Toward a better understanding of methane emissions from individual energy wells in Canada

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Abstract

To meet the Federal and Alberta governments' climate goals of reducing methane emissions by 45% below 2012 levels by 2025, a better quantification of methane emissions from energy sector wells is needed. The two main forms of fugitive natural gas emissions from these individual wells are gas migration (GM) and surface casing vent flow (SCVF). Emissions estimates for methane, including those employed by federal and provincial governments are under scrutiny and considered unreliable. These 'bottom-up' emission estimates are self-reported industry values and are incongruent with academia-performed 'top-down' emission estimates. A recent review of Alberta energy sector wells using the Alberta Energy Regulator's own statistics derived from 'bottom-up' industry self-reporting claim only 5.63% of all energy in the province have GM/SCVF problems. This contrasts with a 2017 'top-down' aerial survey of two regions in Alberta finding discrepancies of 17 times and 5 times greater emissions than industry self-reported data. Additionally, a 2017 'top-down' study of tight-gas Montney wells in northeast BC found 47% of wells to be leaking methane. A clear disconnect is evident with respect to emissions derived from industry and independently reported values. The disconnect is not necessarily the product of 'bottom-up' versus 'top-down' methods, but potentially, that two different groups typically perform these surveys. It is therefore recommended further studies be done to harmonize the discrepancies between 'top-down' and 'bottom-up' derived methane emission estimates. Additionally, it is recommended access to energy wells be granted to independent or regulator surveyors to potentially more accurately quantify their methane emissions.

1.0 Introduction

As a means of mitigating the potentially devastating global effects of anthropogenic climate change, Canada set a bold target of reducing methane emissions from its oil and gas industry to 40-45% below 2012 levels by 2025 (*1*). Fugitive gas emissions from low-permeability reservoirs can be emitted from a well as surface casing vent flow (SCVF) or from the area around a well as gas migration (GM). Quantifying and reducing these fugitive emissions is critical when considering natural gas (NG), whose main component is methane (~90%), as a bridge fuel from more CO_2-intensive fossil fuels such as oil and coal (*2*). Post-combustion, methane emits only ~50% of the CO_2 that coal produces and 73% of what oil (diesel) produces (*3*). However, due to methane's global warming potential (GWP) of 25 times that of CO_2 over a 100 year period (*4*), fugitive methane emissions must be held below 3.6% of total emissions to achieve net CO_2 savings benefits over coal and 0.8% for diesel (*2*). With rates of gas production volumes from geologic reservoirs expected to rise 25% over 2013 volumes by 2035 (*5*), current fugitive emissions must be accurately quantified and reduction techniques must be implemented.

Fugitive gas emissions from leaking wells in the oil and gas sector have been challenging to quantify, and are therefore poorly constrained and likely heavily underestimated (*6*). To achieve Canada's methane reduction goal, a strong understanding of current baseline emissions is needed to determine when/if that goal will be achieved. Governments in Alberta and British Columbia have been pursuing studies and legislation with the aim of better characterizing these baseline emissions. However, there remains a lack of regulation regarding the collection of a robust data set that accurately characterizes methane emissions data.

This paper's goals are to: (1) determine the major sources of methane emissions associated with the shale gas industry from energy wells; and (2) determine the reliability of current estimates and characterization methods of fugitive gases in the shale gas industry and identify potential improvements in quantification methods.

2.0 Sources and Causes of Fugitive Gas Emissions at Individual Wells

There are two forms of fugitive gas emissions from individual energy-related wells (conventional and unconventional oil, gas, water sourcing, produced fluid injection) discussed in this paper: (1) gas migration (GM), when gas migrates up the well bore (in- or outside of the casing) and then migrates outside the casing and cement sheath into adjacent rock formations and aquifers, and can potentially flux across the surface/atmosphere interface (*7*, *8*); and (2) surface casing vent flow (SCVF), a net flux of gas up the well bore inside the surface casing which is vented to atmosphere through the surface casing assembly (*7*)(Figure 1).

