Abandoned oil and gas wells in Western Canada: methane measurements and emission estimates

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Contribution of Authors

This thesis contains a paper titled “Methane emissions from abandoned oil and gas wells in Alberta and Saskatchewan, Canada: the role of surface casing vent flows” which can be found Chapter 3. The final version of this paper was published in Environmental Science and Technology in November 2023. I am the first author of this paper and the research, data analysis and writing are my own. The co-authors of the paper are Khalil El Hachem from the Department of Civil Engineering at McGill University and my supervisor Mary Kang from the Department of Civil Engineering at McGill University.

Abstract

Emissions of greenhouse gases such as carbon dioxide, methane and nitrous oxide from human activities contribute to climate change and global mean surface temperature warming. Reductions in near-term climate forcers such as methane, which has a global warming potential 25 times more potent than carbon dioxide on a 100-year time frame, are crucial to limit further global temperature rises in the near term and allow time for long term and large-scale strategies to come into effect. In Canada and the U.S., the oil and gas sector contribute to 41% and 31% respectively of methane emissions annually but has the highest potential for technologically feasible reduction in the short term compared to other sectors such as waste or agriculture. Accurate quantification of methane emissions across all sectors, including oil and gas, are needed to inform national inventories, regulations and reduction strategies that are key to mitigating climate change.

Methane leakage from abandoned oil and gas wells not only contributes to methane emissions from the oil and gas sector, but also poses a risk to groundwater through subsurface leakage caused by well integrity issues. Despite this, the number of methane emission measurements from abandoned oil and gas wells is small compared to the total population across U.S. and Canada. Additionally, many provinces and states with current and previous history of oil and gas development still have no available direct point-source based measurements, including Canada's largest oil and gas producing provinces of Alberta and Saskatchewan. Furthermore, existing measurements do not differentiate between emissions from aboveground well infrastructure leaks and emissions from surface casing vent flows, an indicator of subsurface leakage.

We conducted chamber-based methane emission measurements of 238 abandoned oil and gas wells across Alberta and Saskatchewan, Canada. We separately quantified emissions from surface casing vents and other emissions from the wellhead infrastructure (including near well gas migration) to develop component-specific emission factors. By combining our measurement-based emission factors with publicly available datasets on abandoned oil and gas wells, we estimated Canada-wide

emissions from abandoned wells including the contribution of emissions from surface casing vent flows associated with subsurface leakage. From our measurements we estimated methane emissions from abandoned wells in Canada to be 85-95 kilotonnes of methane per year, of which surface casing vent emissions represent 75-82% (70 kilotonnes of methane per year). Within our sample set we also measured a super high emitter with a methane emission rate of (5.2×10^6 mg CH_4/h), two to three times higher than the largest previously published measurement from an abandoned oil and gas well. By comparing the occurrence of surface casing vent flows within our sample set to two previous studies based on provincial datasets we found that subsurface leaks are three to five higher than previously estimated.

We conclude that subsurface leakage is a major contributor to methane emissions from abandoned oil and gas wells and that additional point-source and component-based measurements are needed to accurately quantify emissions and determine the prevalence of well integrity issues in abandoned and active well populations. Moreover, the impact of well attributes on methane leakage and temporal variability of emissions from abandoned oil and gas wells also need further investigation. Comprehensive studies at oil and gas wells that combine methane emissions measurements with investigations of other environmental impacts such as groundwater contamination are needed to create mitigation strategies that address emissions and broader environmental impacts.

French Abstract

Les émissions de gaz à effet de serre telles que le dioxyde de carbone, le méthane et l'oxyde nitreux provenant des activités humaines contribuent au changement climatique et au réchauffement de la température moyenne de la surface de la planète. La réduction des facteurs de force climatiques à court terme, tels que le méthane, dont le potentiel de réchauffement climatique est 25 fois plus puissant que le dioxyde de carbone sur une période de 100 ans, est cruciale pour limiter la hausse de la température mondiale à court terme et laisser du temps pour le long terme. et des stratégies à grande échelle pour entrer en vigueur. Au Canada et aux États-Unis, le secteur pétrolier et gazier contribue respectivement à 41 % et 31 % des émissions annuelles de méthane, mais il présente le plus grand potentiel de réduction technologiquement réalisable à court terme par rapport à d'autres secteurs tels que les déchets ou l'agriculture. Une quantification précise des émissions de méthane dans tous les secteurs, y compris le pétrole et le gaz, est nécessaire pour éclairer les inventaires nationaux, les réglementations et les stratégies de réduction qui sont essentielles à l'atténuation du changement climatique.

Les fuites de méthane provenant des puits de pétrole et de gaz abandonnés contribuent non seulement aux émissions de méthane du secteur pétrolier et gazier, mais présentent également un risque pour les eaux souterraines en raison des fuites souterraines causées par des problèmes d'intégrité des puits. Malgré cela, le nombre de mesures des émissions de méthane provenant des puits de pétrole et de gaz abandonnés est faible par rapport à la population totale des États-Unis et du Canada. De plus, de nombreuses provinces et États ayant des antécédents actuels et antérieurs d’exploitation pétrolière et gazière ne disposent toujours pas de mesures directes basées sur des sources ponctuelles, y compris les plus grandes provinces productrices de pétrole et de gaz du Canada, l’Alberta et la Saskatchewan. De plus, les mesures existantes ne font pas de différence entre les émissions provenant des fuites d’infrastructures de puits en surface et les émissions provenant des flux d’évents de tubage de surface, un indicateur de fuite souterraine.

Nous avons effectué des mesures des émissions de méthane dans des chambres de 238 puits de pétrole et de gaz abandonnés en Alberta et en Saskatchewan, au Canada. Nous avons quantifié séparément les émissions provenant des évents du tubage de surface et d'autres émissions provenant de l'infrastructure de la tête de puits (y compris la migration des gaz à proximité du puits) afin d'élaborer des facteurs d'émission spécifiques aux composants. En combinant nos facteurs d'émission basés sur des mesures avec des ensembles de données accessibles au public sur les puits de pétrole et de gaz abandonnés, nous avons estimé les émissions à l'échelle du Canada provenant des puits abandonnés, y compris la contribution des émissions provenant des flux d'évents de tubage de surface associés aux fuites souterraines. À partir de nos mesures, nous avons estimé les émissions de méthane des puits abandonnés au Canada entre 85 et 95 kilotonnes de méthane par an, dont les émissions des évents de tubage de surface représentent 75 à 82 % (70 kilotonnes de méthane par an). Au sein de notre ensemble d'échantillons, nous avons également mesuré un émetteur très élevé avec un taux d'émission de méthane de (5,2 x 106 mg CH4/h), deux à trois fois supérieur à la plus grande mesure publiée précédemment provenant d'un puits de pétrole et de gaz abandonné. En comparant l'occurrence des écoulements d'évents de tubage de surface au sein de notre échantillon à deux études antérieures basées sur des ensembles de données provinciales, nous avons constaté que les fuites souterraines sont de trois à cinq plus élevées que ce qui était estimé précédemment.

Nous concluons que les fuites souterraines contribuent largement aux émissions de méthane provenant des puits de pétrole et de gaz abandonnés et que des mesures supplémentaires de sources ponctuelles et basées sur les composants sont nécessaires pour quantifier avec précision les émissions et déterminer la prévalence des problèmes d'intégrité des puits dans les populations de puits abandonnés et actifs. De plus, l'impact des caractéristiques des puits sur les fuites de méthane et la variabilité temporelle des émissions des puits de pétrole et de gaz abandonnés nécessite également des études plus approfondies. Des études approfondies sur les puits de pétrole et de gaz, combinant des mesures d'émissions de méthane avec des enquêtes sur d'autres impacts environnementaux tels que la contamination des eaux souterraines, sont nécessaires pour créer des stratégies d'atténuation qui traitent des émissions et des impacts environnementaux plus larges.

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1. Introduction

1.1. Climate Change and Methane Emissions from the Oil and Gas Sector

According to the Intergovernmental Panel on Climate Change the global mean surface temperature has increased by 1.1°C relative to the years 1850-1900 in 2011-2020 (Arias et al., 2021). Additionally, the increase of greenhouse gases such as carbon dioxide, methane and nitrous oxide in the atmosphere that contribute to climate change is largely the result of human activities. With continued warming at the current rate, the earth will cross the global warming threshold of 1.5°C within the next 10-15 years (Arias et al., 2021). The current and continued increase in global surface temperatures will lead to an increasing severity and frequency of climate extremes such as temperature, precipitation, droughts, and tropical storms. Direct and indirect risks to natural and human systems also increase with increasing surface temperatures which can impact human health, food security, water availability and species loss (Hoegh-Guldberg et al., 2018; Shindell et al., 2020). In order to limit human induced global warming and prevent irreversible impacts, near-term sustained reductions in methane are required in addition to reaching net zero carbon dioxide emissions in the long term (Arias et al., 2021).

Methane is 80-82.5 times more potent at warming than carbon dioxide over a 20-year timeframe and 27.2-29.8 times more potent on a 100-year time frame (Forster et al., 2021) and has contributed to ~30% of global warming since pre-industrial times (Ocko et al., 2021). However, methane's high global warming potential and relatively short lifetime (<20 years) also provide an opportunity for mitigation that can slow the rate of warming in the short term (Ocko et al., 2021). Reducing methane emissions by 40-45% by 2030 could avoid 0.3°C of warming by 2045 allowing time for larger-scale long-term changes to combat climate change to be enacted (UNEP CCAC, 2021).

Globally, waste (20%), agriculture (40%) and the production and transport (including transmission and distribution) of fossil fuels such as oil, gas and coal (35%) are the top three sources of methane emissions from anthropogenic activities. Where 23% of fossil fuel emissions come from the oil and gas sector consisting of production, processing, transmission and distribution of oil and natural gas (UNEP CCAC, 2021). In Canada and the U.S. methane emissions account for 14% and 12% of annual greenhouse gas emissions in CO_2 eq assuming a GWP of 25 (100-year time frame) (*EPA*, 2023; *ECCC*, 2023). Moreover, the oil and gas sector which includes the production, transmission, processing and distribution of oil and natural gas, contributes to 41% and 33% of annual methane emissions in Canada and the U.S., respectively (*EPA*, 2023; *ECCC*, 2023). Although agriculture and waste also contribute substantially to methane emissions the oil and gas sector has the highest potential for methane mitigation in North America in terms of technical feasibility with a majority of mitigation options available at a relatively low cost compared to other sectors (UNEP CCAC, 2021).

Emissions from the oil and gas sector can be separated into two categories: upstream and downstream oil and gas. Upstream oil and gas emissions are the result of oil and gas extraction and field processing including fugitive, stationary combustion, and transmission emissions. Downstream oil and gas emissions are associated with petroleum refinement, natural gas distribution and post-meter emissions (*ECCC*, 2023). In both Canada and the U.S., a majority of methane emissions are attributed to upstream oil and gas activities (*EPA*, 2023; *ECCC*, 2023). The largest reduction potential within the oil and gas sector includes upstream activities of oil and natural gas production and downstream activities associated with natural gas distribution and use (UNEP, CCAC 2021). Moreover, over 75% of required methane emission reduction across the entire oil and gas sector can be achieved by implementing existing technologies such as leak detection and repair, replacing high leak equipment and recovery and utilization of vented gas (UNEP, CCAC 2021; IEA, 2023). Thus, methane reductions within the oil and gas sector are feasible and necessary in the near-term to contribute to climate change mitigation.

1.2. Emission Inventories and Quantification Techniques

Under the obligations of the United Nations Framework Convention on Climate Change, treaty countries including Canada and the U.S. are required to report national annual GHG emissions from anthropogenic activities. The greenhouse gas inventories for Canada and the U.S. are the Canadian National Inventory Report and U.S.

Environmental Protection Agency Greenhouse Gas Inventory. Inventories rely, in part, on emissions measurements and monitoring to develop and maintain accurate emissions accounting.

Quantification and monitoring techniques can be separated into two broad categories of top-down and bottom-up approaches. In top-down approaches atmospheric emissions measurements are performed on a larger scale (global, continental, regional, and entire systems or complex processes) and typically include multiple emission sources. Global, national, regional, sectoral and process or facility emissions can be estimated from these top-down measurements by implementing modeling techniques (NASEM, 2018). Conversely, bottom-up estimates can be used to estimates large scale emissions by summing up emissions from smaller scale individual processes, components, and sources (NASEM, 2018). Emission factors, which are the average emissions per source, process, or facility are used in conjunction with data on activities emitting greenhouse gases to estimate total emissions. Emission factors and other bottom-up approaches are used in inventories to estimate national emissions, however top-down estimates can be compared to bottom-up estimates for verification.

Emissions are quantified using satellite, aircraft, perimeter, mobile, stationary and point source-based (including chamber) methods (NASEM, 2018). Satellites typically use measurements of sunlight absorption in the atmosphere to determine global and regional emissions. Like satellites, aircrafts also use absorption in addition to mass balance analysis using concentrations measured on closed flight paths. On a smaller scale, mobile (vehicle-based) and stationary (towers) use downwind measurements of tracer gases and inverse dispersion modeling to measure emissions from facilities and other sources. Perimeter measurements use the difference between upwind and downwind measurements of sources to determine emission rates (NASEM, 2018). Lastly, point source-based measurements that quantify emissions directly at the source include hi-flow samplers and chamber methods (Williams et al., 2023).

In chamber methodologies emission sources are enclosed within a chamber and the concentration of gases within the chamber are measured over time to determine mass flow rates (Livingston & Hutchinson, 1995; NASEM, 2018, Williams et al., 2023).

In this study, we use the static chamber methodology to measure methane emissions. The concentration increase within the chamber over time is used to determine the methane emission rate using equation (1) (Kang et al., 2014):

$$F = \frac{dc}{dt} V_{eff} \tag{1}$$

where F is the methane mass flow rate, V_{eff} is the effective volume of the chamber and dc/dt is the slope of the fitted line of concentration data over time inside the chamber. Chamber methodologies and other point source-based measurements can provide measurements of low emission rates and provide high resolution estimates (Williams et al., 2023). However, achieving a sample set that is large and representative is crucial to capturing high emitters. Therefore, there may be need to complement the point-source-based data with measurement made at larger scales to identify high emitters and reconcile emission estimates.

1.3. Abandoned Oil and Gas Wells

Within the oil and gas sector, abandoned oil and gas wells have been shown to be a source of environmental pollutants such as methane, hydrogen sulfide, volatile organic compounds, phosphorous and brine (El Hachem & Kang, 2022; Kang et al., 2014; Warrack et al., 2021). Abandoned oil and gas wells are defined as wells with no recent production of oil and gas, injection of fluids or disposal of waste, and are generally separated into two categories: plugged and unplugged (Alberta Energy Regulator, 2022; *EPA*, 2023; *ECCC*, 2023). Plugged wells are wells that have been permanently sealed (plugged) to prevent migration of gas or fluids while unplugged wells have not been permanently sealed. Terminology for unplugged and plugged AOG wells varies depending on jurisdiction. Commonly used terms for plugged wells include: abandoned, deserted, or long term idle. Terms used for unplugged wells include: suspended, inactive, temporarily abandoned, shut-in, dormant or idle (Alberta Energy

Regulator, 2022; *EPA*, 2023). Lastly, orphan wells are unplugged abandoned wells with no legally responsible party (Kang et al., 2021).

Canada and the U.S. have over 3 million abandoned oil and gas wells combined (Williams et al., 2021; Kang et al., 2021) and with transition from fossil fuels towards alternative energies, this number is likely to grow. Yet recent studies have shown that the number of measurements of methane emissions from this source is small (<0.03%) compared to the population of abandoned oil and gas wells (Kang et al., 2023). In Canada, there are only 115 published point source-based measurements of methane emissions from abandoned oil and gas wells despite the presence of over 400,000 abandoned wells in the country (Williams et al., 2019; Williams et al., 2021; El Hachem and Kang, 2022). Moreover, none of these measurements include wells in Alberta and Saskatchewan which contain 87% of the abandoned oil and gas well population in Canada (Williams et al., 2021). Measurements of methane emission rates from abandoned oil and gas wells in provinces with current and previous history of oil and gas development are needed to collect a representative dataset of methane emissions that can be used to inform inventories and emission reduction policy.

