $5.1 \times 10^{-2}$ (80) | 4.8 (84) | $1.8 \times 10^{-3}$ (114) |

[a]The number of measurements used to calculate each emission factor is shown in parenthesis. "Remainder" refers to the states/provinces not specifically identified in the scenario. Maps of spatial attribution scenarios are provided in Figure S4 in the Supporting Information. [b]Emission factor based on the total dataset average based on the reasoning outlined in the Supporting Information—treatment of zeroes.

and West Virginia, we use the midpoint well counts of Kang et al.[6,17] and Riddick et al.,[9] which are 610,000 for Pennsylvania and 410,000 for West Virginia. For Oklahoma, we use a count of 280,000, which is the midpoint between the state database total (140,283) and a well count from the Independent Petroleum Association of America (422,826).[21] Total AOG well counts for each province and state are provided in Table S2 of the Supporting Information.

**Emission Factor Attribution Scenarios.** We develop five different scenarios to assign emission factors for AOG wells to regions in the U.S. and Canada (Table 1 and Supporting Information—Figure S4). In the first scenario (1), we develop six nationwide emission factors for each country corresponding to the two plugging statuses and three well types. For the second scenario (2), we apply 17 emission factors provided in region-specific studies for four states and one province and apply nationwide emission factors to remaining regions. In the third scenario (3), we divide the U.S. and Canada broadly into the eastern and western regions, resulting in 24 emission factors. The western U.S. is determined to be all states west of the Texas−Louisiana and Minnesota−North Dakota state boundaries, while western Canada represents provinces/territories to the west of the Saskatchewan−Manitoba and Northwest Territories and Nunavut boundaries. These divisions are chosen to evenly distribute measurement data. In the fourth scenario (4), we divide the U.S. into northern and southern regions by the state boundary closest to the 35° latitude, which reflects the distributions of measurement data. In the fifth and final scenario (5), we use 15 emission factors to regions based on oil and gas basins (see the Supporting Information—Figure S4). The basin-specific emission factors can capture impacts of geological factors, operators, policies, and the history of oil and gas development. Because of the lack of empirical data from Canada, we use all available measurement data from the U.S. and Canada to develop emission factors for the first three scenarios for Canada. We do not make estimates for Canada using the fourth and fifth scenarios. We use the five different attribution scenarios to show how different approaches can affect annual emission estimates rather than identify a single scenario as the most representative or "best" estimate. As new data are gathered, the representativeness of emission estimates for AOG wells will improve and other emission factor attribution scenarios may be appropriate.

Following the emission factor attribution scenarios, we determine emission factors based on measurement data for each state/province (Table 1). In cases where data from multiple studies are used to calculate emission factors, we use $EF_{X,a} = \frac{\sum_{i=1} M_{X,i} \times N_{X,i}}{\sum_{i=1} N_{X,i}}$, where $EF_{X,a}$ is the emission factor for well classification $X$ and area $a$, $M_{X,i}$ is the mean methane flow rate from study $i$ and well classification $X$, $N_{X,i}$ is the number of measurements for the well classification $X$ from study $i$, and $i$ represents a study associated with region $a$.