Methane found as SCVF and/or GM is not necessarily the result of oil and gas activity. In large parts of Alberta, biogenic methane (BM) produced by methanogenic bacteria under highly reducing conditions is ubiquitous in shallow groundwater (*7*, *9*). Fortunately, in many instances, methane sources can be isolated based on their carbon isotopic signatures, or $\delta^{13}C_{CH4}$ values. Generally, a $\delta^{13}C_{CH4}$ less than roughly -60‰ is associated with BM, whereas a $\delta^{13}C_{CH4}$ greater than roughly -60‰ is attributed to thermogenic methane (TM), which is methane produced by the cracking of organic-rich material in deep geological source rocks under high pressure and temperature (*9*)(*10*). Using a "gas wetness factor" (GWF) can also assist in differentiating BM from TM. Ethane and higher alkanes only occur in conjunction with TM, as biogenic bacteria cannot synthesise higher alkanes, only methane (*11*).

$$GWF = \frac{C2 + C3 + iC4 + nC4 + C5}{C1 + C2 + \cdots + C5}$$

Where C1 is methane, C2 is ethane, C3 is propane, etc. If this ratio is close to zero, BM is likely present; otherwise, TM is likely present. Interestingly, not all TM is anthropogenic, even when in proximity to current or previous energy activity. TM has been documented worldwide to occur naturally in the form of seeps into underlying fresh groundwater, surface waters, and atmosphere (*12, 13*, *14*). The gas migrates upward from gas-charged formations due to buoyancy and pressure differences, typically through more permeable rock, along natural fracture and fault networks (*12*). It is therefore critical to perform baseline testing of soil and aquifer methane concentrations prior to hydrocarbon exploration/exploitation to differentiate anthropogenic and natural methane concentrations.

Individual energy wells are significant sources of methane emissions, with methane composing 0.6-7.7% of total emissions for each well's lifetime (*15*). Methane emissions typically stem from loss of well integrity. Davis et al. describe 7 main paths for GM/SCVF: (1) between the casing and encompassing cement, (2) between the casing and the cement plug, (3) directly through the cement plug, (4) through shears in the casing or well bore, (5) between the cement and adjacent rock formation, (6) through the cement between linking cavities from the casing side of the cement to the annulus side of the cement, and (7) through the cement between casing and adjacent rock formation (*16*)(Figure 2).

Bachu found numerous trends in which wells appear more susceptible to GM/SCVF, based on an analysis of Albertan wells (*7*). While all forms of wells (vertical, deviated, horizontal, thermal, etc.) can suffer leakage, certain types appeared particularly susceptible. Chief amongst them were thermal wells (wells using steam to produce heavy oil), composing 45.9% of all reported SCVF/GM positive wells in Alberta, despite being <25% of total wells. Interestingly, increased concentrations and rates of GM/SCVF due to methanogenic bacteria were noted at numerous thermal well sites. Heat from thermal wells increased the metabolic rates of proximal methanogenic bacteria (*7*). This led to anthropogenically enhanced concentrations of naturally occurring BM (*7*).

Cementing length also affects well integrity. However, whether a well was cemented to surface or not only appears statistically significant in instances of SCVF, not GM (*7*). This contrasts with Watson and Bachu findings of greater instances of SCVF and GM with wells not fully cemented over their entire length (*17*). Well orientation (vertical or horizontal) also proved statistically uncorrelated to SCVF/GM. Bachu could not conclude if age played a significant role in the number of SCVF/GM instances (*7*). However, normalizing observed SCVF/GM instances to total drilled wells from a given period could produce correlations. When well integrity failure of older wells occurred, it was attributed to age of the well's cement, period technology, and looser regulations surrounding drilling, casing, and cementing (*7*, *12*).

This matches findings identifying cement shrinkage over time as a common phenomenon that negatively impacts the seal quality between the casing and adjacent rock formation, creating conduits within the annulus (*12*). Boothroyd et al. noted the age of a well did not correspond to higher fluxes of SCVF/GM (*18*). However, they determined age was a factor in the number of leaking wells, finding over 75% of wells drilled from 1930-1939 leaked, while less than 50% of wells drilled between 1990 and 2009 leaked (*18*)(Figure 3).

In the overwhelming majority of SCVF/GM instances, the fugitive gas is sourced from the intermediate zone, rather than the production zone (*7*)(Figure 1). Of the 3726 Alberta wells Bachu found with GM, only eight had fugitive gas sourced from a horizon greater than 95% of total depth (*7*). This corresponds with Dusseault and Jackson's observations that multiple-stage hydraulic fracturing of horizontal wells does not affect the likelihood of the well suffering from GM (*12*). They determined the hydraulic fracturing and completion components of bringing a well on production was too distal to the vertical component of the well to induce gas migration (*12*).

