Greenhouse Gas Footprint of Oilfield Flares Accounting for Realistic Flare Gas Composition and Distribution of Flare Efficiencies

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The greenhouse gas footprint of oilfield flares comprises carbon dioxide and uncombusted hydrocarbons. It has been broadly assumed that oilfield flares are 98% efficient, and that the unburned fraction is predominantly methane. Recent studies have shown that neither assumption is necessarily true. Gas associated with tight oil production, now the largest source of flared gas in the United States, is a mixture of hydrocarbons in which methane is not necessarily more than half the total. Aerial surveys have found that while many flares function efficiently, a substantial fraction are very inefficient. This work builds on those studies to show how greenhouse gas footprints can be computed when flared gas is a mixture of hydrocarbons, and when flare efficiencies are best represented as statistical distributions. This work finds that the best estimate of GHG footprint of current Bakken oilfield flares is 56,400 tonnes carbon dioxide equivalent per day, compared to an estimate of 31,400 tonnes carbon dioxide equivalent per day under the assumption of 100% methane flares operating at 98% efficiency. Both these estimates considerably exceed the expected GHG footprint for flares based on data from the Environmental Protection Agency Greenhouse Gas Reporting Program.

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The greenhouse gas footprint of oilfield flares comprises carbon dioxide and uncombusted hydrocarbons. It has been broadly assumed that oilfield flares are 98% efficient, and that the unburned fraction is predominantly methane. Recent studies have shown that neither assumption is necessarily true. Gas associated with tight oil production, now the largest source of flared gas in the United States, is a mixture of hydrocarbons in which methane is not necessarily more than half the total. Aerial surveys have found that while many flares function efficiently, a substantial fraction are very inefficient. This work builds on those studies to show how greenhouse gas footprints can be computed when flared gas is a mixture of hydrocarbons, and when flare efficiencies are best represented as statistical distributions. This work finds that the best estimate of GHG footprint of current Bakken oilfield flares is 56,400 tonnes carbon dioxide equivalent per day, compared to an estimate of 31,400 tonnes carbon dioxide equivalent per day under the assumption of 100% methane flares operating at 98% efficiency. Both these estimates considerably exceed the expected GHG footprint for flares based on data from the Environmental Protection Agency Greenhouse Gas Reporting Program.

Introduction

Flaring from natural gas and petroleum systems is an important challenge to greenhouse gas mitigation. The World Bank estimates that, globally, flares combusting 145 billion cubic meters (5.12 trillion cubic feet) of natural gas account for 350 million tons of carbon dioxide equivalent emissions each year, with U.S. emissions having increased by 48% from 2017 to 2018 [World Bank, 2019].

Flares are an important element of crude oil and natural gas production. To protect health and safety, flammable and toxic vapors that cannot be collected or stored are burned to prevent their accumulation. When flares operate at 100% efficiency, hydrocarbons found in raw natural gas – principally methane, ethane, propane, and butane – are converted to carbon dioxide and water, which are neither flammable nor toxic.

Bunsen burners found in school laboratories, and common gas-fired domestic appliances such as stove tops and water heaters, must operate at or near 100% efficiency in order to prevent the

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accumulation of dangerous gases in schools and homes [Merrin and Francisco, 2019]. An efficient burner of natural gas is characterized by a compact conical blue flame, while inefficient burners are characterized by shapeless and frequently unstable yellow flames [Socratic, 2015]. Oilfield flares rarely operate at or near 100% efficiency. During his career in the oil and gas industry, the author has frequently observed flares having shapeless, unstable, yellow flames. Examples abound in the press [Texas Tribune, 2019]. When flares operate at reduced efficiency, they emit carbon monoxide, particulate matter in the form of black carbon, and hydrocarbon gases.

Whereas carbon dioxide is the most important greenhouse gas, short-lived climate pollutants such as methane and black carbon have a disproportionate effect on climate [IPCC, 2013]. Although their lifetime in the atmosphere is considerably shorter than that of carbon dioxide, their intrinsic radiative forcing is orders of magnitude larger [Alvarez et al., 2012]. This implies that the reduction of methane and black carbon emissions is the easiest way to change the trajectory of global climate change [Shindell et al., 2012; Shindell et al., 2017].