Sources of emissions from abandoned well sites include storage tanks, separation units, wellhead infrastructure, and emissions from subsurface wellbore leakage (Brantley et al., 2014). In this work, we focus on near-well emissions which includes emissions from wellhead infrastructure and emissions from subsurface leakage at wells such as surface casing vent flow and gas migration. Subsurface leakage is important as it has the potential to impact groundwater resources in addition to releasing emissions to the atmosphere (Lackey & Rajaram, 2019; Watson & Bachu, 2009; Wisen et al., 2020). The remediation techniques and cost required to mitigate emissions due to subsurface leakage are typically more complex and expensive than emissions from wellhead infrastructure (Raimi et al., 2021). Furthermore, emissions from surface casing vent flow are accounted for separately in Canada's National Inventory Report. Therefore, specific component-based quantification is not only crucial to achieving accurate inventories but also providing actionable data for regulators and oil and gas companies to achieve emissions reductions and protect groundwater.

1.4. Objectives and Organization of Thesis

Abandoned oil and gas wells contribute to methane emissions from the oil and gas sector and direct point-source based measurements are necessary to inform inventories and emission reduction policies. In addition, the occurrence and contribution of emissions from subsurface leakage and groundwater impacts in abandoned well populations are not investigated in existing measurements. To address these issues, we conducted chamber-based measurements of abandoned oil and gas wells across multiple oil and gas producing regions in Alberta and Saskatchewan, Canada. At each site we separately quantified emissions from wellheads (including near well gas migration) defined in this study as “non-surface casing vent” emissions, and surface casing vent flows that indicate subsurface leakage defined as “surface casing vent” emissions. Using this data we develop component specific emission factors, compare subsurface leak frequency to existing databases and discuss implications for emission mitigation and groundwater protection.

The previous sections introduced the relationship between methane emissions from the oil and gas sector and climate change, emission quantification methods, and the topic of abandoned oil and gas wells. Next, in Chapter 2, we present a review of literature and scientific knowledge on methane emissions from the oil and gas sector, abandoned oil and gas wells, and the problem of well integrity - the technical drivers of leakage in wells. In Chapter 3, we present our paper titled “Methane emissions from abandoned oil and gas wells in Alberta and Saskatchewan, Canada: the role of surface casing vent flows” which was published in Environmental Science and Technology in November 2023 (Bowman et al., 2023). In the paper, we analyze field measurements of methane emissions of abandoned oil and gas wells in Alberta and Saskatchewan, including measurements of surface casing vent flows, and discuss implications for well integrity issues in abandoned well populations. Lastly, Chapters 4 and 5 provide a broader discussion of how this research relates to the study of abandoned oil and gas wells and methane mitigation efforts in the oil and gas sector as well as recommended next steps for future research.

2. Literature Review

2.1. Methane Emissions from the Oil and Gas Sector

Multiple studies have been conducted to quantify methane emissions from the oil and gas sector (Table 1). Moreover, recent work has shown that combining top-down and bottom-up measurements from studies is crucial to ensure accurate inventories and aid in the development of regulations, monitoring, and reduction strategies (Alvarez et al., 2018; Brandt et al., 2014; Johnson, Conrad, et al., 2023; Tyner & Johnson, 2021). Therefore, the following subsections provide definitions and an overview of top-down and bottom-up studies covering individual processes that contribute to emissions from the oil and gas sector including: oil and gas production, natural gas gathering, storage and processing, oil refinement and natural gas distribution.

2.1.1. <u>Oil and Gas Production</u>

Oil and gas production includes well drilling and production of oil and gas from production sites with a majority of these emissions attributed to production sites (*ECCC*, 2023). Production sites contain multiple emission sources including pneumatic devices, tanks, vents, flares, and leaking infrastructure such as wellheads and piping (Brantley et al., 2014; Johnson, Tyner, et al., 2023). Point-source based measurements of these sources have used technologies such as high flow samplers, flow meters and gas analyzers to separately quantify emissions from these sources (Riddick et al., 2019). These studies found that measurement-based estimates of methane emissions are higher than what is in government inventories. For example, a study quantifying emission from abandoned and active oil and gas wells in West Virginia found that methane emissions per conventional active well were 7.5 times higher than what was being used for estimates in the U.S. Greenhouse Gas Inventory (Riddick et al., 2019).

Studies of other on-site equipment/processes such as pneumatic devices and tanks have also shown that component-level emissions are underestimated in inventory and reported emissions (Allen et al., 2013, 2015; Johnson et al., 2022; Wang et al., 2022). However, the limited number and geographic scope of point-source based measurements make it challenging to achieve an accurate characterization of emissions across the entire population of oil and gas production sites in Canada and the U.S leading to increased use of top-down approaches.

Studies using mobile, aircraft and satellite surveys to estimate production site and production region emissions in Canada and the U.S. have found that methane emissions are underreported by industry and underestimated in inventories (Atherton et al., 2017; Brantley et al., 2014; Chan et al., 2020; Chen et al., 2022; Johnson et al., 2017; MacKay et al., 2021; Robertson et al., 2020; Shen et al., 2022; Stokes et al., 2022; Zavala-Araiza et al., 2018; Zhang et al., 2020). MacKay et al., (2021) conducted vehicle-based measurements to calculate site level emission factors of oil and gas production sites across Canadian provinces of Alberta, British Columbia, and Saskatchewan. Based on these emission factors, they determined that site level methane emissions in Alberta were 1.5 times higher than what was reported in inventories, and that emission from oil and gas production had high regional variation. In the U.S., a study in Texas of oil and gas production sites with tank batteries using drone and aircraft-based measurements found that methane emissions measured using aircrafts were higher than emissions estimates developed from equipment counts and emission factors (Stokes et al., 2022).

Although certain studies using mobile, aircraft and satellite methods have attributed atmospheric measurements to specific sources on production sites (Lavoie et al., 2022; Roscioli et al., 2018), there is agreement among researchers that follow-up on site and component specific measurements are necessary to characterize individual sources and inform regulations (Festa-Bianchet et al., 2023; Johnson, Conrad, et al., 2023; Johnson, Tyner, et al., 2023; Rutherford et al., 2021; Tyner & Johnson, 2021). For example, Johnson, Tyner, et al. (2023) combined aerial survey data with on-site measurements of detected sources in British Columbia and found that on-site emissions were dominated by incomplete combustion (methane slip) in compressors as well as intentional and unintentional venting from tanks, flares and pneumatic devices. Lower emitting categories of oil and gas production sites like abandoned oil and gas wells may be missed entirely by satellite, aircraft, and mobile measurements due to their high detection limits. For this reason, many studies measuring abandoned oil and gas wells have used point-source measurements as the primary source of data to accurately characterize emissions from this source (see section 2.2).

2.1.2. Natural Gas Gathering, Processing and Transmission.

Gathering, processing, and transmission systems are composed of multiple segments that transport, process, and store natural gas before reaching distribution. Gathering systems include pipeline networks, compressor stations and storage facilities that are used to transport natural gas from production wells to processing facilities. Processing involves removing impurities and separating natural gas into end use products such as Natural Gas Liquids (Mitchell et al., 2015). Like gathering systems, natural gas transmission systems use pipelines, compressors, and storage to transport processed natural gas to end users. As these systems are often complex and large-scale operations, most methane emission measurements of these sources are conducted using perimeter, vehicle, aircraft, and satellite-based measurements (Subramanian et al., 2015). However, discrete sources such as equipment venting within compressor stations and pipeline leaks have been measured using point-source based methodologies (Subramanian et al., 2015; Zimmerle et al., 2017).

Compressor stations have been shown to be an underreported source (Lavoie et al., 2015; Marchese et al., 2015; Mitchell et al., 2015). However, there is also a large range of variability in the magnitude of emissions due to the existence of short-term high emitting events and super emitting facilities (Lavoie et al., 2015; Mehrotra et al., 2017; Mitchell et al., 2015). For example, in Lavoie et al., (2015) methane emission rate measurements of a single compressor station in Texas were three times greater than the highest emitting compressor station in Mitchell et al., (2015), which measured multiple compressor stations across 13 states including Texas. Other emission sources such as gas pipelines showed conflicting results between studies (Li et al., 2020a, 2020b; Yu et al., 2022; Zimmerle et al., 2017). Using point-source measurements Zimmerle et al., (2017) found that emissions from aboveground equipment of gathering pipeline were small compared to other parts of the gathering system (e.g. compressor stations) in the area of study. Conversely, an aerial study on gathering pipelines in the Permian Basin found that measured emissions were significantly higher than those in Zimmerle et al., (2017) and an order of magnitude higher than reported and inventory emissions (Yu et al., 2022).

2.1.3. Oil Refineries

Oil refineries are facilities that transform crude oil into end use petroleum products such as transportation fuels and petrochemicals (*ECCC*, 2023; *EIA*, 2023). Sources of methane emissions from refineries include flaring, uncontrolled venting and equipment leaks (*EPA*, 2023). Similar to natural gas gathering, processing and transmission, most recent methane measurement studies of oil refineries are based on aircraft or satellite approaches with comparisons to bottom-up measurements and industry-reported inventory data (Lavoie et al., 2017; Mehrotra et al., 2017). A study by Lavoie et al., (2017) investigated methane emissions from crude oil refineries and natural gas fired power plants in Utah, Indiana, and Illinois using aircraft-based measurement. The emission rates for the natural gas fired power plants and refineries measured in the study were significantly larger than what was reported by industry to federal reporting programs. Another study in California using aircraft found that refinery emissions were an order of magnitude higher than reported emissions (Mehrotra et al., 2017). To date, there have been no similar top-down investigations of emissions from refineries in Canada. Furthermore, emission estimates in Canada's National Inventory Report currently rely on extrapolating bottom-up emissions data collected over 20 years ago (*ECCC*, 2023).

2.1.4. Natural Gas Distribution

Natural gas distribution systems are responsible for the transportation of natural gas from transmission pipelines to end users. Sources of emissions within the distribution system include the distribution pipeline, metering and regulations stations and customer meters (Lamb et al., 2015). Studies measuring methane emissions from distribution systems have used mobile and point-source based methods.

Studies have shown that leak frequency and methane emissions from natural gas distribution systems vary depending on location. For example, studies with measurements primarily in urban areas with older pipeline infrastructure made of cast iron found that methane leak occurrence in areas with older infrastructure were higher than those with more updated infrastructure (Hendrick et al., 2016; Jackson et al., 2014; Phillips et al., 2013; von Fischer et al., 2017). Additionally, due to the skewed distribution of emission magnitude among pipelines and metering and regulating stations, there is general consensus among studies that identification and mitigation of high emitters using technology and infrastructure improvements is key to reducing emissions (Lamb et al., 2015; von Fischer et al., 2017).

Table 1: Selection of studies on methane emissions from the oil and gas sector in the U.S. and Canada (excluding AOG well studies).

Study	Source(s) Measured	Location(s)	Measurement Method used
Festa-Bianchet et al., (2023)	Oil production (CHOPS*) sites	Saskatchewan	Aircraft and Point Source
Johnson, Tyner et al., (2023)	Oil and natural gas production sites	British Columbia	Aircraft and Point Source
Chen et al., (2022)	Oil and natural gas production region (basin/regional estimation)	New Mexico (Permian Basin)	Aircraft
Johnson et al., (2022)	Natural gas production sites	West Virginia	Point Source

Lavoie et al., (2022)	Oil production (CHOPS) sites	Alberta	Mobile (vehicle-based)
Shen et al., (2022)	Oil and natural gas production basins (basin/regional and national estimation)	Basins across U.S. and Canada	Satellite
Stokes et al., (2022)	Oil and natural gas production sites with tank batteries	Texas	Aircraft and Unmanned Aerial Vehicle (UAV)
Wang et al., (2022)	Oil and natural gas production sites	Basins in U.S.	Point Source, UAV, Aircraft and Satellite
Yu et al., (2022)	Natural gas gathering pipelines	Permian Basin	Aircraft
Tyner & Johnson (2021)	Oil and natural gas production sites	British Columbia	Aircraft and Point Source
MacKay et al., (2021)	Oil and gas production sites	Alberta, British Columbia, Saskatchewan	Mobile (vehicle-based)
Chan et al., (2020)	Oil and natural gas production regions (basin/regional estimates)	Alberta and Saskatchewan	Stationary (tower-based)
Li et al., (2020a)	Natural gas gathering pipelines	Ohio	UAV and Mobile (vehicle-based)
Li et al., (2020b)	Natural gas gathering pipelines	New Mexico	Mobile (vehicle-based)
Roberston et al., (2020)	Oil and natural gas production sites	New Mexico	Mobile (vehicle-based)
Zhang et al., (2020)	Oil and natural gas production (regional/basin estimation)	Permian Basin	Satellite

Riddick et al., (2019)	Oil and natural gas production wells (active and abandoned)	West Virginia	Point Source
Roscioli et al., (2018)	Oil production (CHOPS) sites	Alberta	Mobile (vehicle-based)
Zavala-Araiza et al., (2018)	Oil and natural gas production sites	Alberta	Mobile (vehicle-based)
Atherton et al., (2017)	Natural gas production and processing sites	British Columbia	Mobile (vehicle-based)
Johnson et al., (2017)	Oil and natural gas production regions	Alberta	Aircraft
Lavoie et al., (2017)	Natural gas fired power plants and petroleum refineries	Utah, Indiana, and Illinois	Aircraft
Mehrotra et al., (2017)	Natural gas fired power plant, petroleum refineries, gas storage facilities and gas compressor stations	California	Aircraft
von Fischer et al., (2017)	Natural gas distribution pipeline	Massachusetts (Boston), New York (Staten Island), Syracuse (New York)	Mobile (vehicle-based)
Zimmerle et al., (2017)	Natural gas gathering pipelines	Arkansas	Point Source
Hendrick et al., (2016)	Natural gas distribution pipelines	Massachusetts (Boston)	Point Source
Allan et al., (2015)	Pneumatic controllers on oil and natural gas production sites	Appalachian, Mid Continent, Gulf Cost and Rocky Mountain regions in U.S.	Point Source

Lamb et al., (2015)	Natural gas distribution pipelines and metering and regulation stations	Oregon, California, Nevada, Utah, Colorado, Texas, Minnesota, Indiana, North Carolina, Pennsylvania, New York and Massachusetts	Point-Source
Lavoie et al., (2015)	Compressor stations and natural gas processing facility	Texas	Aircraft
Mitchell et al., (2015) and Marchese et al., (2015)**	Natural gas gathering and processing facilities including gathering pipelines, compressors, dehydration/treatment systems and natural gas processing plants.	Texas, Utah, Wyoming, Pennsylvania, New Mexico, Kansas, Colorado, Oklahoma, Arizona, New York, West Virginia, Alabama, and Louisiana,	Mobile (vehicle-based)
Subramanian et al., (2015)	Natural gas compressor stations at transmission and storage facilities.	South, Mid-Atlantic Northeast, Midwest and Mountain West regions of U.S.	Point Source and Mobile (vehicle-based)
Brantley et al., (2014)	Oil and natural gas production sites	Texas, Colorado, Wyoming	Mobile (vehicle-based)
Jackson et al., (2014)	Natural gas distribution pipeline	Washington D.C.	Mobile (vehicle-based)
Allen et al., (2013)	Natural gas production sites	Appalachian, Mid Continent, Gulf Coast and Rocky Mountain regions in the U.S.	Point Source and Mobile (vehicle-based)

Phillips et al., (2013)	Natural gas distribution pipelines	Massachusetts (Boston)	Mobile (vehicle-based)

*Cold heavy oil production with sand (CHOPS), **same field measurements used

2.2. Abandoned Oil and Gas Wells

Abandoned oil and gas wells have recently been identified as a source of methane emissions and other environmental contaminants and were added as a source category to Canada's National Inventory Report and U.S. Greenhouse Gas Inventory (Kang et al., 2014, 2016). Methane emissions from abandoned oil and gas wells are quantified in inventories using emission factors which are the arithmetic mean of direct point source-based measurements (Williams et al., 2021). The 2023 Canadian National Inventory Report and U.S. Greenhouse Gas Inventory have used field studies conducted across Canada and the U.S. to calculate emissions factors for abandoned oil and gas wells (El Hachem & Kang, 2022; Kang et al., 2016; Townsend-Small et al., 2016; Williams et al., 2021). In addition to studies used in the current inventories, multiple measurement studies have been conducted in Canada and the U.S. to estimate emissions from abandoned oil and gas wells using point source-based measurements (Table 2).