3.0 Methods for Estimating Fugitive Emissions

There are two methods for estimating individual well fugitive emissions: bottom-up and top-down. Bottom-up measurements are performed at the well head and in Alberta are measured using the Alberta Energy Regulator's (AER) Directive 20 (D-20) approved GM survey and SCVF flow rate quantifying methods. Approved GM surveys can be simple non-ground disturbing hand-held gas composition/concentration meters measuring only near-ground atmospheric gas concentrations. In the more robust D-20 recommended GM survey, soil gas probes are driven into the soil to measure soil gas concentrations at 50cm depth in a perpendicular cross-pattern 2m, 4m, 6m from the well head, and two samples are taken 30cm from the well head on opposite sides of the well head. Bottom-up methods provide a precise location and accurate measurement of emissions from discrete locations. However, they can be unreliable for characterizing emissions from an areally or linearly continuous source such as the area surrounding a well or pipeline infrastructure.

Top-Down methods use ground-based or airborne remote sensing equipment such as portable spectroscopes to measure methane concentrations in the atmosphere, which are then used with meteorological data and numerical models to estimate fluxes (*1*, *5*, *15*). Top-down methods are best at characterizing concentrations from multiple sources within a small area, however they struggle to identify precise leak locations.

4.0 Individual Well Leakage Rates

Bachu, using the AER's database of self-reported instances of GM/SCVF, found 0.73% (3726 wells) of all oil and gas wells (446,289) in Alberta have GM, and 4.9% have SCVF (*7*). Johnson et al. performed aerial surveys over the Red Deer region (50km x 50km) and found methane fluxes 17 times higher than self-reported data but on par with government estimates (*1*). They performed a similar survey over the Lloydminster region (60km x 60km), finding methane fluxes 5 times greater than self-reported data and 3 times greater than government estimates. The surveys focused on all upstream energy sector infrastructure, not just individual wells. However, assuming similar trends for all Alberta oil and gas wells, it shows GM/SCVF from individual wells is likely significantly greater than currently reported, calling into question Bachu's values. In Northeast BC, Atherton et al. surveyed 1481 wells and found 47% leaked methane (*5*)(Figure 4). Note, the survey did not directly measure methane fluxes at the well, but instead sampled the well's likely methane plume (*5*).

In a study of UK on-shore energy wells, Boothroyd et al. reviewed 102 wells that had been properly abandoned to current regulations and found 31 wells (30%) had GM rates significantly greater than adjacent control fields (*18*). Interestingly, 39 wells had lower methane concentrations than their control sites.

Studies by different parties (*5*, *7*, *18*, *19*) have shown a range of 6-47% of wells suffer gas leakage. The true number of leaking wells is likely somewhere in the middle of that range.

5.0 Individual Well Emission Rates Estimates

In Alberta, government data on emission flux rates are almost entirely sourced from industry self-reports and are not published (*7*, *20*). Johnson et al. measured fluxes of 3.05 tCH_4/h and 24.1 tCH_4/h for their Red Deer and Lloydminster region surveys, respectively (*1*)(Figure 5). Recall that these values are for all upstream activity and not just GM/SCVF emissions. For comparison, Caulton et al. analyzed a 2800km^2 region of the Pennsylvanian Marcellus Shale and found methane emissions of 7.2-50.4 $tCH_4/h/km^2$ (*15*). Again, these values are for all energy sector activity in the surveyed area.

For Boothroyd's UK study, methane fluxes were modelled on average to emit 364 ± 677 kg CO_{2eq}/well/year, or 15 ± 27 kg CH_4/well/year, assuming a 25:1 $CO_{2eq}:CH_4$ relationship (*18*). Boothroyd's wide spread is due to a few wells with high methane fluxes and 38% of wells being net methane sinks. This large spread indicates that each well needs to be assessed individually to identify high emitters, rather than rely on an average of all wells.