Previous work has shown that fugitive emissions of short-lived climate pollutants from flares has been underestimated [Gvakharia et al., 2017]. In this work, I calculate the greenhouse gas footprint of flare inefficiency in the Bakken play of North Dakota. To do this, I take into account the actual composition of the field gas being flared and the greenhouse gas effect of each component of that gas. Using the data of Gvakharia et al., I find the fraction of flares that can be classed as super-emitters. I comment on the problem of flares which fail to be ignited, thereby venting raw field gas directly to the atmosphere. Finally, I compare the greenhouse gas emissions calculated in this work to Environmental Protection Agency estimates.

Methods

Note on Units

In reporting volumes of gas, this paper follows the convention of the U.S. petroleum industry [API, 2014; EIA, 2019]. Quantities of natural gas and its constituents are reported in terms of *standard cubic feet* (scf). Gas volumes depend on temperature and pressure; oilfield standard conditions are 60°F (15.556°C = 288.706 K) and 14.73 psia (101.560 kPa). The density of methane at U.S. oilfield standard conditions is 19.215 g/scf. Mscf denotes one thousand standard cubic feet; MMscf denotes one million standard cubic feet.

Outside the United States, gas quantities are commonly reported by the petroleum industry in terms of *standard cubic meters* (Sm^3 or scm), with standard temperature and pressure defined to be 15°C (288.150 K) and 101.325 kPa [Natural Resources Canada, 2016]. The density of methane at international standard conditions is 678.37 g/scm. Standard conditions have been selected so that when converting from scf to scm, merely applying the conversion factor relating cubic feet to cubic meters, 1 m^3 = 35.315 ft^3, produces an error of only 0.03%.

Masses in this paper are reported in kilograms (kg) or metric tonnes (t); Mt denotes millions of metric tonnes.

Quantity and Composition of Bakken Natural Gas

In May, 2014, the month of the Gvakharia et al. [2017] survey, 9.4 billion standard cubic feet of natural gas was flared in the Bakken play [North Dakota, 2019], equal to 300 million cubic feet per day, 27% of total produced gas. In the first four months of 2019 flaring averaged 510 MMscf/d, see Figure 1. However, a larger fraction of produced gas was sold, reducing the percentage of gas flared to 19% [North Dakota, 2019]. In the balance of this report, the present daily average of flared gas in the Bakken is rounded off to 500 MMscf/d.

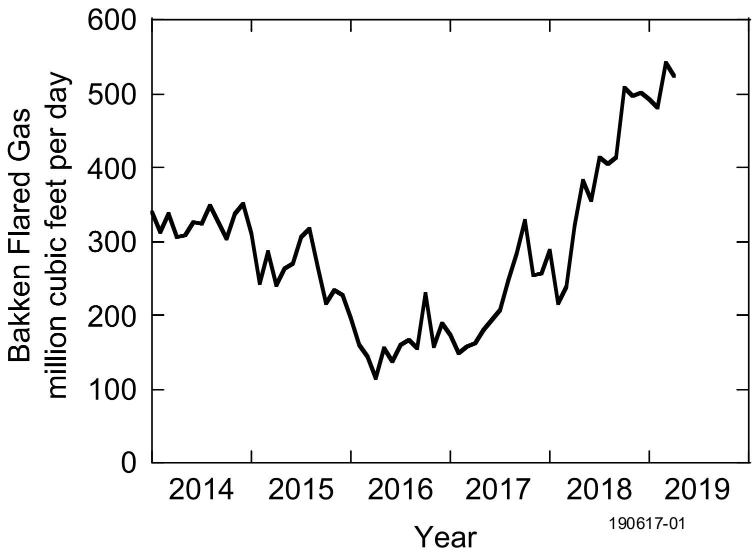

Figure 1. Flared Gas, Bakken [North Dakota, 2019].

The composition of this gas is quite different than the typical pipeline specification of 87% - 97% methane [Union Gas, 2017]. The average raw gas composition, in mole percent, of Bakken well production is reported by Brandt et al., [2015]. Molar percentages are nearly identical to volumetric percentages at standard temperature and pressure.