In the U.S., studies measuring abandoned oil and gas wells have been conducted across nine historical and current oil and gas producing states including multiple studies in Pennsylvania and Oklahoma. Emission factors for plugged abandoned oil and gas wells in the U.S. range from 0.02 kg/y/well to 131.4 kg/y/well, with the highest emission factor from a study in Pennsylvania largely due to venting requirements of plugged wells in coal areas of the state (Kang et al., 2016). For unplugged wells, emission factors are between 23.7 kg/y/well and 310.1 kg/y/well. Lastly, the highest single measurement of an abandoned oil and gas well was from an undocumented well in Pennsylvania (Etiope et al., 2013).

In Canada, point source-based studies have only been conducted in three provinces (El Hachem & Kang, 2022; Williams et al., 2019, 2021). Emission factors developed from these studies are within the range of emission factors found from studies in the U.S. with the exception of soil emissions measurements of abandoned oil and gas wells in New Brunswick, which showed significantly lower emissions (Williams et al., 2019). However, it is important to note that many provinces with abandoned oil and gas wells still have no published point source-based measurements, including Canada's largest oil and gas producing provinces of Alberta and Saskatchewan. Although a study by Vogt et al., (2022) did conduct vehicle-based measurements of active and inactive well sites in Saskatchewan, these measurements did not differentiate between possible leaking infrastructure at the site and emissions at the wellhead.

Table 2: Summary of peer-reviewed emission factors from point-source based measurements of AOG wells in Canada and the U.S.

Study	Measurement Location(s)	Methane emission factor for plugged well (kg/y/well)	Methane emission factor for unplugged well (kg/y/well)
El Hachem & Kang, (2022)	Ontario	18.4	88.5
Williams et al., (2021)	British Columbia and Oklahoma	14.0	96.4
Townsend-Small & Hoschouer, (2021)	Texas		54.3
Lebel et al., (2020)	California	2.5	310.1
Saint-Vincent et al., (2020)	Oklahoma	35.0	23.7
Williams et al., (2019)	New Brunswick	0*	1.5*
Riddick et al., (2019)	West Virginia	1.1	27.2
Pekney et al., (2018)	Pennsylvania		255.5

Townsend-Small et al., (2016)	Wyoming, Colorado, Utah and Ohio	0.02	87.8
Kang et al., (2016)	Pennsylvania	131.4?	192.7
Etiope et al., (2013)	Pennsylvania		14,600**

*Soil emissions measurement, **single measurement

Like other sources of emissions in the oil and gas sector, methane emissions from abandoned oil and gas wells follow a heavy tailed distribution where a small proportion of high or super high emitting wells contribute to a majority of emissions (Williams et al., 2021). Certain well attributes have been shown to impact the magnitude of emissions from abandoned oil gas wells such as plugging status, well type (i.e., gas versus oil) and geographic location (Boothroyd et al., 2016; El Hachem & Kang, 2022; Hachem & Kang, 2023; Kang et al., 2016; Lebel et al., 2020; Riddick et al., 2019; Schout et al., 2019; Townsend-Small et al., 2016; Williams et al., 2021). Other factors such as well age and time since abandonment have shown conflicting results across studies (El Hachem & Kang, 2022). Therefore, more measurements across well populations in various geographic locations are required to characterize emissions from this source and help predict high emitting wells. There has also been limited work on the temporal variation of emissions from abandoned oil and gas wells, with only two studies including repeat measurements to date (Kang et al., 2016; Riddick et al., 2020). Lastly, none of these studies have explicitly characterized the contribution of emissions due to well integrity problems which can have implications for groundwater and human health and safety.

2.3. Well Integrity

In addition to atmospheric emissions, oil and gas production operations can also have subsurface impacts (R. B. Jackson et al., 2013; R. E. Jackson et al., 2013; Sherwood et al., 2016; Watson & Bachu, 2009; Wisen et al., 2020). Oil and gas wells intersect multiple subsurface zones, including those with groundwater. Wells are made of multiple concentric layers of steel casings sealed by cement at different depths. In the centre of multiple casings is the production casing and/or tubing where fluids are injected into or pumped out of the target subsurface layer (Lackey et al., 2017, 2021). Well integrity is the ability of the casing and cement system to form and maintain barriers that contain production fluids and protect groundwater (Hachem & Kang, 2023; Ingraffea et al., 2014; Lackey et al., 2021). The loss of well integrity can lead to subsurface leakage and migration of gases and fluids to the atmosphere or into ground and surface water sources (Hachem & Kang, 2023; Ingraffea et al., 2014; Lackey et al., 2021; Lackey & Rajaram, 2019; Wisen et al., 2020).

Pathways for subsurface leakage include the production tubing, annular spaces between casings or along the outside of casing (Watson and Bachu, 2009). Leakage through the annular spaces can result in surface casing vent flow or surface casing pressure at aboveground well infrastructure (Lackey et al., 2017, 2021; Soares et al., 2021; Watson & Bachu, 2009; Wisen et al., 2020). In Canada, the surface casing vent is left open to the atmosphere leading to surface casing vent flow when gas moves through the surface casing due to subsurface leakage. In other jurisdictions such as the U.S., the surface casing vent is left closed leading to a buildup of pressure within the casing when leakage is present, also known as surface casing pressure (Lackey et al., 2021). Gas migration is the result of leakage outside of the casings and can lead to migration of gases in the subsurface and emission of gases to the atmosphere from soils around wells (Abboud et al., 2021; Ingraffea et al., 2014; Soares et al., 2021)

Subsurface leakage resulting from wellbore integrity problems has been shown to occur in both active and abandoned oil and gas well populations in Canada and the U.S. In Canada, studies analyzing provincial databases of industry reported surface casing vent flow have shown that 6.2% of the well population in Alberta and 10.6% of the wells in British Columbia have reported surface casing vent flow (Abboud et al., 2021; Wisen et al., 2020). Another study from Bachu, (2017) analyzed provincial well failure data with a specific focus on gas migration and found that the incidence of gas leakage from gas migration was low (0.73% of wells in the database). They also found that geographic location within the province as well as production type was a strong indicator of the potential for gas migration occurrence. Lastly, Schiffner et al., (2021) reviewed industry reported surface casing vent flow and gas migrations leaks from abandoned oil and gas wells in Alberta and found that the probability of unresolved leaks had increased from 1971 to 2019, along with the amount of methane emitted per leak.

In the U.S., one study analyzing well inspection reports in Pennsylvania from 2000-2012 found that 0.7-9.1% of active wells showed compromised well integrity (Ingraffea et al., 2014). Another study in Pennsylvania which analyzed inspection reports from 2014-2018 found that emissions from integrity failures could be inaccurately reported and were not included in the state inventory at that time (Ingraffea et al., 2020). Lackey et al., (2021) compiled datasets of industry reported well integrity for wells in Colorado, New Mexico, and Pennsylvania. They found that wells in Colorado and New Mexico had surface casing pressure and other casing flow occurrence between 0.3 and 26.5% depending on well orientation (i.e., vertical versus directional wells). The results from the investigation of Pennsylvania data in Lackey et al., (2021) showed that 14.1% of wells with testing reports showed signs of compromised well integrity, which is higher than what was reported in previous studies in the state.

Assessing subsurface leakage in well populations using industry reported state and provincial databases can be highly uncertain due to underreporting and questions of accuracy of reported information (Bachu, 2017; Ingraffea et al., 2020; Lackey et al., 2021). Additionally, there are few studies that have directly measured wellbore leakage occurrence and their explicit emissions among well populations (Chafin, 1994; Erno & Schmitz 1996). These two studies have limited geographic spread, consider a small number of wells and are ~30 years old. Therefore, there is a need for new direct measurements to build a representative sample set of emissions, especially since geographic location has been identified as a common factor impacting well leakage and emissions (Hachem & Kang, 2023).

3. Methane emissions from abandoned oil and gas wells in Alberta and Saskatchewan, Canada: the role of surface casing vent flows

3.1. Abstract

Abandoned oil and gas wells can act as leakage pathways for methane, a potent greenhouse gas, and other fluids to migrate through the subsurface and to the atmosphere. National estimates of methane emissions remain highly uncertain, and available measurements do not provide details on whether the emissions are associated with well integrity failure (indicating subsurface leaks) or above-ground well infrastructure leaks. Therefore, we directly measured methane emission rates from 238 unplugged and plugged abandoned wells across Alberta and Saskatchewan, Canada, separately quantified emissions from surface casing vents and other emissions from the wellhead (non-surface casing vent), and developed emission factors to estimate Canada-wide emissions from abandoned wells. Our highest measured emission rate (5.2×10^6 mg CH_4/hr) from an unplugged gas well was two to three times higher than the largest previously published emission rate from an abandoned well. We estimated methane emissions from abandoned wells in Canada to be 85-93 kilotonnes of methane per year, of which surface casing vent emissions represented 75-82% (70 kilotonnes of methane per year). We found that subsurface leaks, as evidenced by surface casing vent flows, occurred at 32% of abandoned wells in Alberta, substantially higher than previously estimated using provincial data alone (6% and 11%). Therefore, well integrity failures and groundwater contamination are likely to be more common than previous studies suggest.

3.2. Synopsis

Surface casing vent flows represent 75-82% of methane emissions from abandoned wells and subsurface leaks and impacts to groundwater are three to five times more likely than previously thought.

3.3. Introduction

Abandoned oil and gas wells emit methane (Kang et al., 2014; Townsend-Small et al., 2016), a potent greenhouse gas (Masson-Delmotte et al., 2021), and can act as a subsurface leakage pathway. Abandoned oil and gas wells are defined as wells with no recent production of oil and gas, injection of fluids or disposal of waste and can be plugged or unplugged (Alberta Energy Regulator, 2022; EPA, 2023; ECCC, 2023). For both plugged and unplugged wells, there are many subsurface pathways through which methane and other gases can migrate, and measured emission rates can vary by many orders of magnitude (Wisen et al., 2020). In the U.S. Greenhouse Gas Inventory, the upper uncertainty limit in methane emission estimates from abandoned oil and gas wells is 204%, which is substantially higher than the 15% to 127% in upper uncertainty limits of the remaining top 15 methane sources (EPA, 2023). One driver for the high uncertainty is the emission factor, which is governed by high emitters, defined here for abandoned oil and gas wells to be emission rates greater than 10^4 mg/h (Kang et al., 2019). There are many engineering/construction, geological, and policy factors linked to high emitters; and geographical region, which encompasses all factors, has consistently been shown to be an important predictor of high emitters (Hachem & Kang, 2023). However, prior to this study, there have been no published direct measurements of abandoned oil and gas wells in Alberta and Saskatchewan, the provinces with 87% of all abandoned oil and gas wells in Canada (Williams et al., 2021). Therefore, to reduce uncertainties, improve inventory estimates and inform mitigation strategies, additional measurements of methane emission rates from abandoned oil and gas wells in Canada, especially Alberta and Saskatchewan, are needed.

To reduce methane emissions from abandoned oil and gas wells, regulators and industry not only require quantification of emissions, but also component-level identification of emission sources to better inform monitoring, mitigation, and inventories. Methane emission sources at abandoned oil and gas well sites include surface casing vents, wellhead infrastructure, and gas migration. Although mobile measurements of methane emissions from abandoned oil and gas wells have been conducted in Saskatchewan (Vogt et al., 2022), these measurements do not differentiate between emissions from surface casing vents, the rest of the wellhead, and other potentially leaking infrastructure on the well site. This differentiation is important for Canada's National Inventory Report (ECCC, 2023), as methane emissions from surface casing vents are accounted for separately from the rest of the wellhead infrastructure for abandoned oil and gas wells, as with active wells (ECCC, 2023). In the U.S., methane emissions from surface casing vents of abandoned oil and gas wells are not estimated, and the current estimate is based primarily on wells without surface casing vents (EPA, 2023). In addition, mitigation strategies for methane emissions from surface casing vents, an indicator of subsurface leakage, are fundamentally different from mitigation strategies for methane emissions from aboveground wellhead infrastructure, such as piping and fixtures. Therefore, for both the national greenhouse gas inventories (ECCC, 2023; EPA 2023) and for mitigation, there is a need to attribute methane emissions to specific components at the abandoned well site.

Well integrity is the ability of wellbore barriers to contain production fluids within the wellbore and prevent uncontrolled subsurface leakage, groundwater contamination, and/or emissions (Ingraffea et al., 2020; Lackey et al., 2021). Subsurface leakage pathways at oil and gas wells include the production tubing and annular spaces between and outside casings, which can lead to gas in the surface casing and gas migration through soil (Soares et al., 2021; Wisen et al., 2020). In Canada, surface casings are vented, leading to surface casing vent flows in the presence of subsurface leakage; in the U.S., surface casing vents tend to be closed, causing casing pressures to build up in the presence of leakage (Lackey et al., 2021). Gas migration represents outside-of-the-casing leakage into subsurface environments, including groundwater, and can lead to gas emissions at the ground surface from soils surrounding the wells (Abboud et al., 2021; Soares et al., 2021). Gas migration and surface casing vent flows are indicators of wellbore integrity issues and require wellbore treatments such as cement squeezes and casing repair (Hachem & Kang, 2023; Ingraffea et al., 2014; Sanabria et al., 2016; Singh et al., 2019; Yousuf et al., 2021). In contrast, methane emissions from above-ground wellhead infrastructure often are relatively easy fixes, such as tightening of joints and replacement of parts, and are more likely to originate from the producing formation, indicating plugging can reduce the emissions. Overall, the presence of surface casing vent flows and gas migration are indicators of well integrity failures, which increase the potential for methane emissions and groundwater contamination (Ingraffea et al., 2014, 2020; Lackey & Rajaram, 2019; Soares et al., 2021).

Well integrity failures are not necessarily addressed through well plugging and can persist after the well is properly plugged. Plugged wells are wells that have been permanently sealed (plugged) within the wellbore along zones that are required to be protected by regulations (e.g., groundwater, coal seams, oil and gas reservoirs). Plugging does not address all leaks such as those through the annulus and there generally are sections that remain unplugged. Although surface casing vents are no longer present in plugged, cut and buried wells, they may still be present in plugged wells without surface clean-up (i.e., downhole abandoned). Therefore, characterizing methane emissions in terms of surface casing vents and aboveground infrastructure is important for development of actionable methane emission reduction strategies and to understand the broader environmental impacts of abandoned oil and gas wells, particularly with respect to groundwater.

Here, we present measurements of methane flow rates from wells across six regions in Alberta and Saskatchewan, Canada (Figure 1), the two provinces with 87% of abandoned oil and gas wells in the country. We measured and quantified methane flow rates from surface casing vent flows and other emissions at the wellhead including near-well (< 1m) gas migration ("non-surface casing vent" emissions) separately. Using publicly available information from provincial databases, we characterized abandoned oil and gas wells by status and type and determined average emissions per well or emission factor, as well as emission factors specifically for surface casing vent and non-surface casing vent emissions. Finally, we compared our findings to previous studies and current metrics used in the Canadian National Inventory Report and the U.S. Greenhouse Gas Inventory (EPA, 2023; ECCC, 2023). Our results provide previously unavailable direct measurements of methane emissions from abandoned oil and gas wells in Alberta and Saskatchewan, the largest oil-and-gas-producing provinces in Canada. Our component-level approach to analyzing abandoned oil and gas well emissions that goes beyond well-level emissions quantification has widespread implications to policy and industry operations in Canada and internationally.

3.4. Materials and Methods

3.4.1. Well status and type definitions

We determined well information including location, status and type using the publicly available Alberta Energy Regulator ST37 and the Saskatchewan Mining and Petroleum GeoAtlas databases for all wells in the two provinces. Here, we classified wells into two abandoned oil and gas well status categories of “Abandoned (Plugged)” and “Suspended (Unplugged)”. “Suspended (Unplugged)” wells are wells that are non-producing or no longer being used for their designated function and are deemed suspended by provincial regulations. These wells include wells that may have temporary or zonal plugging but are still treated as suspended wells. We define “Abandoned (Plugged)” wells as those that have been permanently plugged and have a license status and inspection requirements that correspond to this certification. We also define four well type categories, which are “Crude Oil”, “Gas”, “Injection Disposal and Storage” and “Other”. We geospatially analyzed all 375,241 wells in the Alberta (305,718 wells in the Alberta Energy Regulator ST37 accessed in May 2022) and Saskatchewan (69,523 wells in the Saskatchewan Mining and Petroleum GeoAtlas accessed in September 2022) databases, including those that we measured, following the abandoned oil and gas well status categories using the methodology outlined in the Supporting Information.