6.0 Methane Emission Estimates Reliability

The understanding surrounding GM/SCVF emissions estimates is poorly constrained. The Conference Board of Canada emissions estimates of SCVF/GM are not categorized separately, but instead lumped in as 'fugitive' emissions (*7*, *21*). This government data is based on bottom-up self-reporting from industry that is now considered to be a gross underrepresentation of NG GM/SCVF emissions from the oil and gas industry (*1*, *5*, *20*). This means Bachu's value of 5.63% of Alberta's wells suffering GM/SCVF likely greatly underestimates the true pervasiveness of GM/SCVF, (*7*). In Alberta, only wells within the Required Testing Area (RTA) require bottom-up GM testing following rig release; all other locations only need testing upon abandonment (*7*, *20*). However, the RTA covers <10% of Alberta, and outside of this area wells are only GM tested if the well owner desires – most wells are never tested prior to abandonment. The RTA comprises 6.2% of the total energy wells drilled after 1995 in Alberta, and Bachu reported 2185 wells (66.7% of all 3276 GM wells) testing positive for GM occurred in the RTA (*7*, *20*). If 66.7% of positive wells occur in an area covering only 10% of Alberta's land, it is reasonable to infer that total GM/SCVF positive wells, and therefore emissions, are likely underestimated.

Individual flow rates for a well's SCVF are simple to measure at the source (bottom-up); however, well owners in nearly all instances will not allow academic monitoring and disclosure of their well's fugitive emissions (*20*, *22*). Instead, top-down aerial and off-lease ground surveys are used to assess fugitive emissions. Following publication of studies using these remote sensing/top-down techniques finding 5-7 times greater emissions at upstream sites than from self-reported data, and findings indicating 47% of wells surveyed in NE BC leak, it is clear that self-reported data is incongruent with top-down emission estimates (*1*, *5*, *7*).

7.0 Conclusions

Numerous factors lead to well integrity failure causing GM/SCVF. However, hydraulic fracture stimulation is not a significant contributor. Instead, it is likely poor cement coverage in the well, selection of cement with physical and chemical properties ill-suited for the well bore, and the cement's natural propensity to shrink and degrade over time, creating various conduits for gas to migrate up the wellbore/casing.

Further refinement is needed to harmonize existing differences between top-down and bottom-up methane flux assessments for individual well sites in the oil and gas sector. Top-down methane emissions estimates from these sites are far greater than their current bottom-up self-reported industry values. It is therefore recommended that further studies of top-down and bottom-up approaches be pursued to reconcile these two characterizations of methane emissions. Crucially, this will allow governments to know the extent of methane emissions and set and meet accurate goals for methane reductions. Additionally, it is highly recommended the RTA be expanded to cover all of Alberta and GM/SCVF testing be required on all non-abandoned wells. This is a relatively simple way to get more accurate bottom-up data for all future wells in Alberta. As this data would be self-reported by industry, it is essential that government inspectors follow up with their own emissions testing to ensure compliance.