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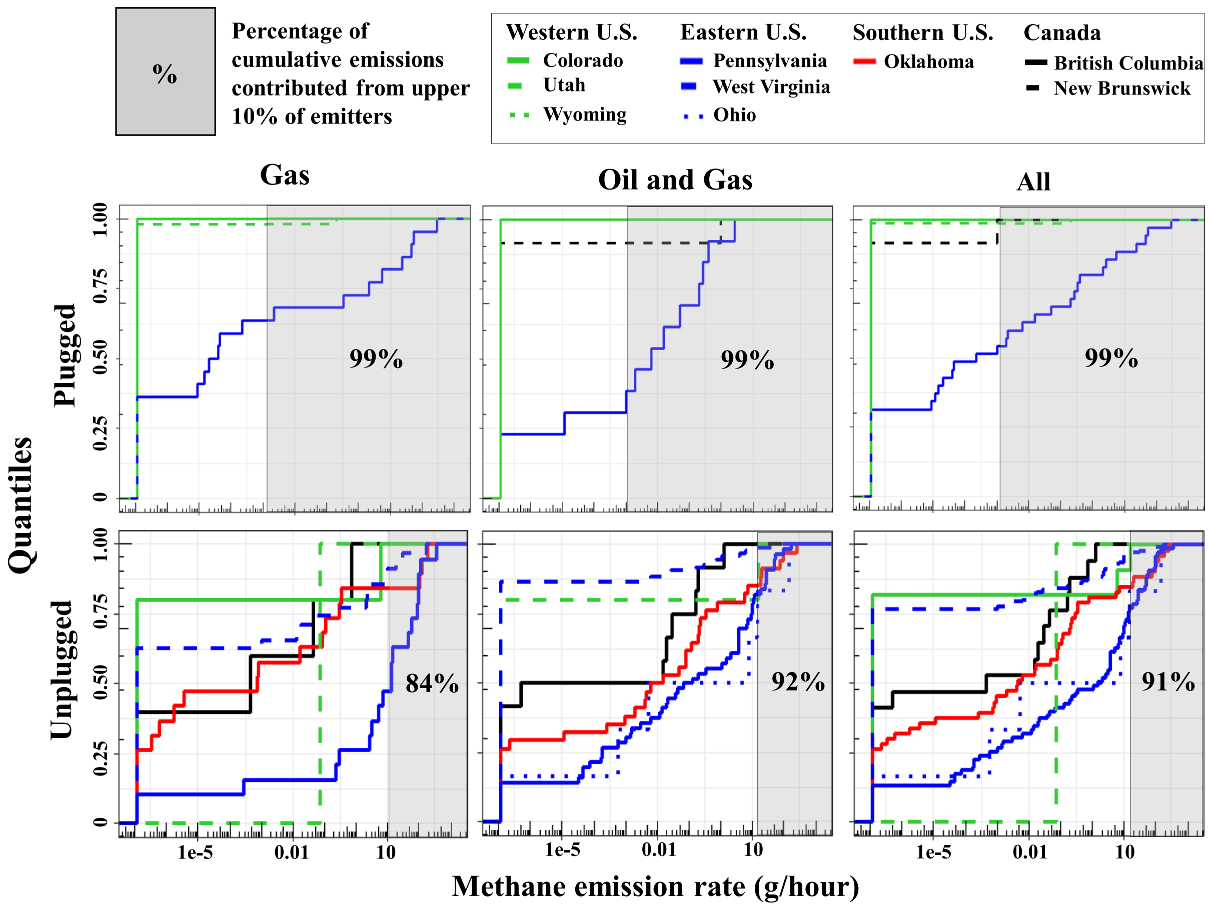


**Figure 1.** Empirical cumulative distributions of measured methane flow rate from unplugged (top) and plugged (bottom) AOG wells in the U.S. and Canada. Each curve represents a state/province. Blue and green curves represent eastern and western states in the U.S., respectively. Red curves represent Oklahoma, which is in the southern U.S. Black curves represent Canadian provinces. Shaded regions in each plot represent the 90−100th percentile of methane emission rates for that group, with the annotation showing the percentage of cumulative emissions, the top 10% of AOG wells.

**Uncertainty Analysis.** We evaluate uncertainties in annual methane emissions from AOG wells using Monte Carlo simulations of the emission factors and well counts following approach 2 of the IPCC guidelines.[22] First, methane emissions are aggregated for a region and well classification following the emission factor attribution scenarios. We use bootstrapping with 2000 iterations with replacement to resample our methane flow rate data to obtain a distribution of emission factors. The bootstrapped distribution of emission factors is fitted to a probability density function using the "fitdistrplus" package in R[23] to obtain parameters to be used in the Monte Carlo simulations. We assume an asymmetrical triangle distribution for well counts ranging from the state/provincial/territorial database well number to an upper range determined either from a secondary source (e.g., research articles, Independent Petroleum Association of America[21]) or a default of +100% (see the Supporting Information—uncertainties in the number of AOG wells). Using these distributions, we obtain a set of 1,000,000 estimates of annual methane emissions. We determine the lower and upper limit in methane emission estimates from the 2.5th and 97.5th percentile values of the simulated annual methane emissions. These steps are repeated for each emission factor attribution scenario.

## RESULTS

**Methane Flow Rates and Emission Factors.** Available measurements of methane flow rates are from seven states and two provinces and cover the two plugging types (unplugged and plugged) and three well types (O&G, gas-only, and unknown) that we use in our analysis. In terms of regions, most measurements are from West Virginia ($n$ = 259) and Pennsylvania ($n$ = 119), with the smallest number of measurements being from Ohio ($n$ = 12), New Brunswick ($n$ = 12), and Wyoming ($n$ = 12). There are 288 measurements from plugged wells, with 85 of those measurements being from plugged gas wells, 92 from O&G wells, and 112 from an unknown well type. A total of 310 unplugged wells have been measured, of which 65 are unplugged gas wells, 113 are O&G wells, and 132 are from an unknown well type.