3.4.2. Site selection and field measurements

We selected measurement regions with varying production types (i.e., oil, gas, or enhanced recovery) to try to achieve a representative sample set of well types. In addition, to increase measurement efficiency, we targeted areas within these regions with a relatively high suspended and abandoned well density. We based our final site selection on legal and logistical site access and well site configuration. We measured all sites that could be measured according to site access and configuration and did not consult provincial surface casing vent flow/gas migration databases during site selection to limit potential bias. We quantified methane flow rates at each well site using a two-step process including chamber-based measurements (El Hachem & Kang, 2022; Kang et al., 2014; Williams et al., 2023), which are also described in the Supporting Information.

3.4.3. Emission factors and national emission estimates

In the context of abandoned wells, emission factors are typically the average of measured methane flow rates per well; but in this paper, we also provide two sub-well emission factors to represent surface casing vent emissions and non-surface casing vent emissions. These emission factors are multiplied by activity data (total number of wells or surface casing vents) to calculate total emissions from abandoned wells for emission inventories. We also calculated separate methane emission factors for Alberta and Saskatchewan and for each status and well type. Negative emission rates, which indicate methane oxidation in the soils within the chamber(s) is greater than well emissions (El Hachem & Kang, 2022; Kang et al., 2016; Williams et al., 2021), were included in the calculation of the mean of each category. At wells where both the surface casing vent and non-surface casing vent components were measured, methane emissions from each component were added together to determine the wells' total or combined emissions. For well types (gas, crude oil, injection disposal and storage and other) within a given well status category (abandoned/plugged or suspended/unplugged) with fewer than two measurements, the entire well status category average was used as the default emission factor. See Supporting Information Table's S5-S10 for well counts and confidence intervals associated with each calculated average value.

To determine total emissions from abandoned oil and gas wells in Alberta and Saskatchewan, we multiplied our component-based and combined emissions factors with well counts from our well database compiled from provincial sources (Table S7, S9 and S11). To determine total emissions from provinces and territories other than Alberta and Saskatchewan, we utilized well counts from the National Inventory Report (ECCC, 2023) and combined them with our component-based and combined emission factors for Alberta or Saskatchewan or emission factors from measurements previously done in Ontario (El Hachem & Kang, 2022) (Table S8, S10 and S12). Provinces and territories other than Alberta with listed onshore abandoned oil and gas well populations in the National Inventory Report are British Columbia, Manitoba, Northwest Territories, Yukon, Ontario, Quebec and New Brunswick (ECCC, 2023).

Since there is no known inventory of the number of wells with surface casing vents in Canada, we estimated the proportion of unplugged and plugged wells that had surface casing vents from our fieldwork observations of the infrastructure present at all measured wells. We found that 89% of all unplugged wells and 52% of all plugged wells measured had surface casing vents. See supporting information for more details on uncertainties and methodology used to estimate emissions.

3.5. Results

3.5.1. Combined methane flow rates from both surface casing vent and non-surface casing vent sources

Our combined methane flow rate measurements at 238 abandoned oil and gas wells, ranged from -5.0x10^1 to 5.2x10^6 mg/h and revealed the existence of high (>104 mg/h) and super-high emitters, which we define as well emitting >10^5 mg/h (or >1 t/y). These combined well measurements include methane emissions from both surface casing vent and non-surface casing vent sources. We also found a well with a combined flow rate exceeding the highest measured emission rate from an abandoned well in previously published literature (Figure 2). Our highest measured combined well flow rate was 5.2x10^6 mg/h (4.5x10^4 kg/y) from an unplugged gas well in Alberta, which is two to three times higher than the largest published emission rate of 2x10^6 mg/h for an abandoned well in Pennsylvania (Etiope et al., 2013). In Alberta, we found 14 wells

(11%) to be high emitters. Similarly, in Saskatchewan, we found 11 wells (11%) to be high emitters. We also found that both provinces have “super-high emitters”, with Alberta having eight super high emitters (6%) and Saskatchewan having three (3%). Overall, we found that positive combined methane flow rates varied by nine orders of magnitude from 10^{-3} mg/h to 10^{6} mg/h, broader than previously determined in a single study for methane emissions from abandoned wells (El Hachem & Kang, 2022; Kang et al., 2016; Pekney et al., 2018; Riddick et al., 2019; Townsend-Small et al., 2016; Williams et al., 2021).

Our results showed that gas wells emitted more compared to the well type categories of crude oil, injection disposal and storage and other, with average combined methane flow rates of $1.6x10^{5}$ mg/h for unplugged wells and $1.5x10^{3}$ mg/h plugged wells (Figure 2). Gas wells accounted for five out of the eight measured super high emitters in Alberta. In Saskatchewan, gas wells were on average the highest emitting well type for unplugged wells with an average flow rate of $1.4x10^{4}$ mg/h. The highest measured combined methane flow rate ($1.8x10^{5}$ mg/h) in Saskatchewan was from an unplugged gas well. Among plugged wells in Saskatchewan, an observation well which we categorize as well type “Other” (Table S4) was the highest emitter with a combined methane flow rate of $1.2x10^{2}$ mg/h. We note that due to site access limitations, we did not measure any plugged gas wells in Saskatchewan but did measure other types of plugged wells (crude oil, injection, disposal and storage and other). Confidence intervals and well counts of our measurements can be found in Tables S5-S10 in Supporting Information.

We found that on average, plugged wells emit less methane than unplugged wells. In Alberta, unplugged wells had an average combined flow rate of $8.9x10^{4}$ mg/h which is 95 times higher than plugged wells ($9.4x10^{2}$ mg/h). Similarly, the average combined flow rate of unplugged wells in Saskatchewan was $8.1x10^{3}$ mg/h, which is 225 times higher than plugged wells ($3.6x10^{1}$ mg/h). However, the existence of plugged wells with combined flow rates between 10^{2} and 10^{4} mg/h may indicate insufficient plugging or unresolved wellbore integrity issues at certain wells, as these flow rates exceed those measured at control locations (Figure S2), typically located several meters away from the wellhead.

By comparing our combined emission factors (average emissions per well) with respect to geographic regions, we found large variations in emissions from abandoned oil and gas wells at the provincial and sub-provincial level (Table S15). Grande Prairie, Alberta, had the highest combined emission factor compared to all other regions in Alberta and Saskatchewan at 5.2×10^{3} kg/y/well, which is 12 times larger than the next two highest emitting regions of Medicine Hat, Alberta, (4.2×10^{2} kg/y/well) and Lloydminster, Alberta, (4.2×10^{2} kg/y/well). In Saskatchewan, the region with the highest combined emission factor, on average, of 1.8×10^{2} kg/y/well was Lloydminster. The region with the lowest combined emission factor out of all measured regions in Alberta and Saskatchewan was Estevan, Saskatchewan, at 2.0×10^{0} kg/y/well.

3.5.2. Surface casing vent and non-surface casing vent methane flow rates and occurrences of high surface casing vent flow rates

Methane flow rates from surface casing vents were higher, on average, than non-surface casing vent methane flow rates in Alberta; but methane flow rates from surface casing vents were lower, on average, than non-surface casing vent methane flow rates in Saskatchewan (Figure 3). In Saskatchewan, methane flow rates from surface casing vents ranged from -4.9×10^{0} mg/h to 3.2×10^{2} mg/h and were, on average, 1.28×10^{1} mg/h. In Alberta, methane flow rates from surface casing vents ranged from -1.9×10^{1} mg/h to 5.2×10^{6} mg/h and were, on average, 8.1×10^{4} mg/h. Therefore, the average methane flow rate from surface casing vents in Alberta was three orders of magnitude higher than the average methane flow rate from surface casing vents in Saskatchewan. For non-surface casing vent emissions, the methane flow rate ranges were -2.0×10^{2} mg/h to 9.8×10^{5} mg/h for Alberta and -7.2×10^{1} mg/h to 1.8×10^{5} mg/h for Saskatchewan, and the averages were within one order of magnitude variation at 1.4×10^{4} mg/h for Alberta and 8.1×10^{3} mg/h for Saskatchewan. We also found that wells with high methane flow rates from surface casing vents tend to have low methane flow rates from non-surface casing vent components and wells with high non-surface casing vent methane flow rates tend to have low methane flow rates from surface casing vents in both Alberta and Saskatchewan (Figure S3). See Supporting Information Table S5 for number of measurements and confidence intervals associated with non-surface casing vent and surface casing vent measurements.

We found that the occurrence of leakage over 100 mg/h for non-surface casing vent flow rates is 32% and 25% in Saskatchewan and Alberta, respectively. We defined a threshold of 100 mg/h for our measurements as leakage higher than natural soil emissions, because 100 mg/h was more than two times higher than the average methane flow rate of controls normalized to the area of the surface casing vent chamber (4.0×10^1 mg/h) (Supporting Information). For surface casing vents the occurrence of methane flow rates over 100 mg/h in Saskatchewan at 3.5% of the measured wells was much lower than the 32% occurrence in Alberta. The 32% leakage occurrence we determined based on our measurements in Alberta is also higher than the 10.8% and 6.2% leakage occurrence rates determined through provincial databases in Alberta and British Columbia, respectively (Abboud et al., 2021; Wisen et al., 2020) (Figure 4). Additionally, we found that 68% of the wells we measured in Alberta that were emitting over 100 mg/h were either not listed (50%) on the database or recorded as remediated or died out (18%) in the Alberta Energy Regulator provincial surface casing vent flow and gas migration database (Alberta Energy Regulator Vent Flow and Gas Migration Report), accessed in September 2022. The same comparison cannot be made for Saskatchewan as a publicly available database of surface casing vent flow and gas migration is not available.

3.5.3. Emission factors and national inventory estimates

For all of Canada, we estimated the annual combined methane emissions from abandoned oil and gas wells based on our measurements (85-93 kt) to be 37-50% higher than the National Inventory Report estimates (62 kt) (ECCC, 2023). In the National Inventory Report and our estimates, the majority of methane emissions from abandoned oil and gas wells were surface casing vent emissions (Figure S4). Using our measurement-based emission factors for surface casing vent and non-surface casing vent emissions, we estimate annual surface casing vent methane emissions to be 70 kt (75-82% of the combined abandoned oil and gas well methane emission estimate of 85-93 kt). Annual surface casing vent emission estimates in the National Inventory Report are 40 kt (ECCC, 2023), 75% lower than our estimate (Figure S4). This difference may be driven by uncertainties in both emission factors and the number of surface casing vents.

We found that the emission factors developed from this study were generally higher than those in current inventory reports for Canada and the U.S. (Table S5) (EPA, 2023; ECCC, 2023). Both the Canadian National Inventory Report and U.S. Greenhouse Gas Inventory use region specific emission factors broken down into well type and status categories. Emission factors for abandoned oil and gas wells in the Canadian National Inventory Report range from 0.40 kg/y/well for plugged crude oil wells (rest of Canada region) to 192.72 kg/y/well for unplugged gas wells (rest of Canada region) (ECCC, 2023). In the U.S. Greenhouse Gas Inventory emission factors for states outside of the Appalachian basin (non-Appalachian region) range from 0.02 kg/y/well for plugged wells to 87.8 kg/y/well for unplugged wells (EPA, 2023). In our study we obtained emission factors for non-surface casing vent flow emissions at abandoned oil and gas wells that ranged from 0.2 kg/y/well for plugged crude oil wells in Saskatchewan to 278 kg/y/well for unplugged gas wells in Alberta. The upper range of our non-surface casing vent emission factors is 1.4 and 3.2 times higher than the highest emission factor used in the Canadian National Inventory Report (192.72 kg/y/well) and U.S. National Inventory Report (non-Appalachian region) (87.8 kg/y/well), respectively. It is important to note here that these comparisons are only for non-surface casing vent emissions. Therefore, for the U.S. the underestimation is much larger than the 3.2 factor since they do not account for surface casing vent emissions.

Unlike the non-surface casing vent emission factors, direct comparisons cannot be made to surface casing vent emission factors in the Canadian National Inventory Report. For Alberta, the National Inventory Report estimates emissions from surface casing vents by combining industry reported incident, remediation and volumetric flow rate test information from the Alberta Energy Regulator Vent Flow and Gas Migration

Report with gas compositions from producing formations (ECCC, 2023). For Saskatchewan, the National Inventory Report extrapolates information from previous studies that provided national upstream oil and gas inventory estimates for the years 2000, 2005 and 2011 (ECCC, 2023).

Finally, we found that the upper uncertainty limit of our lower national emission estimate of 85 kt was significantly higher than the upper uncertainties for abandoned oil and gas well emissions in the Canadian National Inventory Report and U.S. Greenhouse Gas Inventory (Table S13). We found that the upper uncertainty bound of emissions from abandoned oil and gas wells in our study was 380%, almost double that of the U.S. Greenhouse Gas Inventory (206%) and six times higher than Canada's National Inventory Report (61%). The details of the methodology used to estimate our total emissions uncertainty ranges are provided in Supporting Information.

3.6. Discussion

3.6.1. Super-high methane flow rate from an unplugged gas well exceeds previously published measurements.

We found that approximately 5% of abandoned oil and gas wells measured were super-high (>10^5 mg/h) emitters, whereas 11% were high emitters (>10^4 mg/h). Among the super-high emitters there was a single well with a methane flow rate two to three times higher than the previously published highest emission rate from an abandoned well (Etiope et al., 2013). This measurement alone increased the emission factor for unplugged wells by a factor of two. There may still be other super high-emitting abandoned oil and gas wells in Alberta and elsewhere with methane flow rates exceeding our highest measured value, which contributes to uncertainty in methane emissions from abandoned oil and gas wells in Canada and elsewhere.

Our ability to identify such a super-high emitter may have been due to our explicit attempt to cover different well types (e.g., oil, gas, injection, disposal), statuses and geographic regions. Geographic region has consistently been identified in published literature as a factor that can impact leakage and emissions from oil and gas wells

(Hachem & Kang, 2023). Therefore, we measured eight sub-provincial regions from Estevan in southeastern Saskatchewan to Grand Prairie in northwestern Alberta (Figure 1). We found strong sub-provincial and inter-provincial variations. Despite this, there still are provinces/states/territories with ongoing or historical oil and gas production that have no published measurements such as Manitoba, Quebec, Northwest Territories, Alaska, and North Dakota (Hachem & Kang, 2023; Klotz et al., 2023), and even where measurements are available (e.g., Ontario), they can be highly localized (El Hachem & Kang, 2022).

Because additional measurements of super-high emitters can substantially change emission estimates, it may be worthwhile to explore opportunities for aerial or vehicle-based surveys to detect super-high emitters (Delre et al., 2022; Korbeń et al., 2022; Lebel et al., 2020; Vogt et al., 2022), which can then be followed up with component-specific measurements requiring site access. Aerial or vehicle-based surveys can reduce site access issues and potentially increase the number of wells screened and identify more super high emitters. Nevertheless, direct component level and site level measurements are still needed to measure lower flow rates (≤104 mg/h) and to differentiate between collocated sources (Hachem & Kang, 2023; Williams et al., 2023), such as surface casing vent and non-surface casing vent emissions.

3.6.2. Surface casing vent flows dominate methane emissions at abandoned oil and gas wells, indicating subsurface leaks are substantial.

We found that the majority of methane emissions from abandoned oil and gas wells in Canada are from the surface casing vents in both the National Inventory Report and our measurement-based estimates. These findings indicate that subsurface leaks due to wellbore integrity problems are significant. Based on these results, emissions from abandoned oil and gas wells are likely to be substantially underestimated in regions where surface casing vent emissions are not explicitly accounted for, such as the U.S. In Canada, the National Inventory Report accounts for methane emissions from surface casing vents of abandoned oil and gas wells using provincial databases such as the Alberta Energy Regulator Vent Flow and Gas Migration Report. By comparing our measurements to previous studies estimating leakage occurrence rate using the British Columbia and Alberta provincial databases, we found our leak occurrence rates to be higher at 32% (Figure 4). This 32% is higher but comparable to the 26.5% well integrity failure occurrence estimated as the upper range using Colorado and New Mexico datasets (Lackey et al., 2021). We also found that 67% of the wells with surface casing vent emission rates over 100 mg/h are not included in the Alberta Energy Regulator's database. Therefore, measurements are needed to verify and improve provincial databases of surface casing vent leakage, thereby reducing uncertainties in emission estimates and better managing well integrity issues.