8.0 Figures

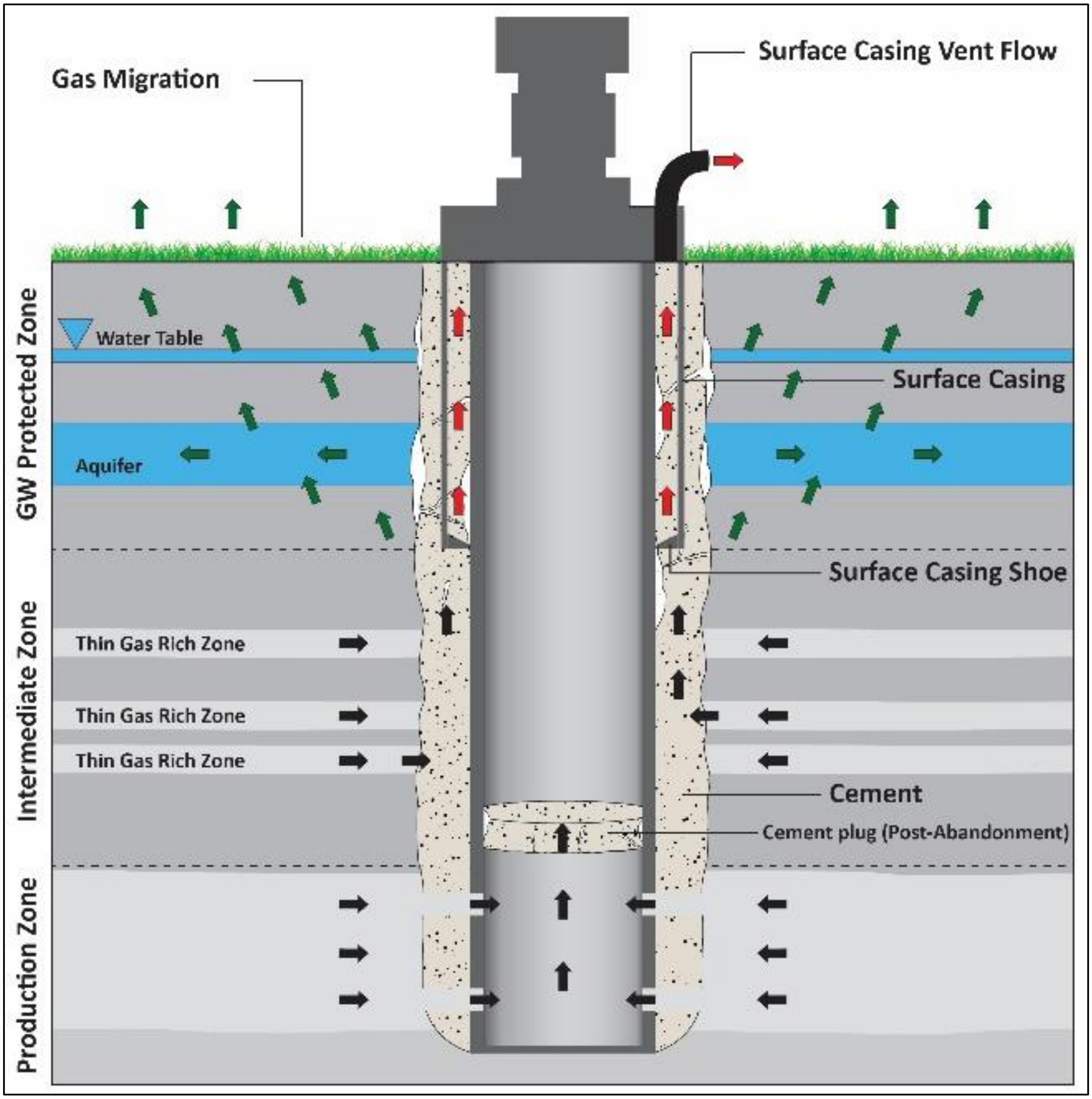

Figure 1. Black arrows show natural gas entering the well bore, both from the production zone and intermediate zone, where they travel up the well bore's annulus or inside the production/intermediate casing. These natural gas molecules can then migrate out into the adjacent rock, soil, or aquifers and be emitted as gas migration (green arrows) or continue up within the surface casing and be emitted from the surface casing vent assembly as surface casing vent flow (red arrows). Gas migration can stay in the rock, soil or aquifers or flux across the soil/atmosphere boundary into the atmosphere.