Empirical cumulative distributions from all well types and statuses exhibit heavy-tailed distributions (Figure 1). For plugged wells, we find that 99% of emissions are attributed to 10% of plugged wells. Unplugged wells show slightly lower percentages, with unplugged gas wells having 84% of cumulative methane emissions attributed to 10% of wells. Overall, the top 10% of AOG wells are responsible for 96% of cumulative methane emissions.

Based on our synthesis of all available methane emission data from AOG wells, average methane flow rates range from


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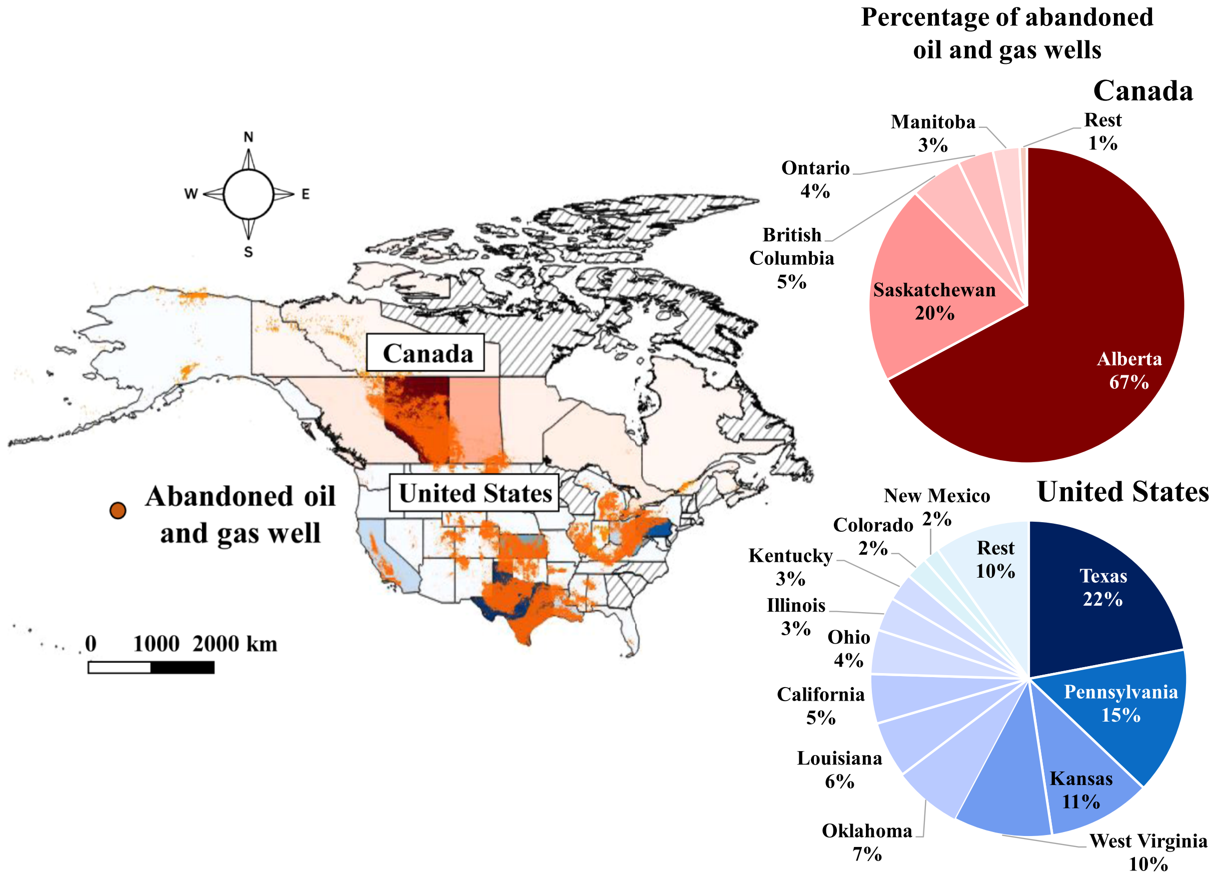


**Figure 2.** Map of all active and AOG onshore well locations (left) gathered from publicly available databases for the U.S. and Canada. Pie charts (right) show percentages of AOG wells in each state/province/territory relative to those across the country. States/provinces/territories in the map and the pie charts are presented using the same color scheme.