In the U.S., many jurisdictions require surface casing vents to be closed, but the annuli can still be vented or bled off (Ingraffea et al., 2014, 2020). The U.S. Greenhouse Gas Inventory does not estimate such emissions from surface casing vents of abandoned oil and gas wells and many of the measurements for abandoned oil and gas wells used to determine the emission factors do not include surface casing vent emissions. Importantly, if the fluids from the surface casing vents do not become methane emissions to the atmosphere, they may be migrating in the subsurface and impacting groundwater instead (Lackey et al., 2017). At the same time, groundwater monitoring is not comprehensive enough to identify contamination due to leaky wells (Kang et al., 2023).

3.6.3. Plugging alone may not sufficiently protect groundwater

We found that high non-surface casing vent emissions often correspond to low surface casing vent emissions and possibly subsurface leakage and groundwater contamination. In other words, the highest emitting wells with leaks coming predominantly from wellhead infrastructure may not be the wells with the most subsurface leakage. This can also be true if the surface casing vent is closed, as is common practice in the U.S. Therefore, focusing plugging and remediation efforts on wells with high methane emissions may leave wells with subsurface leakage unplugged. This is a concern since there are voluntary carbon credit methodologies and federal programs focused on plugging to mitigate methane emissions from abandoned oil and gas wells in Canada and the U.S. (Boutot et al., 2022; Kang et al., 2023; ACR, 2023).

At wells with well integrity failure and subsurface leakage (identified by surface casing vent flow, sustained casing pressure or gas migration observations), plugging may not fix leakage issues (Kang et al., 2021; Wisen et al., 2020). The process of fixing subsurface leakage is typically more complex and expensive than the average plugging procedure (Raimi et al., 2021) but must be addressed prior to plugging. Once plugged, subsurface leakage via the annulus may go unchecked leading to persistent groundwater impacts, emissions to the atmosphere, or other environmental risks such as explosive hazards (Ingraffea et al., 2014; Jackson et al., 2013; Kang et al., 2020; Schout et al., 2019; Warrack et al., 2021; Wisen et al., 2020). Therefore, without careful consideration of all well integrity issues and subsurface leakage potential, the $4.7-billion orphaned well plugging program in the U.S., a part of the Bipartisan Infrastructure Law (Boutot et al., 2022; Kang et al., 2023), and carbon crediting methodologies may lead to unintended groundwater impacts.

Our study and recent work on state and provincial databases show that wellbore integrity issues exist in the abandoned oil and gas well populations in Canada, the U.S., and likely elsewhere, and these issues are likely underreported, or not reported at all depending on the jurisdiction (Abboud et al., 2021; Ingraffea et al., 2014, 2020; Lackey et al., 2021; Wisen et al., 2020). Overall, the widespread occurrence of subsurface leakage in the abandoned oil and gas well population may mean that plugging alone cannot remediate all impacts of abandoned oil and gas wells, and investigations of subsurface leakage is important for understanding and mitigating methane emissions from abandoned oil and gas wells and broader environmental impacts.

3.7. Figures

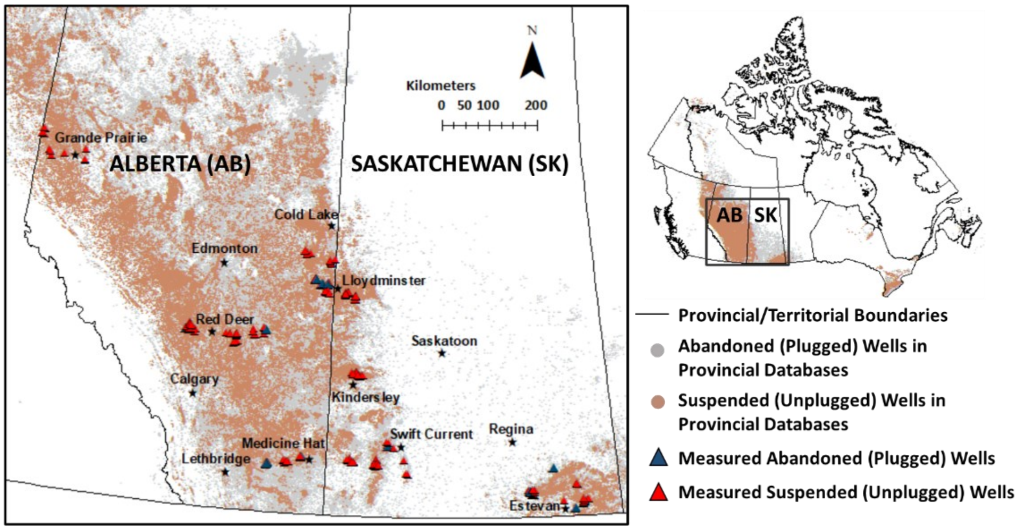

Figure 1. Measured abandoned oil and gas well locations in Alberta and Saskatchewan (triangles), with blue triangles representing abandoned (plugged) wells and red triangles representing suspended (unplugged) wells. All abandoned and suspended wells on provincial databases are shown in gray and brown circles respectively.

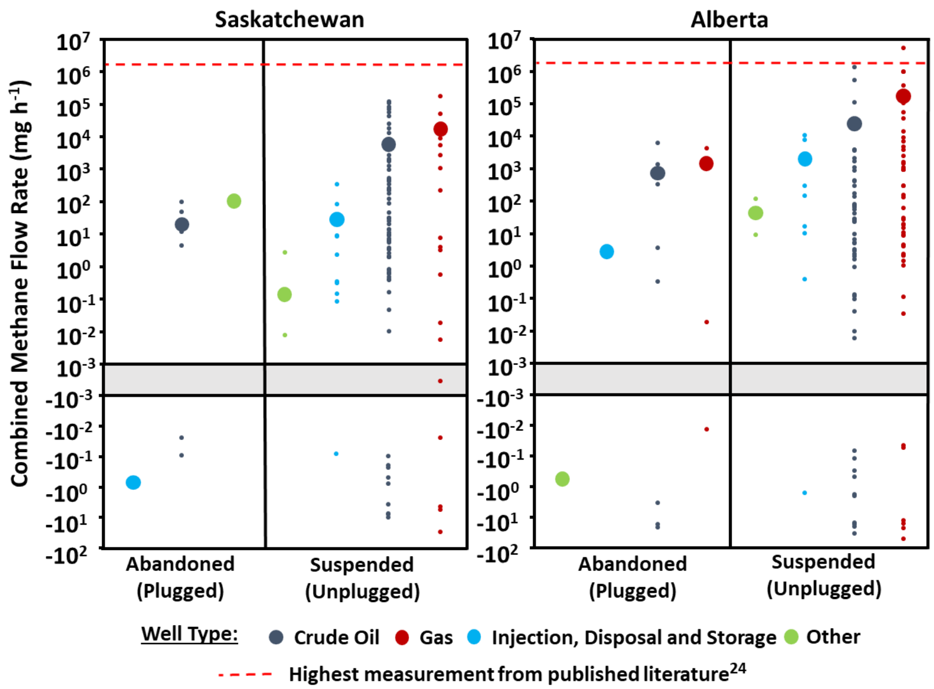

Figure 2. Combined measured methane flow rates according to well status (abandoned or suspended) and well type (crude oil, gas, injection, disposal and storage, and other) in Saskatchewan (left) and Alberta (right). The combined well measurements include methane emissions from both surface casing vent and non-surface casing vent sources. Large circles represent arithmetic mean of measured flow rates (emission factor) in each category and dots are individual measurements. Red dashed line represents the highest measurement from published literature (Etiope et al., 2013). Gray areas represent methane flow rates <0.001 and >-0.001 mg/h/well.

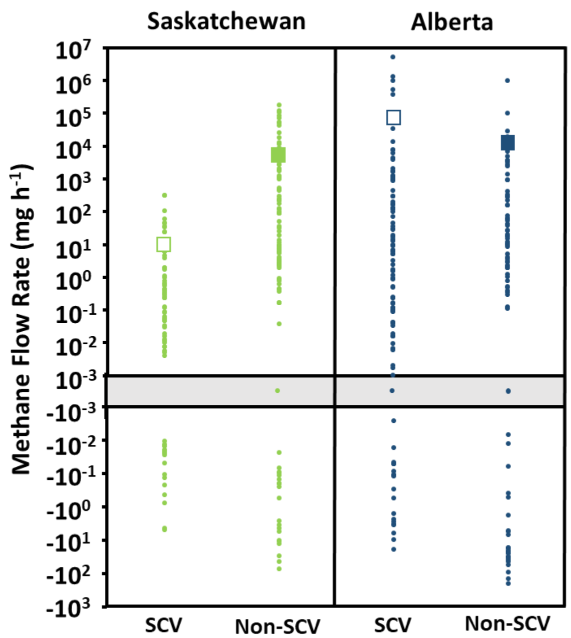

Figure 3. Measured surface casing vent (SCV) and non-surface casing vent (non-SCV) methane flow rates by province (Saskatchewan and Alberta). Large squares represent mean of measurements (emission factor) and dots are individual measurements. Grey area represents methane flow rates <0.001 and >- 0.001 mg/h.

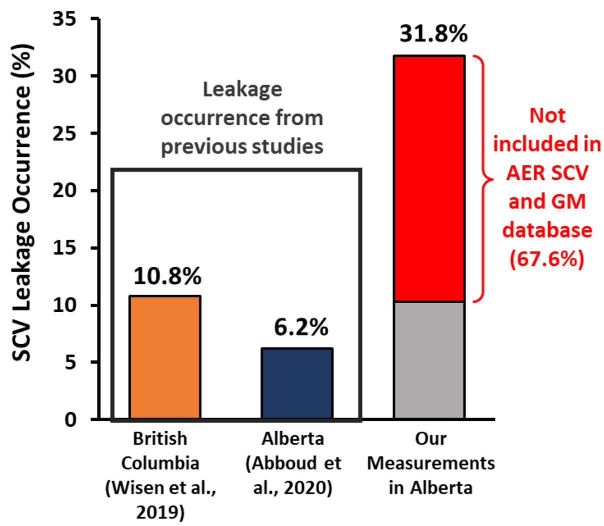

Figure 4. Comparison of surface casing vent (SCV) leakage occurrence from our field measurements in Alberta (>100 mg/h) to previous studies based on provincial databases for British Columbia (Wisen et al., 2020) (orange) and Alberta (Abboud et al., 2021) (dark blue). In our measurement-based surface casing vent leakage occurrence (the rightmost bar), the red portion represents the occurrences at wells not included in the Alberta Energy Regulator's Surface Casing Vent and Gas Migration (AER SCV and GM) database and the gray portion represents the occurrences at wells included in Alberta Energy Regulator's Surface Casing Vent and Gas Migration (AER SCV and GM) database.

3.8. Acknowledgment

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4. Discussion, Future Work and Limitations

4.1. Additional point source-based measurements are needed to characterize methane emissions from abandoned oil and gas wells and oil and gas production sites.

In Chapter 3, we estimated emissions from abandoned oil and gas wells in Canada to be 85-93 kt, which would make up 5-6% of the current Canadian National Inventory estimate for the oil and gas sector (ECCC, 2023). Despite this non-negligible contribution, uncertainties related to this emission source remain high, indicating more work is needed to accurately quantify emissions from abandoned oil and gas wells.

Attributes impacting the magnitude of emissions and the occurrence of super high emitters in abandoned oil and gas wells are still widely unknown, with many studies showing conflicting results for multiple factors (Hachem & Kang, 2023). By conducting 238 measurements across multiple oil and gas producing regions in Alberta and Saskatchewan we were able to identify sub-regional and provincial variation in emissions as well as the existence of a super high emitter within our sample set. However, access issues and time constraints prevented the collection of measurements across the entire cross section of wells in the province and one-time measurements gave no insight into temporal variation of emissions. Additionally, the frequency of occurrence of super high emitters in abandoned oil and gas well populations of Alberta and Saskatchewan is still unknown. More measurements are needed to increase the diversity in the sample set within Alberta and Saskatchewan as well as provide insights into the frequency of super high emitters and temporal variation of emissions.

Due to the existence of geographic variation in emissions from abandoned oil and gas wells and varying regulatory practices across jurisdictions, the results of this study may not fully represent the population of abandoned wells outside of Alberta and Saskatchewan but can be used to inform further measurement plans. More measurements are needed across other jurisdictions in Canada, the U.S. and internationally to fully characterize emissions from this source. To date only two studies, to our knowledge, have been conducted in countries outside of Canada and the U.S. that directly measured emissions from abandoned oil and gas wells using point-source methodologies (Boothroyd et al., 2016; Schout et al., 2019).

One option to increase the number and frequency of measurements would be the use of aircrafts and mobile measurements. However, these measurement techniques have been shown to have relatively high detection limits and struggle to quantify collocated sources (Williams et al., 2023). Abandoned oil and gas wells are generally lower emitting than active production sites and other high emitting sources in the oil and gas sector, apart from high and super high emitters. Multiple studies, including this work, have also shown emissions from abandoned oil and gas wells follow a skewed distribution (El Hachem & Kang, 2022; Kang et al., 2016; Williams et al., 2021), meaning that it is likely a majority of the population of abandoned wells do not emit at high enough levels to be accurately detected and quantified by current satellite, aircraft or vehicles based technologies (Williams et al., 2023). With advances in sensing technology, mobile and airborne measurement platforms may be able to detect high methane emitters in the future; however, chamber-based direct measurements are likely to still be needed to capture the full distribution of methane emission rates of abandoned oil and gas wells.

Results from this study have also shown how separate quantification of collocated sources such as surface casing vents and wellheads is crucial on oil and gas production sites (including abandoned oil and gas well sites), as different emission sources are often quantified separately in inventories and governed by different regulations. Despite the limitations of detection limits and source attribution, high-resolution aircraft and vehicle-based studies may be used to identify super high emitting sources and understand their frequency in larger sample sets of abandoned oil and gas wells. Overall, this study has added to the increasing body of work that emphasizes the importance of point-source based measurements on oil and gas production sites (including abandoned sites) to complement top-down approaches for adequate characterization of sources (Festa-Bianchet et al., 2023; Johnson, Conrad, et al., 2023; Johnson, Tyner, et al., 2023).

4.2. Relationships between emissions from subsurface leakage and groundwater impacts of abandoned oil and gas wells are understudied.

Recent research conducted on the occurrence of groundwater contamination in relation to oil and gas production activities have shown that subsurface leakage from well integrity issues can contribute to the presence of methane in groundwater (Sherwood et al., 2016). However, current groundwater monitoring is too limited to provide broader insight into the extent of groundwater contamination from subsurface well leakage (Jackson et al., 2013; Kang et al., 2023). Nevertheless, studies have shown that oil and gas wells (including abandoned wells) act as subsurface leakage pathways for methane to migrate to the atmosphere and that subsurface leakage from well integrity problems are often underreported (Ingraffea et al., 2014, 2020; Lackey et., 2021). Despite the existence of studies on groundwater impacts and methane emissions from oil and gas wells there is still little empirical understanding on the relationship between them due to a lack of targeted studies that measure both simultaneously in the field.

In our study (Chapter 3), we investigated the relationship between emissions from surface casing vent flows indicating subsurface leakage and emissions from leaking wellhead infrastructure. We found that wells with high emitting wellheads may not be wells with the most subsurface leakage through comparisons of emissions from wellhead infrastructure and surface casing vents. However, without measurements of groundwater methane concentrations we were unable to determine the degree to which varying emissions from these sources also impacted groundwater. Studies conducting concurrent measurements of emissions and groundwater quality at the same site may provide insight into how emissions (or lack thereof) from wellheads, gas migration, surface casing vent flow or presence of surface casing pressure impact groundwater methane concentrations and vice versa. Such comprehensive measurement campaigns better inform mitigation strategies that address both emissions and groundwater impacts from abandoned oil and gas wells.