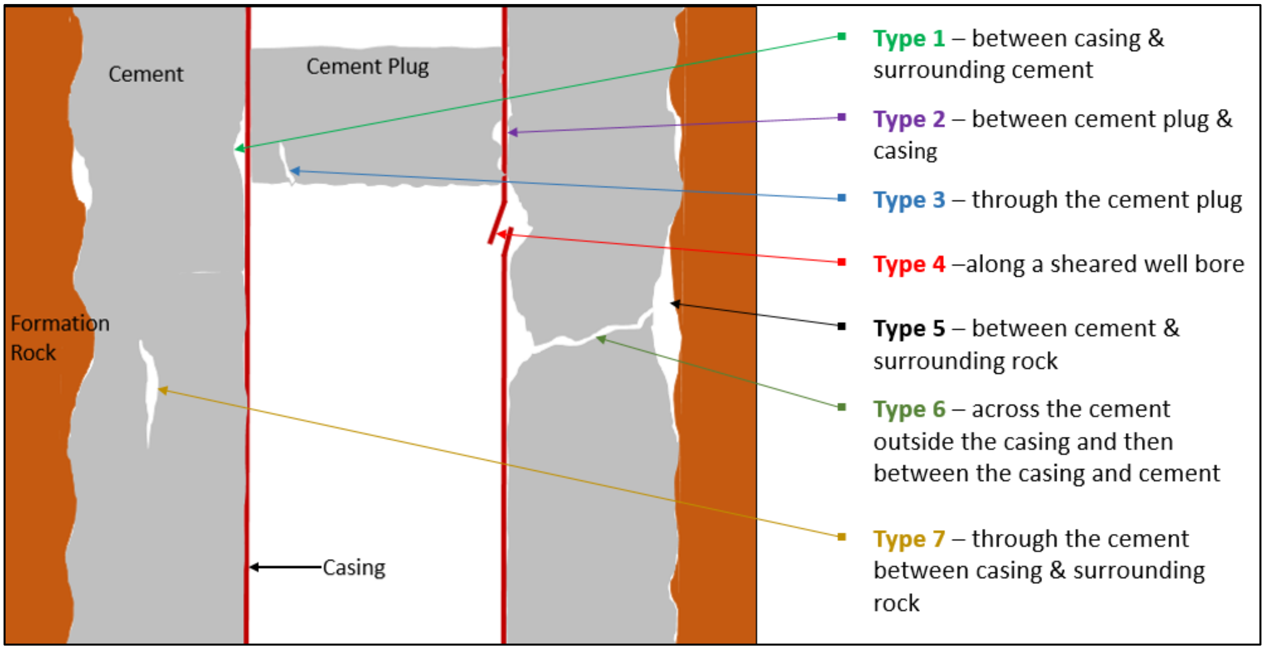

Figure 2. Showing the seven main conduits in an energy well through which GM/SCVF occurs.

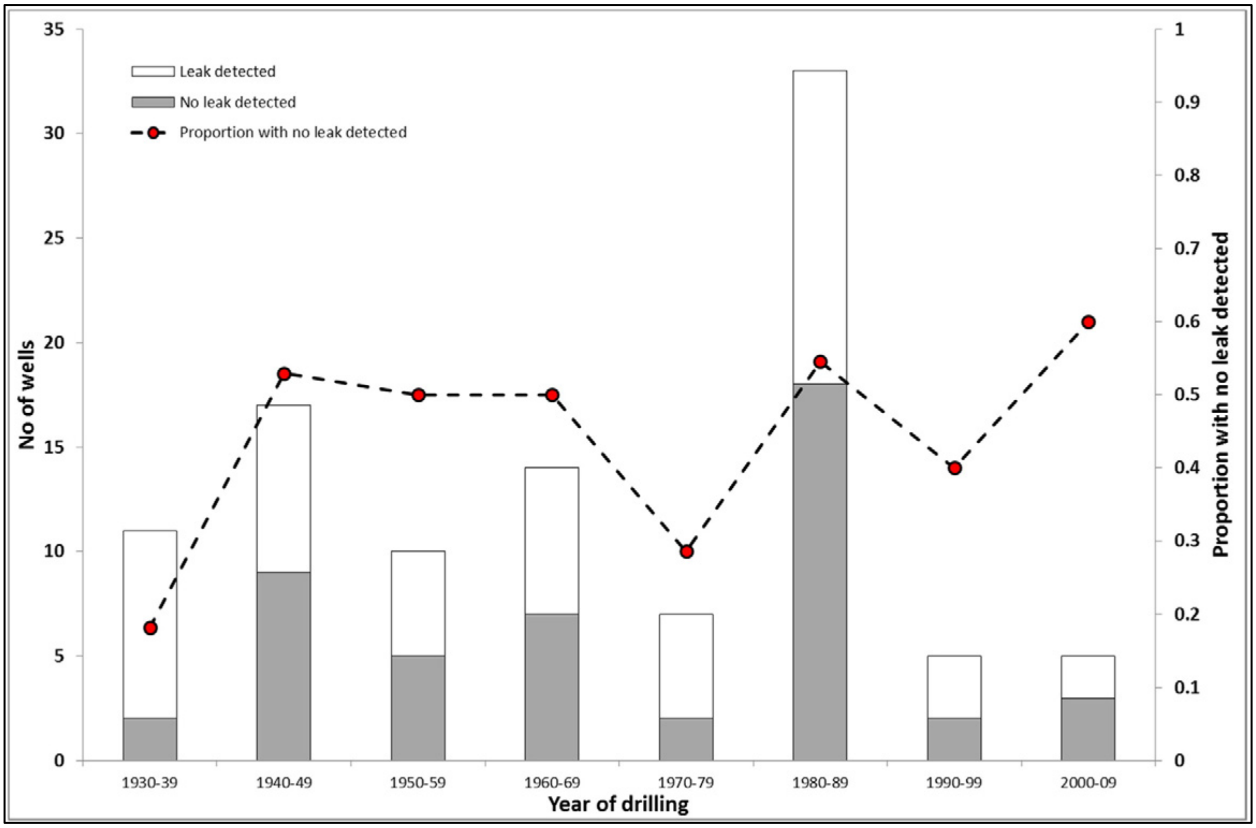

Figure 3. From Boothroyd et al. (*18*). Showing the number of wells surveyed (total height of column) based on the well's age (year drilled). The grey indicates the number of wells drilled that decade that were not detectably leaking when surveyed. Red circles indicate the percentage of wells surveyed from that decade that did not detectably leak when surveyed.