$1.8 \times 10^{-3}$ g/h to 48 g/h based on the plugging status, well type, and region (Table 1). In terms of the plugging status, unplugged gas wells are the highest methane emitters overall, averaging 11 g/h, compared to 1.6 g/h from plugged wells. In terms of the well type, abandoned gas wells emit on average 12 g/h methane, which is almost double the emissions from abandoned O&G wells at 6.6 g/h. In addition to dependence on well classifications, emission factors also vary regionally. Notably, unplugged O&G wells in Ohio (i.e., 34 g/h) emit more methane than unplugged O&G wells in Oklahoma (i.e., 14 g/h), Pennsylvania (i.e., 12 g/h), Colorado (i.e., 3.2 g/h), and British Columbia (i.e., 0.14 g/h) (Table 1). Plugged gas wells also show regional variability, with plugged gas wells in Pennsylvania averaging 18 g/h compared to $4.1 \times 10^{-3}$ g/h in Utah.

**Number of AOG Wells.** We estimate the total number of AOG wells to be 4,047,809 for the U.S. based on our compilation of state/provincial/territorial databases, research articles, and national repositories of drilled and active wells. In the U.S., compiling regional databases alone gives a total of 2,485,445 AOG wells, leaving 1,562,364 AOG wells undocumented by the relevant state agencies. For Canada, a compilation of regional databases gives a total of 312,445 AOG wells. Based on the difference in cumulative drilled wells and active wells provided by the CAPP,[18] we estimate 372,925 AOG wells in Canada, meaning at least 60,483 wells are not included in databases of provincial/territorial agencies. The figure 372,925 is likely an underestimation of the total number of AOG wells in Canada because the total number of drilled wells provided by CAPP is limited to those drilled from 1955 onward and there are historical documents confirming that oil and gas activity in Canada began in the 1850s.[24,25]

Most wells in the U.S. are unplugged wells with an unknown type (1,044,976 wells). This is followed by 836,850 plugged O&G wells, 693,921 unplugged O&G wells, 558,019 unplugged gas wells, 488,751 plugged wells of unknown type, and 425,291 plugged gas wells. In Canada, the well classification with the largest number of wells is plugged wells with an unknown type at 74,113 wells, followed by 65,316 unplugged O&G wells, 63,377 unplugged wells with an unknown type, 61,773 unplugged gas wells, 55,067 plugged O&G wells, and 53,279 plugged gas wells. Although we assign 37% of AOG wells in Canada and the U.S. to the unknown well type, they are still assigned an emission factor based on the reported plugging statuses of all AOG wells, which is the current approach used in the Canadian and U.S. inventories. A total of 37% of wells are assigned an unknown well type.

States with the highest AOG well counts in the U.S. are Texas, Pennsylvania, Kansas, West Virginia, and Oklahoma, which collectively account for 65% of the total AOG well count in the U.S. In Canada, Alberta and Saskatchewan contain 87% of AOG wells in the nation, with the majority of the remaining wells located in British Columbia, Ontario, and Manitoba. Of these ten states/provinces across Canada and the U.S., there are direct methane flow rate measurements for only three states (Pennsylvania, West Virginia, and Oklahoma) and one province (British Columbia). These measurements collectively


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represent less than 0.01% of all AOG wells in Canada and the U.S. (Figure 2).

The number of AOG wells is increasing in Canada and the U.S. (Figure 3). In Canada, the largest year-to-year increase in AOG wells since 1956 was in 2015 with an increase of 27,000 wells, whereas the smallest was in 2012 with 100 wells. A linear regression shows an average of 5800 wells abandoned per year from 1956 to 2012. In Canada, both the variability and annual growth rate of wells have increased since the mid 1950's, averaging 3200 wells abandoned per year from 1956 to 1986 and 8800 wells abandoned per year from 1987 to 2017. In the U.S. from 2000 to 2013, an average of 18,600 wells were abandoned per year, with a maximum of 35,500 in 2008 and a minimum of −4000 in 2009. The negative numbers of AOG wells drilled per year, represent a decrease in total AOG well numbers, and is likely a result of idle/inactive wells being re-entered into the production life cycle. Overall, the growing number of AOG wells implies that methane emissions from AOG wells are likely to be increasing.