5. Conclusion

Accurate quantification of methane emission sources is crucial to creating effective mitigation strategies and policies that can limit further anthropogenic driven global warming in the near-term. Our work investigated methane emissions from abandoned oil and gas wells, a source within the oil and gas sector. We identified the need for more point-source based measurements, specifically in the oil and gas producing provinces of Alberta and Saskatchewan, Canada, to better inform inventories, regulations, and methane mitigation strategies. We also found that there was limited research on the contribution of subsurface leakage from abandoned oil and gas wells to methane emissions and other environmental impacts such as groundwater contamination.

By conducting component-specific chamber-based measurements of abandoned oil and gas wells across Alberta and Saskatchewan we were able develop component specific emission factors (surface casing vent and non-surface casing vent) and estimate methane emissions from abandoned wells in Canada to be 85-95 kilotonnes of methane per year. From these estimates we found that emissions from subsurface leakage in the form of surface casing vent emissions contribute to 75-82% (70 kilotonnes of methane per year) of national methane emissions from abandoned oil and gas wells. Through analysis of surface casing vent emission occurrence within our sample set of measured wells, we found that the prevalence subsurface leakage from well integrity issues (and likely groundwater impacts) are underestimated by provincial databases.

We recommend additional and repeated of measurements of wells across within Alberta and Saskatchewan as well across Canada, the U.S., and the world to better characterize and estimate emissions from this source. Finally, we recommend comprehensive on-site investigations of oil and gas wells that study the relationships between emissions from surface infrastructure, emissions from subsurface leakage and groundwater quality so that efforts to mitigate emissions do not lead to unintended impacts on other aspects of the environment.

6. References

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7. Appendix: Methane emissions from abandoned oil and gas wells in Alberta and Saskatchewan, Canada: the role of surface casing vent flows – Supporting Information

SI-1: Materials and Methods

Well Status and Type Definitions

Tables S1-S4 contain the categorization of wells in Alberta and Saskatchewan based on available information in the Alberta Energy Regulator ST37 and Saskatchewan Mining and Petroleum GeoAtlas provincial databases. In Alberta, we determined well status of abandoned (plugged) or suspended (unplugged) from the “License Status” and “Mode Description” categories (Table S1). The Alberta Energy Regulator uses license status as a reference for required regulations and monitoring during the life cycle of well. However, certain license statuses such as “Issued” and “Amended” do not provide enough information on the current activity of the well (Abboud et al., 2021); therefore, we used the “Mode Description” column as a secondary source of information to determine the status of the well. Well type (gas, crude oil, injection, disposal and storage or other) for Alberta wells was determined using information from the “Fluid Description” and “Type Description” categories (Table S2). In Saskatchewan “Well Status” and “Wellbore Completion Current Status” categories were used to determine well status and well type, respectively (Table S3 and S4).

Our definition of plugged wells excludes wells that may only have temporary or zonal plugging (with other zones unplugged) while still being in the suspension stage. We have also added well type categories of “Injection, Disposal and Storage” and “Other”, which were generally not included or explicitly identified in previous literature or national inventory reports. We added these categories to account for the oil and gas related wells that may not have been strictly for production but can still act as leakage pathways for methane. The “Other” well type category accounts for wells listed in databases with N/A or unknown types, which can often occur when a well becomes abandoned or plugged and for older wells. The “Other” well type category also includes well types such as observation, test, and relief wells. Lastly, in Tables S1-S4, we included wells with the well status categories “Active” and “Not Applicable” (Table S1 and S3) as well as the well type category of “Industrial, Farm and Water Source Wells” (Table S2 and S4), but these wells are not included in the abandoned oil and gas well counts used in this paper.

<u>Methane Flow Rate Measurements</u>

Methane flow rate measurements were conducted using a two-part process. First, we performed screening measurements using a Sensit Portable Methane Detector to identify leakage points on the aboveground wellhead infrastructure, the surface casing vent, and the soils surrounding the wells, including buried wells. Next, we conducted methane flow rate measurements at each site using a static chamber methodology (Kang et al., 2014; Williams et al., 2023). Where possible, we deployed separate chamber measurements to quantify methane flow rates of the surface casing vent and wellhead as shown in Figure S1. As the chamber set up for wellheads and surface casing vents included soil from within the chamber (including near well gas migration) we refer to the two components measured by separate chambers as “surface casing vent” and “non-surface casing vent”. We assumed that there is less contribution from gas migration compared to surface casing vent measurements, which is supported by our screening measurements around surface casing vents measured in in the field. We classified emissions from measurements of buried wells as “non-surface casing vent” emissions. A single control measurement was also taken between 2-8 meters away at each wellsite to infer background emissions. However, we note that in some cases these “control” measurements may capture gas migration as well. We used a Sensit Portable Methane Detector or a Picarro GasScouter G4301 to measure methane concentrations within the chamber over time. We also collected gas samples throughout each chamber measurement for quality control. These gas samples were analyzed at McGill University using a Picarro G2210-I (El Hachem & Kang, 2022).

The static chamber methodology involves use of linear regression to determine methane flow rates (Kang et al., 2014; Williams et al., 2023). Methane flow rates with both an R^2 value less than 0.5 and p-value greater than 0.05 (at 95% significance level) were taken as zero but included as an emission rate. Based on this cutoff, a total of 11 control measurements (4.7% of all control measurements), 1 surface casing vent measurement (0.5% of all SCV measurements), and 4 non-surface casing vent measurements (2.1% of all non-SCV measurements) were taken as zeros.

National Emission Estimates

Methane emissions from abandoned oil and gas wells can be calculated by multiplying emission factors or emissions per well by the number of wells commonly referred to as “Activity Data” (ECCC, 2023). For wells with surface casing vents, we separately quantified non-surface casing vent and surface casing vent emissions with different emission factors and activity data found in Tables S7-S10. For wells without surface casing vents, we estimated a range of emissions using activity data and emission factors found in Table S11 and S12.

Activity data for wells with and without surface casing vents was determined from database analysis and data used in the current National Inventory Report (ECCC, 2023). To determine the number of abandoned oil and gas wells in Alberta and Saskatchewan, we used the well status and type definitions in Tables S1-S4 to analyze the Alberta Energy Regulator ST37 (accessed May 2022), and the Saskatchewan Mining and Petroleum GeoAtlas (accessed September 2022) databases (AER ST37, 2023; Saskatchewan Geological Survey, 2023). For abandoned oil and gas wells in all other provinces and territories, we obtained activity data used in the 2021 National Inventory Report via correspondence with Environment Climate Change Canada (ECCC, 2023). National Inventory Report activity data is split into unplugged, plugged, and unknown plugging statuses, as well as into well type categories of oil, gas and other. We estimated the proportion of wells with surface casing vents from field observations of surface casing vents at measured wells. From these observations we found the 89% and 52% of all abandoned oil and gas wells has surface casing vents in the unplugged and plugged categories, respectively. The proportion of wells with surface casing vents was applied to the number of abandoned oil and gas wells in each province/territory to determine the number of wells with surface casing vents found in Tables S7-S10. Similarly, the proportion of wells without surface casing vents (11% for unplugged and 48% for plugged wells) was applied to the number of abandoned oil and gas wells in each province/territory to determine the number of wells without surface casing vents found in Tables S11 and S12.

For wells with surface casing vents, we estimated non-surface casing vent emissions by multiplying the non-surface casing vent emission factors (non-surface casing vent emissions per well) by the number of wells with surface casing vents (Tables S7 and S8). We estimated surface casing vent emissions by multiplying surface casing vent emission factors (emissions per surface casing vent) by the number of wells with surface casing vents (Tables S9 and S10). We applied Alberta non-surface casing vent and surface casing vent emission factors to British Columbia, Northwest Territories and Yukon. We applied Saskatchewan non-surface casing vent and surface casing vent emission factors to Manitoba. For non-surface casing vent emissions in Ontario, Quebec and New Brunswick, we applied the emission factors of a study recently performed in Ontario (El Hachem & Kang, 2022), which did not measure surface casing vents. Therefore, to determine surface casing vent emissions in Ontario, Quebec and New Brunswick, we applied emission factors calculated from all surface casing vent measurements from this study.

For wells without surface casing vents, an upper and lower range of emissions was estimated using activity data and emission factors contained in Tables S11 and S12. For the lower estimate, we assumed that emissions from wells without surface casing vents can be represented by just the non-surface casing vent emission factors. For the upper estimate for wells without surface casing vents, we used the combined emission factors (surface casing vent and non-surface casing vent) as we assumed that well integrity failures are equally likely in wells without surface casing vents and will produce emissions. In the worst-case scenario, we assumed that all emissions that would have come from the surface casing vent were emitted through some other pathway such as the main borehole and the annular space. For both the lower and upper estimates of wells without surface casing vents we applied Alberta emission factors to British Columbia, Northwest Territories and Yukon. We applied Saskatchewan emission factors to Manitoba. For emissions from wells without surface casing vents in Ontario, Quebec and New Brunswick, we applied the emission factors of a study recently performed in Ontario (El Hachem & Kang, 2022).

Uncertainties

Table S5 contains confidence intervals for surface casing vent, non-surface casing vent emission factors and Table S6 contains confidence intervals for combined well emission factors for Alberta and Saskatchewan. Abandoned oil and gas well emissions typically follow a non-normal distribution (Williams et al., 2021), therefore we used the accelerated percentile method of the “bootci” function in MATLAB with 100,000 bootstrap samples to calculate the confidence intervals.

For all activity data we assumed uncertainty bounds of ±10% based on the U.S. Environmental Protection Agency uncertainty methodology for abandoned oil and gas wells (EPA, 2018). Tables S7-S10 contain the upper and lower estimates of activity data based on this uncertainty range.

Tables S13 and S14 contain the upper and lower uncertainty range for our national emission estimates. These values were calculated by first multiplying the lower and upper bounds of the 95% confidence interval of the emission factor used for each well type and status category with the respective lower and upper bounds of the activity data for that category. This process was repeated for all well status and type categories in every province. The resulting lower and upper uncertainty bounds for emissions of each well type and status category in each province were then summed together to determine the lower and upper uncertainty bounds for the national emission estimates.

SI-2: Supplementary Results

Control Emission Rates

We found that on average, methane flow rates from control measurements were orders of magnitude smaller than surface casing vents and non-surface casing vent measurements in Saskatchewan and Alberta (Figure S2). For direct comparison, we normalized the control methane flow values by the areas of the chambers used for our surface casing vents and non-surface casing vent measurements. In Saskatchewan, the average methane flow rate of control measurements was 1.1×10^{-1} mg/h/control (normalized by surface casing vent chamber area) or 6.4×10^{-1} mg/h/control (normalized by non-surface casing vent chamber area), which are three and five orders of magnitude smaller than surface casing vent and non-surface casing vent average emissions, respectively. In Alberta, control measurements emitted on average 7.8×10^{1} mg/h/control (normalized by surface casing vent chamber area) which is three orders of magnitude smaller than surface casing vent and non-surface casing vent average flow rates. When Alberta control measurements were normalized by the non-surface casing vent chamber area, the average methane flow rate rate was 4.3×10^{2} mg/h/control which is two orders of magnitude smaller than average surface casing vent and non-surface casing vent methane flow rates.

Methane emissions from controls in Alberta were higher than those in Saskatchewan due to one very high control measurement in Alberta. This high control measurement had a flow rate of $9.5x10^3$ mg/h/control (normalized by surface casing vent chamber area chamber) or $5.3x10^4$ mg/h/control (normalized by non-surface casing vent chamber area), which is 684 times higher than the next highest measurement and is likely an indication of gas migration. We note that we only observed one high control measurement out of >238 control measurements, which corresponds to 0.4%. Upon exclusion of this high control measurement the average control methane flow rate in Alberta was reduced to $-3.1x10^{-2}$ mg/h/control (surface casing vent chamber normalized) or $-1.7x10^{-1}$ mg/h/control (normalized by non-surface casing vent chamber area). Lastly, the average methane flow rate for all control measurements in Alberta and Saskatchewan, including the one potential gas migration measurement is $4.0x10^1$ mg/h/control (normalized by surface casing vent chamber area) or $2.3x10^2$ mg/h/control (normalized by non-surface casing vent area).

Emission Factors

We found that the emission factors developed from this study were generally higher than those in current inventory reports for Canada and the U.S. (EPA, 2023; ECCC, 2023) (Table S5). The Canadian National Inventory Report and U.S. Greenhouse Gas Inventory both use region specific emission factors broken down into well type and plugging status categories. Unplugged gas wells were the highest emitting well type in Alberta for non-surface casing vent emissions with an emission factor of 278 kg/y, almost 44% higher than the highest Canadian National Inventory Report emission factor for unplugged gas wells (Table S5). In Saskatchewan, unplugged gas wells were also the highest emitting well type for non-surface casing vent emissions, with an emission factor of 140 kg/y, higher than the emission factor listed in the National Inventory Report for Ontario (88.48 kg/y). For unplugged crude oil wells, the non-surface casing vent emission factors for Alberta (15 kg/y) and Saskatchewan (74 kg/y) were lower than the National Inventory Report emission factor of 105.12 kg/y (rest of Canada region).

Compared to the U.S. Greenhouse Gas Inventory (non-Appalachian region) emission factors, our non-surface casing vent emission factors for unplugged abandoned oil and gas wells in Alberta (1.1 kg/y/well) and Saskatchewan (0.3 kg/y/well) were larger than the 0.02 kg/y/well used in the Greenhouse Gas Inventory. For Saskatchewan, the non-surface casing vent emission factor for unplugged wells (76 kg/y/well) was comparable to the 87.78 kg/y/well used in the Greenhouse Gas Inventory. However, our non-surface casing vent emission factor for unplugged wells in Alberta (137.9 kg/y/well) is 60% higher than the 87.78 kg/y/well used for unplugged abandoned oil and gas wells in the U.S. Greenhouse Gas Inventory (non-Appalachian region).

<u>Uncertainties</u>

Table S5 and S6 contain the confidence intervals for non-surface casing vent, surface casing vent and combined emission factors from our measurement in Alberta and Saskatchewan. We found that unplugged gas wells in Alberta have the highest uncertainty for component specific and combined emissions. The largest upper bound of the 95% confidence interval for surface casing vent emission factors was 6,222 kg/y (369% above the mean) from unplugged gas wells in Alberta. For non-surface casing vent and combined emission factors, the largest upper uncertainties were also from unplugged gas wells in Alberta at 1479 kg/y (433% above the mean) and 5772 kg/y (307% above the mean), respectively.

We found that the upper uncertainty limit of our lower estimate of national methane emissions from abandoned oil and gas wells in our study was higher than in the U.S. and Canadian inventory (Table S13). The upper uncertainty bound of emissions in our study was 380% above the lower estimate of 85 kt, which is higher than the 61% and 204% upper uncertainty in the Canadian and U.S. inventories respectively.

SI-3: Supporting Figures

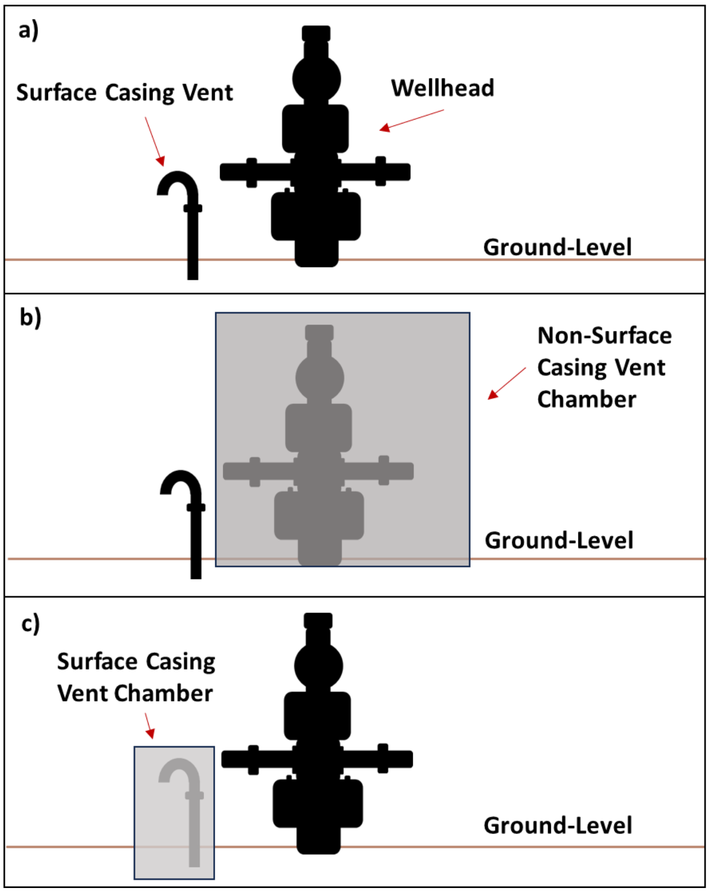

Figure S1. a) example of abandoned oil and gas well site configuration with surface casing vent and wellhead infrastructure. b) non-surface casing vent chamber measurement configuration. c) surface casing vent chamber measurement configuration.