Quantity of Flared Hydrocarbon Gases

Gvakharia et al., [2017] report airborne surveys, conducted in May 2014, of visible flares in the Bakken region. Revisited flares were found to have variable combustion efficiencies, and therefore each of the 52 usable observations of 37 flares was treated as an independent observation. Observations were binned according to the fraction of methane remaining in the flare plume, R_i. The fraction of observations falling in each bin, $D(R_i)$, ("density" in the terminology of Gvakharia et al.) was displayed as a histogram. The authors found a nearly log-normal distribution of remaining methane. Although the most common percentage of uncombusted methane was near the expected value of 2% [EPA, 1996; Caulton et al., 2014; Lavoie et al., 2017], the distributions for methane and ethane, which were similar, were significantly skewed toward higher emissions.

The cumulative fraction of observations, Cum, for flare plumes with remaining methane fractions $R_i < R$, is calculated by

$$Cum(R) = \sum_{R_i=0}^{R} D(R_i) \qquad (1)$$

Figure 2 shows the cumulative fraction of observations (red curve and left vertical axis), plotted against fraction of remaining methane in the flare plumes (horizontal axis). The median observed fraction of uncombusted methane is 0.025. However, 9% of flares leave a tenth or more of inlet methane uncombusted.

I assume these observations are representative of the Bakken play as a whole. I further assume that the fraction of methane that has not been combusted mirrors the fraction of other hydrocarbon components of the raw natural gas mixture that escape combustion. The similarity of methane and ethane remaining gas histograms [Gvakharia et al., 2017] supports this assumption. Noncombustible gases (carbon dioxide, nitrogen, oxygen, and argon), which account for 4.4% of the Bakken raw gas mixture, flow through the flare unchanged and are not included in the hydrocarbon gas analysis. Hydrogen sulfide, 0.01% of the raw gas mixture, oxidizes to water and sulfur dioxide and also is not included.

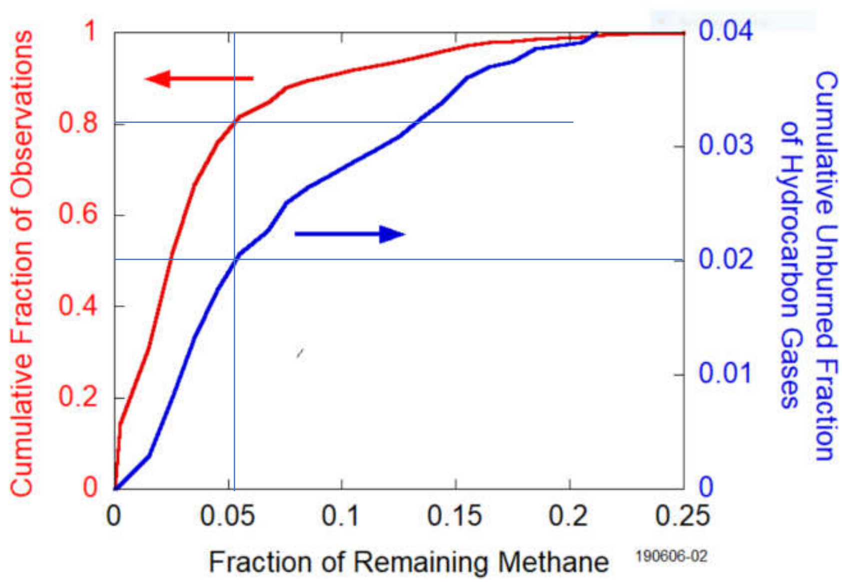

Figure 2. Red curve: Cumulative fraction of 52 observations of Bakken flares as a function of fraction of uncombusted methane. Data from [Gvakharia et al., 2017]. Blue curve: Cumulative unburned fraction of hydrocarbon gases.

The cumulative unburned fraction of hydrocarbon gases, F(R), for flare plumes with remaining methane fractions $R_i < R$, is calculated by

$$F(R) = \sum_{R_i=0}^{R} R_i \cdot D(R_i) \qquad (2)$$

This function is plotted (blue curve and right vertical axis) in Figure 2. Although flares typically allow 2% of hydrocarbon gases to escape unburned, inefficient flares increase the average unburned fraction to 4%, as reported by Gvakharia et al. 20% of flares, those passing unburned more than 5% of inlet gas, are responsible for half of the hydrocarbon emissions from flares.