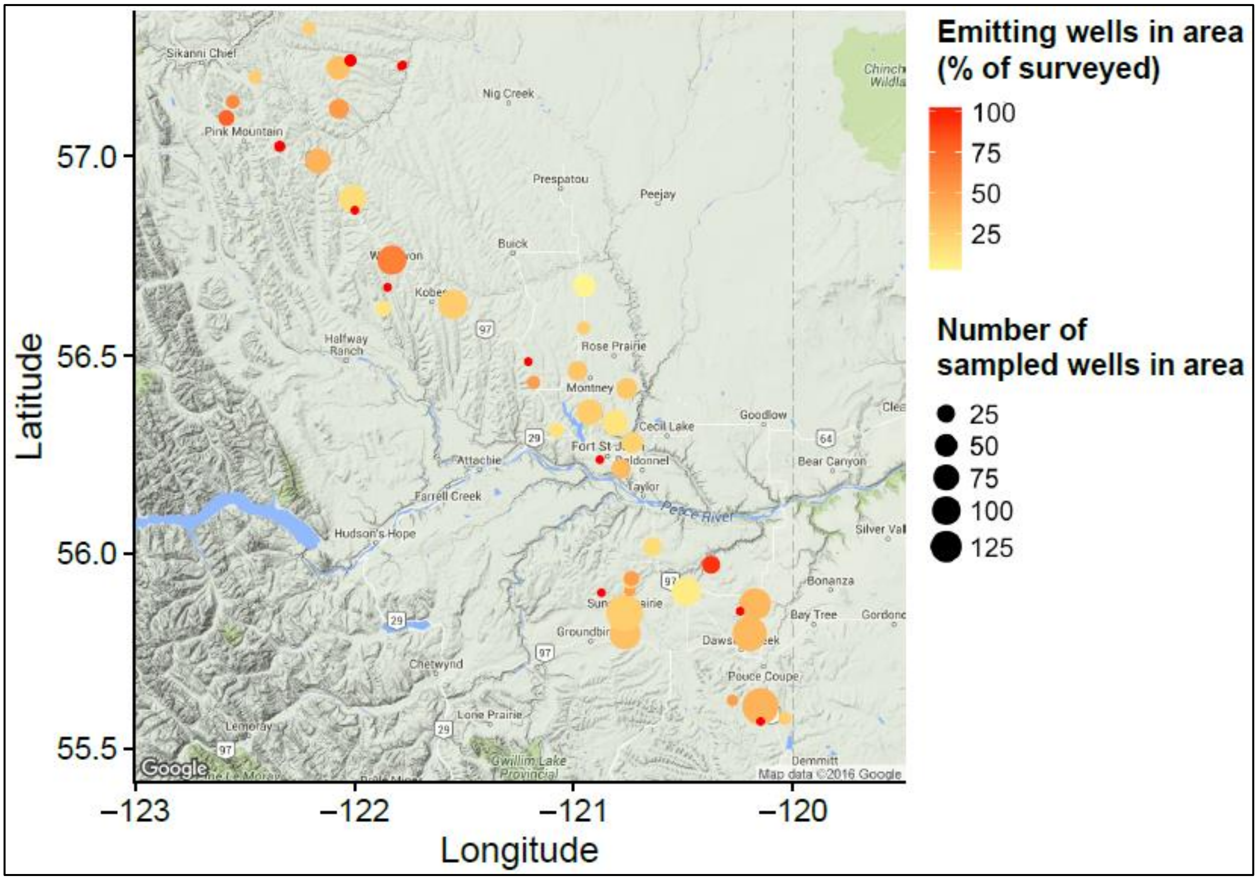

Figure 4. From Atherton et al. (*5*). Showing the number of wells indirectly surveyed, the percentage of those wells emitting methane, and their general location in NE BC(*5*).