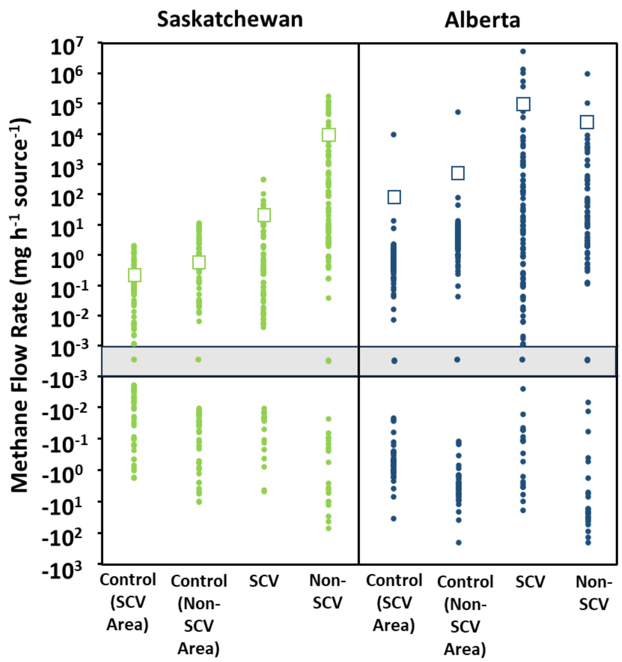

Figure S2. Control (surface casing vent “SCV” chamber and non-surface casing vent “non-SCV” chamber normalized values), surface casing vent (SCV) and non-surface casing vent (non-SCV) methane flow rates from measured abandoned oil and gas wells in Saskatchewan (left) and Alberta (right). Dots are individual measurements for each source. Rectangles represent the mean of measurements. Grey area represents flow rates <0.001 and >-0.001 mg/h/source.

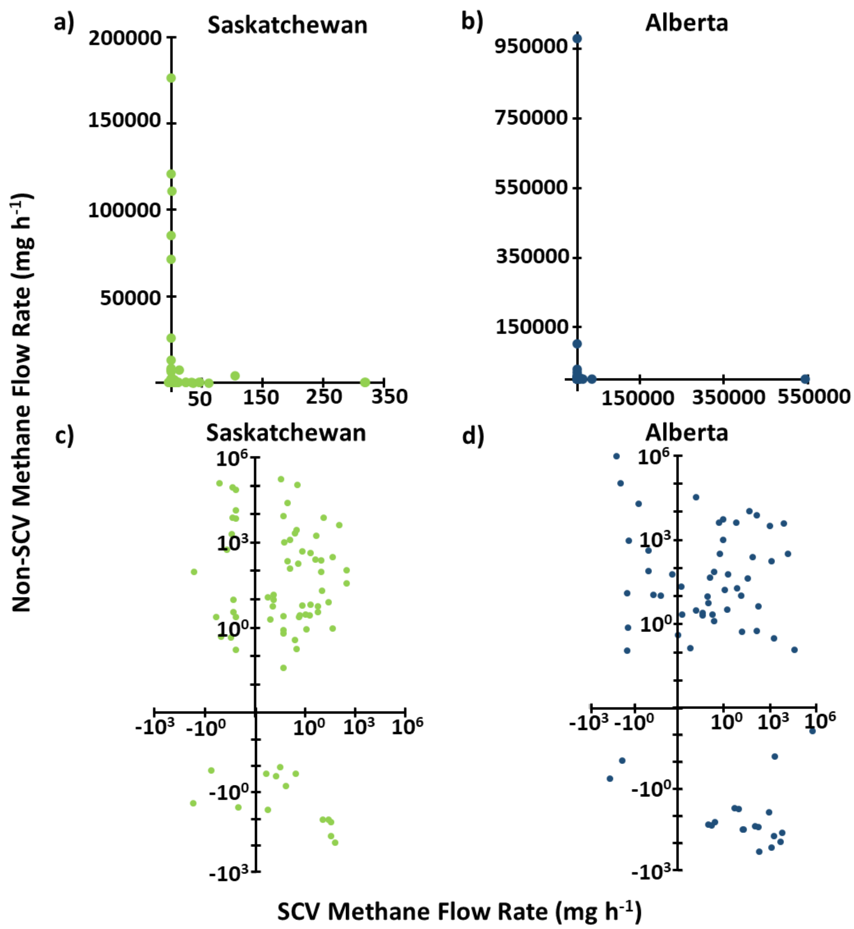

Figure S3. a) and b) linear scatter plots of surface casing vent (SCV) and non-surface casing vent (non-SCV) methane flow rates for Saskatchewan and Alberta, respectively. c) and d) logarithmic scatter plots of surface casing vent (SCV) and non-surface casing vent (non-SCV) methane flow rates for Alberta and Saskatchewan, respectively.

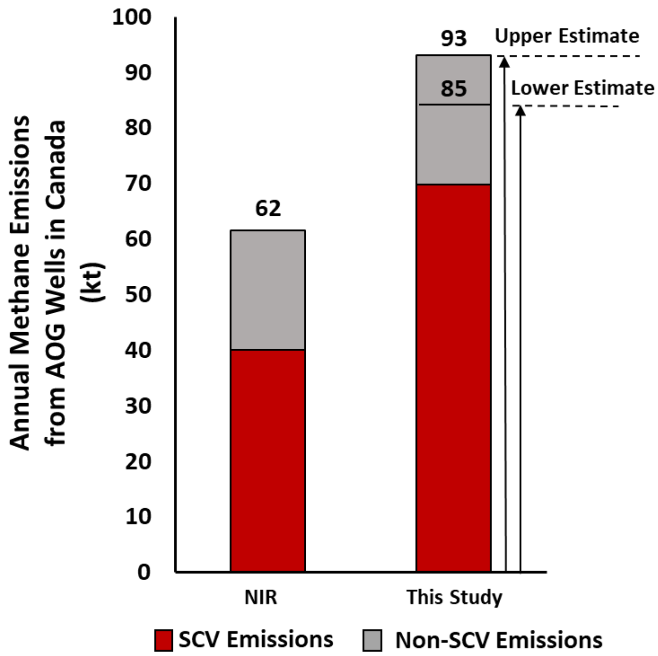

Figure S4. Annual methane emissions from abandoned oil and gas wells in Canada, including surface casing vent (SCV) and non-surface casing vent (non-SCV) emissions. The Canadian National Inventory Report (NIR) estimate is for 2021 (ECCC, 2023). A breakdown of emissions by province provided in Table S11 and S12 for the lower and upper estimates, respectively.

SI-4: Supporting Tables

Table S1. Well status designation methodology for Alberta.

	Well Status Indicator Categories in Alberta Energy Regulator ST37 (May 2022)	
Status used in this paper	**"License Status"**	**Inclusions or exclusions based on "Mode Description" categories in database.**
Suspended (Unplugged)	Suspended	All mode types
	Issued, Amended	Suspended, Abandoned Zone, Abandoned and Whip-stocked
Abandoned (Plugged)	Abandoned, RecCertified, RecExempt	All mode types
	Issued, Amended	Abandoned, Junked and Abandoned, Closed
Active[a]	Re-entered	All
	Issued, Amended	Pumping, Flowing, Gas Lift, Abandoned and Re-Entered
Not Applicable or Unknown[a]	Issued, Amended	Not Applicable, Drilled and Cased, Drilled and Completed, Potential, Preset, Testing, Test Completed
	Drilled and Cased	All mode types

[a] Not included in abandoned oil and gas well statuses or well counts.

Table S2. Well type designation methodology for Alberta.

	Well Type Indicator Categories in Alberta Energy Regulator ST37 (May 2022)
Well type used in this paper	**Inclusions add exclusions based on "Fluid Description" and "Type Description" categories in database.**
Oil	Wells with "Fluid Description" of Crude Bitumen, Crude Oil
Gas	Wells with "Fluid Description" of Gas, Coalbed Methane – Coals only, Coalbed Methane and Shale and Other Sources, Coalbed Methane-Coals and other Lithium, Shale Gas only, Shale Gas and Other Sources, Liquid Petroleum Gas. Excluding gas wells from Farm, Industrial and Storage "Type Description"
Injection, Disposal and Storage	Wells with "Type Description" of Storage, Disposal, Injection, Cyclical, Cavern, Steam Assisted Gravity Drain and "Fluid Description" that is not covered in Oil or Gas categories except for Gas or Liquid Petroleum Gas wells with "Type Description" Farm or Industrial and Helium wells.
Other	All other wells "Fluid Description" not covered by previous sections without the "Type Description" of Injection, Disposal, Cyclical, Storage, Steam Assisted Gravity Drain, Farm, Industrial or Source. Excluding helium wells.

Industrial, Farm and Water Source Wells[a]	Waste, Water and Gas wells with "Type Description" of Farm or Industrial. All wells with "Type Description" of Source wells and all wells with "Fluid Description" of helium.

[a] Not included in abandoned oil and gas well statuses or well counts.

Table S3. Well status designation methodology for Saskatchewan.

	Well Type Indicator Column in Saskatchewan Mining and Petroleum GeoAtlas (September 2022)
Well status used in this paper	**"Well Status"**
Suspended (Unplugged)	Suspended
Abandoned (Plugged)	Abandoned, Downhole Abandoned, Abandoned (Junked), Downhole Abandoned (Junked)
Active[a]	Active, Abandoned Re-entered, Downhole Abandoned and Re-entered, Deepened (Re-Entered)
Not Applicable or Unknown[a]	Cased, Completed, Drilling, Planned, Planned (Cancelled), Preset

[a] Not included in abandoned oil and gas well statuses or well counts.

Table S4. Well type designation methodology for Saskatchewan.

	Well Type Indicator Column in Saskatchewan Mining and Petroleum GeoAtlas (September 2022)
Well type used in this paper	**"Wellbore Completion Current Status"**
Oil	Oil Producer and Water Injector, Oil Producer/ Alt Press Maint Water injector/gas injector, Oil Well
Gas	Gas Producer and Gas Injector, Gas Vent Well, Gas Well
Injection, Disposal and Storage	Air Injector (Combustion) Well, Alternating Press Maint – Water Injector/Air Injector, Alternating Press Maint – Water Injector/Gas Injector, CO2 Injector (Permanent), Cyclic Oil / Solvent Injector, Cyclic Oil/Steam Injector, Disposal Well, Gas Storage (Cavern) Well, Gas Storage Well, Liquid Gas/ NGLS Storage Well, Oxygen Injector, Permanent Oil/CO2 Injection, Permanent Oil/Steam Injection, Polymer Injection, Steam Injector (Permanent), Waste Disposal (Cavern), Waste Disposal Well.
Other	Observation Well, Relief Well, Stratigraphic Test Well
Industrial, Farm and Water Source Wells[a]	Water source well, other minerals, all potash related wells, grout well, backfill wells

[a] Not included in abandoned oil and gas well statuses or well counts.

Table S5. Component-specific emission factors and confidence intervals from measurements. The number of measurements for each category and component are in brackets next to emission factor.

Province	Status	Type	Surface casing vent (SCV) emission factor (kg/y/SCV)	Lower (L) and Upper (U) 95% CI around mean (L, U) (kg/y/SCV)	Non-surface casing vent (non-SCV) emission factor (kg/y/well)	Lower (L) and Upper (U) 95% CI around mean (L, U) (kg/y/well)
Alberta	**Abandoned (Plugged)**	**All**	23 (4)	(-0.02, 50)	1.1 (12)	(-0.08, 5.1)
		Crude Oil	23 [a] (2)	(-0.02, 50)	1.8 (8)	(-0.06, 6.8)
		Gas	23 [a] (2)	(-0.02, 50)	1.1 [a] (2)	(-0.08, 5.1)
		Injection, Disposal and Storage	23 [a] (0)	(-0.02, 50)	1.1 [a] (1)	(-0.08, 5.1)
		Other	23 [a] (0)	(-0.02, 50)	1.1 [a] (1)	(-0.08, 5.1)
	Suspended (Unplugged)	**All**	740 (103)	(200, 2732)	137 (75)	(15, 705)
		Crude Oil	362 (49)	(39, 1454)	15 (34)	(3.2, 45)
		Gas	1326 (44)	(179, 6222)	278 (35)	(11, 1479)
		Injection, Disposal and Storage	18 (8)	(0.7, 43)	5.9 (5)	(-0.05, 24)
		Other	740 [a] (2)	(200, 2732)	137 [a] (1)	(15, 705)
Saskatchewan	**Abandoned (Plugged)**	**All**	0.04 (4)	(0.006, 0.07)	0.3 (8)	(0.07, 0.7)
		Crude Oil	0.05 (3)	(0.02, 0.07)	0.2 (6)	(0.02, 0.5)
		Gas	0.04 [a] (0)	(0.006, 0.07)	0.3 [a] (0)	(0.07, 0.7)
		Injection, Disposal and Storage	0.04 [a] (1)	(0.006, 0.07)	0.3 [a] (1)	(0.07, 0.7)
		Other	0.04 [a] (0)	(0.006, 0.07)	0.3 [a] (1)	(0.07, 0.7)
	Suspended (Unplugged)	**All**	0.1 (81)	(0.05, 0.3)	76 (98)	(40, 142)
		Crude Oil	0.1 (61)	(0.05, 0.3)	74 (71)	(36, 140)
		Gas	0.001 (8)	(2×10^{-4}, 0.003)	140 (16)	(27, 521)
		Injection, Disposal and Storage	0.3 (10)	(-0.005, 1.1)	0.1 (9)	(0.03, 0.4)
		Other	0.1 [a] (2)	(0.05, 0.3)	76 [a] (2)	(40, 142)

[a] For well type categories where less than 3 measurements are available, well status emission factor is used.

Table S6. Combined (non-surface casing vent and surface casing vent) emission factors and confidence intervals from measurements. The number of measurements for each category are in brackets next to emission factor.

Province	Status	Type	Combined emission factor (kg/y/well)	Lower (L) and Upper (U) 95% CI around mean (L, U) (kg/y/well)	Lower (L) and Upper (U) 95% CI around mean (L, U) (% of mean)
Alberta	**Abandoned (Plugged)**	**All**	8.2 (13)	(1.3, 22)	(-84, 171)
		Crude Oil	8.5 (8)	(1.1, 30)	(-87, 253)
		Gas	13 (3)	(-2x10^{-5}, 38)	(-100, 200)
		Injection, Disposal and Storage	8.2 [a] (1)	(1.3, 22)	(-84, 171)
		Other	8.2 [a] (1)	(1.3, 22)	(-84, 171)
	Suspended (Unplugged)	**All**	779 (111)	(265, 2608)	(-65, 235)
		Crude Oil	345 (53)	(46, 1355)	(-87, 293)
		Gas	1418 (48)	(311, 5772)	(-78, 307)
		Injection, Disposal and Storage	21 (8)	(0.7, 57)	(-96, 169)
		Other	779 [a] (2)	(265, 2608)	(-65, 235)
Saskatchewan	**Abandoned (Plugged)**	**All**	0.3 (8)	(0.08, 0.7)	(-73, 115)
		Crude Oil	0.2 (6)	(0.04, 0.6)	(-83, 147)
		Gas	0.3 [a] (0)	(0.08, 0.7)	(-73, 115)
		Injection, Disposal and Storage	0.3 [a] (1)	(0.08, 0.7)	(-73, 115)
		Other	0.3 [a] (1)	(0.08, 0.7)	(-73, 115)
	Suspended (Unplugged)	**All**	71 (106)	(37, 131)	(-46, 86)
		Crude Oil	70 (75)	(35, 135)	(-50, 93)
		Gas	118 (19)	(22, 448)	(-81, 279)
		Injection, Disposal and Storage	0.4 (10)	(0.04, 1.6)	(-91, 290)
		Other	71 [a] (2)	(37, 131)	(-46, 86)

[a] For well type categories where less than 3 measurements are available, well status emission factor is used.