Results and Discussion

Greenhouse Gas Inventory of Combusted and Fugitive Raw Natural Gas

While investigations of oilfield greenhouse gas emissions have focused primarily on carbon dioxide and methane, higher hydrocarbons including ethane, propane, butane, pentane, and hexane, play non-negligible roles. Gas associated with tight oil production is unusually rich in the higher hydrocarbons. Tight oil from the Bakken play is perhaps the most extreme example, with higher hydrocarbons representing 46.7% of produced gas [Brandt et al., 2015]. Higher hydrocarbon content is 28.4% of Niobrara gas and 31.1% of Eagle Ford gas [Conder & Lawlor, 2014]. The atmospheric concentration of ethane has been increasing since 2009 [Kort et al., 2014], coincident with the sudden advent of tight oil production in the United States [Kleinberg, et al., 2018].

The greenhouse gas footprint of fully combusted Bakken gas is computed in Table 1. When sent to a flare, higher hydrocarbons produce substantial amounts of carbon dioxide because each molecule of alkane C_xH_{2x+2} burns to form x molecules of CO_2. Thus pentane (C_5H_{12}) and hexane (C_6H_{14}), despite constituting less than 4% of the feed gas, account for more than 10% of the carbon dioxide emitted.

The results for vented gas shown in Table 2 do not include pentane or hexane, which are excluded from this analysis because their global warming potentials are not available. Based on the trend in GWP, it seems reasonable to assume their contribution to the vented gas GHG footprint will be relatively small.

Gas	Mole Fraction in Flare[a]	Volume Sent to Flare MMscf/d	Fully Combusted $V(CO_2)/V(gas)$	CO_2 Produced MMscf/d	CO_2 Mass[b] t/d
CO_2	0.0070	3.5	1	3.5	186
CH_4	0.4924	246.2	1	246.2	13,070
C_2H_6	0.2103	105.2	2	210.4	11,164
C_3H_8	0.1509	75.5	3	226.5	12,016
C_4H_{10}	0.0674	33.7	4	134.8	7,156
C_5H_{12}	0.0216	10.8	5	54.0	2,867
C_6H_{14}	0.0165	8.3	6	49.5	2,628
Total CO_2 + hydrocarbons	0.9661	483.1		924.7	49,085

(a) [Brandt, et al., 2015]; (b) CO_2 Density = 53.085 t/MMscf @ 60°F, 14.73 psia. Sums may not be exact due to rounding.

Table 1. Carbon dioxide production resulting from full combustion of hydrocarbon gases; total input to flares = 500 MMscf/d.

Gas	Vented Volume MMscf/d	Density[a][b] kg/m^3	Density[c] t/MMscf	Vented Mass t/d	GWP (100 Year) t(CO2eq)/t(gas)	CO_2eq t/d
CO_2	3.5	1.842	53.085	186	1	186
CH_4	246.2	0.668	19.251	4740	28[d]	132,710
C_2H_6	105.2	1.264	36.427	3830	10.2[e]	39,070
C_3H_8	75.5	1.882	54.238	4092	9.5[e]	38,876
C_4H_{10}	33.7	2.489	71.731	2418	6.5[e]	15,713
CO_2 + C1 . . . C4	464.0			15,266		226,554

(a) [Engineering ToolBox, 2003]; (b) 20°C, 101.325 kPa; (c) 60°F, 14.73 psia;
(d) [IPCC, 2013]; (e) [Hodnebrog et al., 2018]. Sums may not be exact due to rounding.

Table 2. Greenhouse gas footprint if gases are vented; total vented gas = 500 MMscf/d. Pentane and hexane are excluded because GWP data are unavailable; their contribution is expected to be relatively small.

The processes described here are linear, so the greenhouse gas footprints shown in the last columns of Tables 1 and 2, calculated for a flaring rate of 500 MMscf/d, can be linearly scaled for other flaring rates. Linearity also implies that if a flare leaves a fraction R of its feed gas uncombusted its greenhouse gas footprint is [U·R + C·(1-R)], where U is the GHG footprint of completely uncombusted (vented) gas in tonnes of CO_2eq, and C is the GHG footprint of completely combusted gas in tonnes of CO_2.