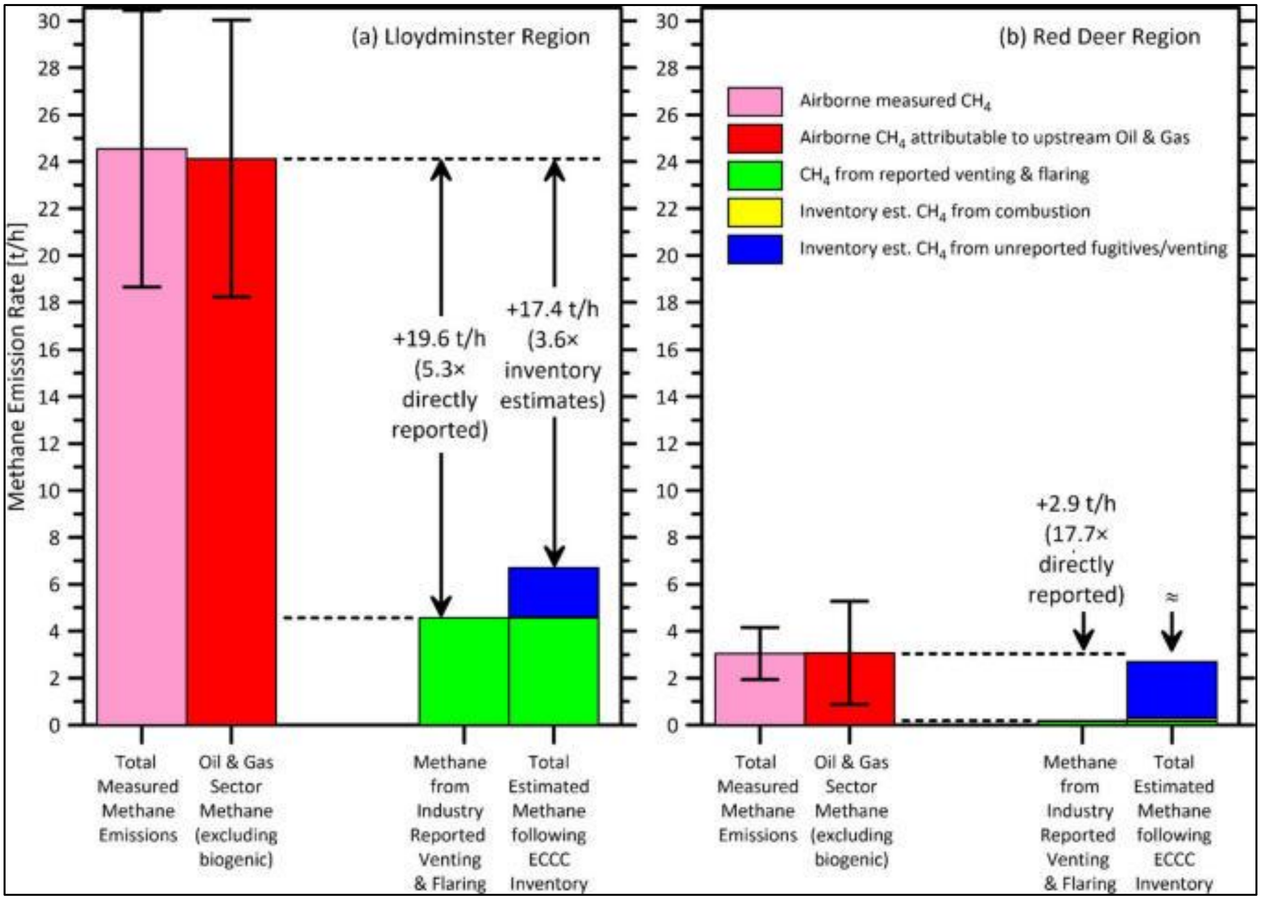

Figure 5. From Johnson et al., (*1*). Showing the flux of methane from the Lloydminster study area (a) and the Red Deer study area (b). Of note for (a), oil and gas sector methane emissions surveyed were 5.3 times greater than industry self-reported values and 3.6 times greater than Environment and Climate Change Canada's (ECCC) estimates. For (b), where GM testing is not mandatory prior to abandonment, emissions were 17.7 times greater than industry self-reported values, and in line with ECCC estimates.

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