Table S7. Activity data and emission factors used to estimate non-surface casing vent emissions for wells with surface casing vents in Alberta and Saskatchewan.

Province	Status	Type	Activity data (number of wells with surface casing vent)	Lower (L) and Upper (U) estimate (+ or – 10%) (number of wells with surface casing vent)	Emission factor for non-surface casing vent (non-SCV) (kg/y/non-SCV)
Alberta	**Abandoned (Plugged)**	**Crude Oil**	16 587	(14 929, 18 246)	1.8
		Gas	17 785	(16 006, 19 563)	1.1
		Injection, Disposal and Storage	2273	(2046, 2501)	1.1
		Other	76 619	(68 957, 97 247)	1.1
	Suspended (Unplugged)	**Crude Oil**	31 768	(28 591, 34 944)	15
		Gas	25 149	(22 634, 27 634)	278
		Injection, Disposal and Storage	4406	(3965, 4846)	5.9
		Other	16 910	(15 219, 18 601)	137
Saskatchewan	**Abandoned (Plugged)**	**Crude Oil**	11 643	(10 479, 12 808)	0.2
		Gas	4974	(4477, 5472)	0.3
		Injection, Disposal and Storage	1113	(1002, 1224)	0.3
		Other	5559	(5003, 6115)	0.3
	Suspended (Unplugged)	**Crude Oil**	17 382	(15 644, 19 120)	74
		Gas	3184	(2866, 3503)	140
		Injection, Disposal and Storage	1438	(1294, 1582)	0.1
		Other	11	(10,12)	76

Table S8. Activity data and emission factors used to estimate non-surface casing vent emissions for wells with surface casing vents in rest of Canada.

Province/ Territory	Status	Type	Activity data (number of wells	Lower (L) and Upper (U)	Emission factor for non-surface	Lower (L) and Upper (U) 95% CI around Mean

			with surface casing vent)	estimate (+ or – 10%) (number of wells with surface casing vent)	casing vent (non-SCV) (kg/y/non-SCV)	(L, U) (kg/y/non-SCV)
Ontario	**Plugged**	**Crude Oil**	1358	(1222, 1494)	18	(0.9, 86)
		Gas	3234	(2910, 3557)	18	(0.9, 86)
	Unplugged	**Crude Oil**	1400	(1260, 1540)	88	(8.8, 243)
		Gas	3657	(3291, 4023)	88	(8.8, 243)
Quebec	**Plugged**	**Gas - Other**	403	(363, 443)	32	(7.9, 359)
New Brunswick	**Plugged**	**Crude Oil**	39	(35, 43)	18	(0.9, 86)
		Gas	79	(71, 87)	18	(0.9, 86)
	Unplugged	**Crude Oil**	17	(15, 19)	88	(8.8, 243)
		Gas	31	(28, 34)	88	(8.8, 243)
Manitoba	**Plugged**	**Crude Oil**	1121	(1009, 1233)	0.2	(0.02, 0.5)
	Unplugged	**Crude Oil**	190	(171, 209)	74	(36, 141)
British Columbia	**Plugged**	**Crude Oil**	470	(423, 517)	1.8	(-0.06, 6.8)
		Crude Oil – Other[a]	659	(593, 724)	1.1	(-0.07, 5.1)
		Gas	1757	(1581, 1932)	1.1	(-0.07, 5.1)
		Gas – Other[a]	2464	(2217, 2709)	1.1	(-0.07, 5.1)
	Unplugged	**Crude Oil**	692	(622, 761)	15	(3.2, 45)
		Crude Oil – Other[a]	85	(77, 94)	4.9	(-0.04, 20)
		Gas	2910	(2619, 3201)	278	(11, 1479)
		Gas – Other[a]	360	(324, 396)	4.9	(-0.04, 20)
Northwest Territories	**Unknown**[b]	**Crude Oil**	612	(551, 673)	13	(3, 37)
		Gas	641	(577, 706)	263	(10, 1411)
Yukon	**Plugged**	**Gas**	33	(30, 37)	1.1	(-0.07, 5.1)
	Unplugged	**Gas**	11	(10, 12)	278	(11, 1479)

[a] Crude Oil-Other and Gas-Other emission factors calculated from the arithmetic mean of measurements of wells categorized as injection, disposal and storage and other in this study.

[b] Unknown status emission factor calculated as the arithmetic mean of measurements of all wells (unplugged and plugged) of that well type.

Table S9. Activity data and emission factors used to estimate surface casing vent emissions for wells with surface casing vents in Alberta and Saskatchewan.

Province	Status	Type	Activity data (number of wells with surface casing vent)	Lower (L) and Upper (U) estimate (+ or – 10%) (number of wells with surface casing vent)	Emission factor for surface casing vent (SCV) (kg/y/SCV)
Alberta	**Abandoned (Plugged)**	**Crude Oil**	16 587	(14 929, 18 246)	23
		Gas	17 785	(16 006, 19 563)	23
		Injection, Disposal and Storage	2273	(2046, 2501)	23
		Other	76 619	(68 957, 97 247)	23
	Suspended (Unplugged)	**Crude Oil**	31 768	(28 591, 34 944)	362
		Gas	25 149	(22 634, 27 634)	1326
		Injection, Disposal and Storage	4406	(3965, 4846)	18
		Other	16 910	(15 219, 18 601)	740
Saskatchewan	**Abandoned (Plugged)**	**Crude Oil**	11 643	(10 479, 12 808)	0.05
		Gas	4974	(4477, 5472)	0.04
		Injection Disposal and Storage	1113	(1002, 1224)	0.04
		Other	5559	(5003, 6115)	0.04
	Suspended (Unplugged)	**Crude Oil**	17 382	(15 644, 19 120)	0.1
		Gas	3184	(2866, 3503)	0.001
		Injection, Disposal and Storage	1438	(1294, 1582)	0.3
		Other	11	(10,12)	0.1

Table S10. Activity data and emission factors used to estimate surface casing vent emissions for wells with surface casing vents in rest of Canada.

Province/ Territory	Status	Type	Activity data (number of wells with surface casing vent)	Lower (L) and Upper (U) estimate (+ or – 10%) (number of wells with surface casing vent)	Emission factor for surface casing vent (SCV) (kg/y/SCV)	Lower (L) and Upper (U) 95% CI around Mean (L, U) (kg/y/SCV)
Ontario	**Plugged**	**Crude Oil**	1358	(1222, 1494)	11	(0.01, 43)
		Gas	3234	(2910, 3557)	12	(0.02, 32)
	Unplugged	**Crude Oil**	1400	(1260, 1540)	161	(18, 657)
		Gas	3657	(3291, 4023)	1122	(152, 5279)
Quebec	**Plugged**	**Gas**	403	(363, 443)	12	(0.02, 32)
New Brunswick	**Plugged**	**Crude Oil**	39	(35, 43)	11	(0.01, 43)
		Gas	79	(71, 87)	12	(0.02, 32)
	Unplugged	**Crude Oil**	17	(15, 19)	161	(18, 657)
		Gas	31	(28, 34)	1122	(152, 5279)
Manitoba	**Plugged**	**Crude Oil**	1121	(1009, 1233)	0.05	(0.02, 0.07)
	Unplugged	**Crude Oil**	190	(171, 209)	0.1	(0.05, 0.3)
British Columbia	**Plugged**	**Crude Oil**	470	(423, 517)	23	(-0.01, 50)
		Crude Oil – Other[a]	659	(593, 724)	23	(-0.01, 50)
		Gas	1757	(1581, 1932)	23	(-0.01, 50)
		Gas – Other[a]	2464	(2217, 2709)	23	(-0.01, 50)
	Unplugged	**Crude Oil**	692	(622, 761)	362	(40, 1454)
		Crude Oil – Other[a]	85	(77, 94)	14	(0.7, 41)
		Gas	2910	(2619, 3201)	1326	(179, 6222)
		Gas – Other[a]	360	(324, 396)	14	(0.7, 41)

Northwest Territories	**Unknown**[b]	**Crude Oil**	612	(551, 673)	349	(39, 1382)
		Gas	641	(577, 706)	1269	(174, 5984)
Yukon	**Plugged**	**Gas**	33	(30, 37)	23	(40, 1454)
	Unplugged	**Gas**	11	(10, 12)	1326	(179, 6222)

[a] Crude Oil-Other and Gas-Other emission factors calculated from the arithmetic mean of measurements of wells categorized as injection, disposal and storage and other in this study.

[b] Unknown status emission factor calculated as the arithmetic mean of measurements of all wells (unplugged and plugged) of that well type.

Table S11. Activity data and emission factors used calculate upper and lower estimates of emissions from wells without surface casing vents in Alberta and Saskatchewan

Province	Status	Type	Activity data (number of wells with surface casing vent)	Lower (L) and Upper (U) estimate (+ or – 10%) (number of wells with surface casing vent)	Emission factor for lower estimate [a] (kg/y/well)	Emission factor for upper estimate [b] (kg/y/well)
Alberta	**Abandoned (Plugged)**	**Crude Oil**	15 311	(13 780, 16 843)	1.8	8.5
		Gas	16 416	(14 775, 18 059)	1.1	13
		Injection, Disposal and Storage	2099	(1889, 2308)	1.1	8.2
		Other	70 725	(63 652, 777 98)	1.1	8.2
	Suspended (Unplugged)	**Crude Oil**	3926	(3534, 4319)	15	345
		Gas	3108	(2797, 3419)	278	1418
		Injection Disposal and Storage	545	(490, 599)	5.9	21
		Other	2090	(1811, 2299)	137	779

Saskatchewan	**Abandoned (Plugged)**	**Crude Oil**	10 748	(9673, 11 822)	0.2	0.2
		Gas	4591	(4132, 5051)	0.3	0.3
		Injection Disposal and Storage	1027	(924, 1129)	0.3	0.3
		Other	5131	(4618, 5644)	0.3	0.3
	Suspended (Unplugged)	**Crude Oil**	2148	(1933, 2363)	74	70
		Gas	394	(354, 433)	140	118
		Injection, Disposal and Storage	178	(160, 196)	0.1	0.4
		Other	1	(1,2)	76	70

[a] Lower estimate emission factors are the same as non-surface casing vent emission factors presented in Table S5.

[b] Upper estimate emission factors are the same as combined emission factor presented in Table S6.

Table S12. Activity data and emission factors used calculate upper and lower estimates of emissions from wells without surface casing vents in Alberta and Saskatchewan

Province/ Territory	**Status**	**Type**	**Activity data (number of wells with surface casing vent)**	**Lower (L) and Upper (U) estimate (+ or – 10%) (number of wells with surface casing vent)**	**Emission factor for lower estimate (kg/y/well)[a]**	**Emission factor for upper estimate (kg/y/well)[b]**
Ontario	**Plugged**	**Crude Oil**	1254	(1128, 1379)	18	18
		Gas	2985	(2687, 3284)	18	18
	Unplugged	**Crude Oil**	173	(156, 190)	88	88
		Gas	452	(407, 497)	88	88
Quebec	**Plugged**	**Gas**	372	(335, 409)	32	32
New Brunswick	**Plugged**	**Crude Oil**	36	(32, 40)	18	18
		Gas	73	(66, 80)	18	18
	Unplugged	**Crude Oil**	2	(1, 3)	88	88
		Gas	4	(3, 5)	88	88

Manitoba	**Plugged**	**Crude Oil**	1034	(931, 1138)	0.2	0.2
	Unplugged	**Crude Oil**	23	(21, 25)	74	70
British Columbia	**Plugged**	**Crude Oil**	433	(390, 477)	1.8	8.5
		Crude Oil – Other[c]	608	(547, 669)	1.1	8.2
		Gas	1621	(1459, 1784)	1.1	13
		Gas – Other[c]	2274	(2047, 2501)	1.1	8.2
	Unplugged	**Crude Oil**	85	(76, 94)	15	345
		Crude Oil – Other[c]	11	(10, 12)	4.9	17
		Gas	359	(324, 395)	278	1418
		Gas – Other[c]	44	(40, 49)	4.9	17
Northwest Territories	**Unknown[d]**	**Crude Oil**	100	(90, 110)	13	292
		Gas	104	(94, 115)	263	1299
Yukon	**Plugged**	**Gas**	31	(28, 34)	1.1	13
	Unplugged	**Gas**	1	(1, 1)	278	1418

[a] Lower estimate emission factors for all provinces except for Ontario, Quebec and New Brunswick are from the non-surface casing vent emission factors presented in Table S5.

[b] Upper estimate emission factors for all provinces except for Ontario, Quebec and New Brunswick are from combined emission factors presented in Table S6.

[c] Crude Oil-Other and Gas-Other emission factors calculated from the arithmetic mean of measurements of wells categorized as injection, disposal and storage and other in this study.

[d] Unknown status emission factor calculated as the arithmetic mean of measurements of all wells (unplugged and plugged) of that well type.

Table S13. Total lower emission estimate per province/territory. Provinces/territories are in order of greatest to least combined annual methane emissions.

Province/Territory	Annual methane emissions from non-surface casing vents[a] (kt)	Annual methane emissions from surface casing vents (kt)	Combined annual methane emissions (kt)	Lower (L) and upper (U) uncertainty range for combined emissions (L, U) (kt)	Lower (L) and upper (U) uncertainty range for combined emissions (L, U) (%)
All provinces/ territories	15	70	85	(11, 407)	(-87, 380)
Alberta	11	60	71	(8.9, 344)	(-88, 382)
British Columbia	0.9	4.2	5.1	(0.5, 27)	(-90, 417)
Ontario	0.7	4.4	5.0	(0.6, 25)	(-89, 391)
Saskatchewan	2.0	0.003	2.0	(0.7, 5.1)	(-63, 162)
Northwest Territories	0.2	1.0	1.2	(0.1, 5.6)	(-90, 416)
New Brunswick	0.009	0.04	0.05	(0.005, 0.2)	(-89, 387)
Quebec	0.03	0.005	0.03	(0.005, 0.)	(-82, 975)
Yukon	0.003	0.01	0.02	(0.002, 0.09)	(-90, 417)
Manitoba	0.02	8×10^{-5}	0.02	(0.007, 0.03)	(-57, 112)

[a] Includes non-surface casing vent emissions of wells with surface casing vents and emissions from wells without surface casing vents.

Table S14. Total upper emission estimate per province/territory. Provinces/territories are in order of greatest to least combined annual emissions.

Province/Territory	Annual emissions from non-surface casing vents[a] (kt)	Annual methane emissions from surface casing vents (kt)	Combined annual methane emissions (kt)	Lower (L) and upper (U) uncertainty range for combined emissions (L, U) (kt)	Lower (L) and upper (U) uncertainty range for combined emissions (L, U) (%)
All provinces/ territories	23	70	93	(13, 436)	(-86, 373)
Alberta	18	60	78	(10, 371)	(-87, 374)
British Columbia	1.4	4.2	5.7	(0.6, 29)	(-89, 408)
Ontario	0.7	4.4	5.0	(0.6, 25)	(-89, 391)
Saskatchewan	1.9	0.003	1.9	(0.7, 5.1)	(-63, 162)
Northwest Territories	0.3	1.0	1.2	(0.1, 6.2)	(-88, 403)
New Brunswick	0.01	0.04	0.05	(0.005, 0.2)	(-89, 387)
Quebec	0.03	0.005	0.03	(0.005, 0.3)	(-82, 975)

Yukon	0.005	0.01	0.02	(0.002, 0.1)	(-89, 406)
Manitoba	0.02	$8x10^{-5}$	0.02	(0.007, 0.03)	(-57, 112)

[a] Includes non-surface casing vent emissions of wells with surface casing vents and emissions from wells without surface casing vents.

Table S15. Average methane emissions per abandoned oil and gas well of provincial sub-regions.

Province	Sub-region	Well count	Average methane emission rate per abandoned oil and gas well (kg/y/well)
Alberta	Lloydminster	43	$4.2x10^{2}$
	Grande Prairie	11	$5.2x10^{3}$
	Red Deer	49	$3.7x10^{1}$
	Medicine Hat	21	$4.2x10^{2}$
Saskatchewan	Lloydminster	30	$1.8x10^{2}$
	Kindersley	19	$6.1x10^{1}$
	Estevan	32	$2.0x10^{0}$
	Swift Current	33	$2.3x10^{1}$

SI-5: References for Supporting Information

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