Assuming the data are representative of contemporary emissions, the methane histogram of Gvakharia et al. [2017] can be used to estimate the greenhouse gas footprint of Bakken play flaring.

$$\text{GHG Footprint} = \sum_{R_i=0}^{1} D(R_i) \cdot \left[U \cdot R_i + C \cdot (1 - R_i)\right] \qquad (3)$$

where, for 500 MMscf/d flaring of feed gas with average Bakken composition [Brandt et al., 2015], U = 226,554 t(CO_2eq)/d and C = 49,085 t(CO_2)/d).

If the feed gas is 100% methane, complete combustion of 500 MMscf yields 500 MMscf of carbon dioxide, which has a mass of (500 MMscf/d) x (53.085 t/MMscf) = 26,543 t(CO_2)/d. If the methane is vented, 500 MMscf(CH_4)/d = 9625 t(CH_4)/d. A 100-year GWP = 28 t(CO_2eq)/t(CH_4) implies 269,516 t(CO_2eq)/d.

Feed Gas	Fraction Uncombusted Feed Gas	Greenhouse Gas Footprint t(CO_2eq)/d
100% Methane	0	26,543
	0.02	31,402
	Observed Distribution[(b)]	36,606
	1.00	269,516
Bakken Mixture[(a)]	0	49,085[(c)]
	0.02	51,162
	Observed Distribution[(b)]	56,435
	1.00	226,554[(d)]

(a) [Brandt et al., 2015]; (b) [Gvakharia et al., 2017];
(c) Including pentane and hexane; (d) Excluding pentane and hexane

Table 3. Bakken greenhouse gas footprints under various assumptions on feed gas composition and flaring efficiency. Included are 100% efficient flaring (fraction uncombusted = 0) and venting (fraction uncombusted = 1.00). Total feed gas is 500 MMscf/d.

Table 3 summarizes estimates of greenhouse gas footprints under various assumptions on feed gas composition and flaring efficiency.

Note that for 100% methane, the GHG footprint for venting is close to ten times that for complete combustion. This is as expected. Complete combustion of one mole of methane (16.04 g) yields one mole of carbon dioxide (44.01 g). Venting of 16.04 g of methane, multiplied by a 100-year global warming potential of 28 [IPCC, 2013] implies a greenhouse gas footprint of 449.1 g(CO_2eq).

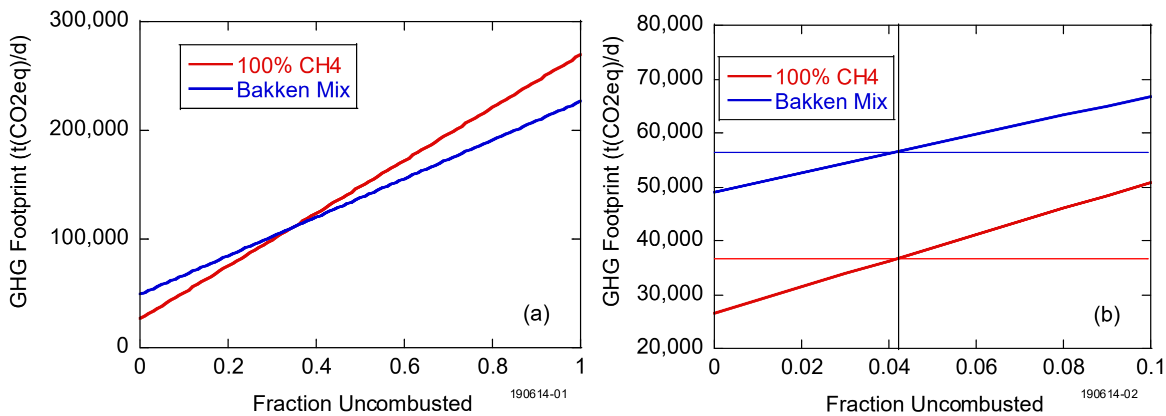

Figure 3. Greenhouse gas footprint of flares totaling 500 MMscf/d, as a function of fraction of feed gas uncombusted. Red lines: 100% methane; Blue lines: average Bakken feed gas composition [Brandt et al., 2015]. (a) Full range of flare inefficiencies, 0 = complete combustion, 1 = venting without combustion. (b) Detail showing GHG footprint of observed distribution of Bakken flare efficiencies [Gvakharia et al., 2017] for 100% methane (horizontal red line) and average Bakken feed gas composition [Brandt et al., 2015] (horizontal blue line). Field average flare efficiency is 0.042 (vertical black line).