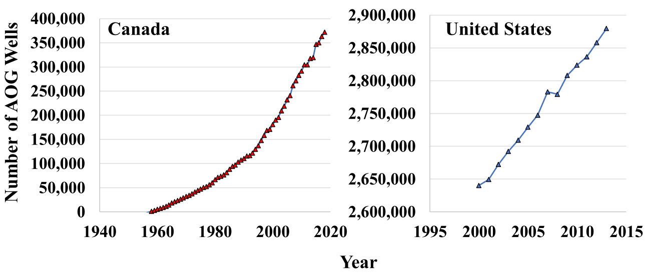


**Figure 3.** Annual growth rates of AOG well counts in Canada from 1956 to 2017 and the U.S. from 2000 to 2013. The count of AOG wells calculated from the difference between active and cumulative drilled wells for that year.

**National Methane Emission Estimates.** We estimate annual methane emissions from AOG wells across the U.S. to be 0.32 (1—Total) to 0.36 (3—east/west) MMt of $CH_4$ emitted annually (Figure 4). All five scenarios show higher methane emissions than the U.S. EPA's estimate for 2018 of 0.28 MMt of methane per year. The states with the most methane emitted annually, on average, are Pennsylvania (0.088 MMt of methane), Texas (0.086 MMt of methane), West Virginia (0.051 MMt of methane), and Kansas (0.027 MMt of methane). Breakdowns of emissions by the well type and plugging status for all five scenarios are shown in Figure S5 of the Supporting Information.

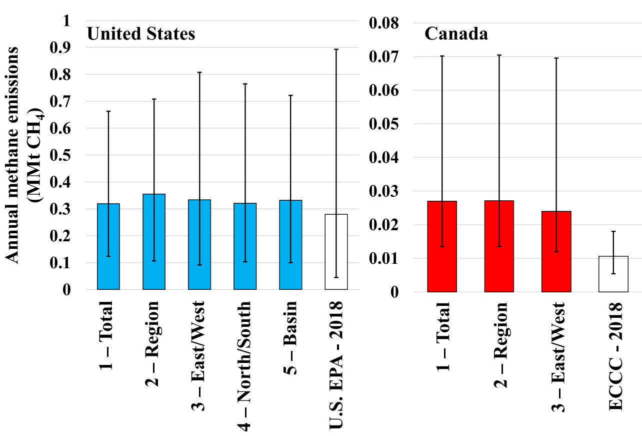


**Figure 4.** Bar plot of annual methane emissions (expressed in million metric tonnes of methane) from AOG wells from the U.S. (blue bars), Canada (red bars), and the most recent national inventory estimates (white bars). The 95% uncertainties are shown in black lines.

Annual methane emissions from AOG wells in Canada average at 0.026 MMt of $CH_4$ (Figure 4) and range between 0.027 MMt of $CH_4$ (1—total, 2—region) and 0.024 MMt of methane (3—east/west). All three scenarios indicate that emissions are nearly three times the $10 \times 10^{-2}$ MMt of $CH_4$ estimated by Environment and Climate Change Canada for 2018.[2] The primary region contributing to methane emissions from AOG wells is Alberta (0.022 MMt of methane), followed by Saskatchewan ($4.7 \times 10^{-3}$ MMt of methane) and British Columbia ($1.8 \times 10^{-3}$ MMt of methane) (see the Supporting Information Figure S6).

The results of our uncertainty analysis show upper uncertainty bounds ranging from +100 to +140% and lower bounds of −60 to −70% for the U.S. We find that the upper uncertainty bounds are roughly half of the +218% reported by the U.S. EPA.[1] For Canada, the upper uncertainty bounds of +160 to +190% are higher than the +69.9% reported by ECCC,[2] with lower uncertainty bounds of −50% on average, which are similar to the −47% reported by ECCC.[2] However, these ranges do not account for uncertainties arising from differences between emission factor attribution scenarios, meaning that uncertainties are likely to be higher than those reported. In short, compared to previous national inventories, we find that uncertainties in methane emissions from AOG wells are higher in Canada and lower in the U.S.

## DISCUSSION

Our estimates for annual methane emissions from AOG wells are consistently higher than those reported in the latest inventory report by 150%[2] for Canada and by 20% for the U.S.[1] The reasons for the larger degree of underestimation in the Canadian inventory are due to our use of a larger number of wells and higher emission factors. In contrast, the difference in the U.S. inventory is primarily due to our use of a larger number of wells. Nevertheless, emissions factors for the "entire U.S." relied on data that were not distributed throughout the country but focused on western states, Wyoming, Utah, and Colorado and missing data from major oil- and gas-producing states such as Texas, Oklahoma, and California.

We find uncertainty ranges for methane emissions from AOG wells to be lower than those of the latest national inventory report for the U.S. but higher than those in the Canadian inventory. Methane emissions from AOG wells remain the most uncertain anthropogenic methane source in the U.S. and increase to the most uncertain anthropogenic methane source in the Canadian national GHG inventory. Methane emissions from AOG wells correspond to 1−4% of methane emissions from the energy sector in the Canadian inventory and 1−13% in the U.S. inventory. Overall, methane emissions from AOG wells are higher than previous estimates and remain one of the most uncertain anthropogenic methane emission sources.

There is an overall lack of measurement data in Canada and the U.S., with less than 0.01% of AOG wells in the U.S. and Canada measured to date. The few available emission measurements are not in the states/provinces where the majority of emissions from AOG wells are found such as Texas and Alberta. Therefore, to reduce the high uncertainties, these regions should be targeted in future measurement studies.


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All available measurements show statistically heavy-tailed distributions, similar to active operations.[13,20] Unplugged gas wells show the least-skewed distribution in methane flow rates with 84% of cumulative emissions attributed to the top 10% of emitters, compared to the remaining well types and plugging statuses which range from 91−99% (Figure 1). Moreover, unplugged gas wells have the highest emission factor among any of the well classifications.

Only 10 high-emitting wells with over 100 g/h have been measured to date, yet they contribute roughly 65% of cumulative emissions (i.e., superemitters) from all studies. Although mitigating a small number of sites can reduce a large percentage of methane emissions, it also means that AOG wells with methane flow rates much higher than those measured to date may exist. Gathering new measurements from regions without prior data may greatly enhance the representativeness of emission factors, help characterize and identify the highest emitters that heavily influence emission factors, and provide information on how these emissions are distributed regionally and across well classifications.

Emission factors are shown to vary regionally and across well classifications for the five scenarios we employ. Unplugged oil wells in West Virginia emit less methane than those in Pennsylvania and Oklahoma, and plugged gas wells in Pennsylvania emit an order of magnitude more methane than those in other regions. This difference can be explained by the fact that plugged wells in coal areas in Pennsylvania are vented, highlighting how regional practices can influence emission factors. In other regions, plugged wells emit much less methane than unplugged wells, which highlights the general effectiveness of plugging procedures in preventing methane migration to the atmosphere. In addition, there are a number of factors that could influence methane emissions from AOG wells that are not investigated in this work. Well-specific factors such as the well age,[14] abandonment date,[14] well bore deviation,[14] well platform (i.e., onshore vs offshore),[26−28] and external factors (e.g., earthquakes)[29] could control methane emissions from AOG wells, meaning that emission factors may need to reflect these relationships.

A large source of uncertainty in current methane emission inventories is the number of wells. Both Kang et al.[6] and Riddick et al.[9] show that regional databases are likely underestimating well counts by a factor of ten for Pennsylvania and West Virginia. If undocumented wells for all states/provinces/territories follow the same trends as observed in Pennsylvania and West Virginia, the uncertainty ranges we employ to well counts may still be underestimating the uncertainty in well numbers. Historical analyses of the many oil- and gas-producing regions could help narrow these ranges in AOG well numbers. Alternative approaches such as helicopters, unmanned aerial vehicles, and ground-based magnetic surveys could also provide reasonable approximations of undocumented well numbers.[10,15,30] Overall, the number of AOG wells remains an uncertain input in the estimation of annual methane emissions.

A 60 year analysis of wells abandoned annually in Canada shows that the growth rate and variability of AOG wells drilled per year have almost tripled from 1956−1986 compared to 1987−2018 (Figure 3). Therefore, it is important to evaluate mitigation strategies such as well plugging, re-entering unplugged wells into the production life cycle or for alternative uses (e.g., geothermal), or reducing the number of new wells drilled. In order to lower methane emissions from AOG wells, it is critical that AOG wells be plugged according to modern standards, that idle/suspended/dormant wells be either plugged or mitigated without remaining unplugged and inactive for extended periods of time, and that undocumented wells are located and characterized.[10,15,31]

Methane emissions from AOG wells are currently the 10th and 11th largest anthropogenic methane emission sources in the U.S. and Canada, respectively. The emissions are highly uncertain and are expected to increase in the future. Therefore, it is important to accurately estimate methane emissions from AOG wells. To do this, efforts are needed to ensure that (a) emission factors represent the wide range of regions and well classifications, (b) well counts are accurate, and (c) both emission factors and well counts are applied in a way that best represents methane emissions from the millions of AOG wells across the U.S., Canada, and elsewhere.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c04265.

Additional text, figures, and tables (PDF)

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### Notes

The authors declare no competing financial interest.

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