An overview of the results is shown in Figure 3(a). At 100% flare efficiency (fraction uncombusted = 0) gas which includes higher hydrocarbons has a higher GHG footprint than pure methane because each molecule of hydrocarbon reacts with oxygen to form several molecules of carbon dioxide. When gas is vented (fraction uncombusted = 1), greenhouse gas footprints are much larger, with the venting of methane having a larger effect than the venting of the Bakken mixture. When vented, the influence of the higher hydrocarbons on emission mass is proportional to the number of carbon atoms in their molecules, through their gas-phase density. However, the 100-year global warming potential of methane [IPCC, 2013] is significantly larger than that of the higher hydrocarbons [Hodnebrog et al., 2018].

The Bakken field-average GHG footprint of 500 MMscf/d flaring is 56,435 t(CO_2eq)/d. Figure 3(b) shows the effective field-average fraction of uncombusted flare gas is 4.2%., as asserted by Gvakharia, et al. [2017].

Unignited Flares

I have shown that unburned field gas is the source of a non-negligible quantity of short-lived climate pollutants. Figure 2 data shows that 9% of ignited flares leave 10% or more of their feed gas uncombusted. A potentially even more serious problem is that of unignited flares. By law, all flares must be equipped with pilot lights, so that any combustible gas routed to the flare is automatically burned; the pilot light should be continuously monitored detect the presence of a flame. [EPA, 2008].

Nonetheless, there are both anecdotal [Energy Voice, 2018; Martinez News-Gazette, 2018; Boothroyd, 2018; Kairos Aerospace, 2019] and systematic [Lyon et al., 2016] reports of unlit flares. Failure to ignite a flare is an easily correctable oversight, and therefore may not be quantified or reported. Inspection of flare stacks for methane emissions is mandated by the Environmental Protection Agency, but only a few times a year [EPA, 2016; EPA, 2018a]. The aerial survey of Gvakharia, et al. was confined to visible flares, a reasonable protocol given their survey constraints. In order to fully assess the influence of unignited flares, systematic surveys of oil and gas infrastructure similar to that of Lyon et al. [2016] are required.

Discussion

For 500 MMscf/d of flaring in the Bakken, the approximate volume in 2019, we can expect a greenhouse gas footprint of about 56,000 t(CO_2eq)/d = 20 Mt(CO_2eq)/y. This is 8% of 253 Mt(CO_2eq)/y, the annual national emissions of greenhouse gases of natural gas and petroleum supply systems [EPA, 2019b, Table ES-4]. It is also 6% of 350 Mt(CO_2eq)/y, the annual global emissions from flaring [World Bank, 2019] – assuming the global and national figures are correct.

Bakken activity dominates the Williston Basin, where in 2017 onshore natural gas and petroleum systems production facilities (exclusive of gathering and boosting, processing, and transmission) emitted 12 Mt CO_2eq/y, according to the Environmental Protection Agency Greenhouse Gas Reporting Program (GHGRP) [EPA 2019a]. Nationally, flaring accounts for 15% of onshore natural gas and petroleum systems production facilities emissions [EPA, 2018b, Figure 5], suggesting that flare emissions totaled 1.8 Mt CO_2eq/y in the Bakken. I believe this estimate considerably underestimates the actual GHG footprint of Bakken flares.

According to the North Dakota Department of Mineral Resources, 79 billion cubic feet of gas was flared from Bakken wells in 2017 [North Dakota, 2019]. Assuming very conservatively that all the gas was methane and all flaring was 100% efficient, carbon dioxide production would be (79×10^6 Mscf/y)x(0.019 t/Mscf)x(44/16) = 4.1 Mt(CO_2)/y. Thus the 2017 EPA estimate must be at least a factor of 2.3 smaller than the amount of CO_2 actually emitted from flares that year.

Moreover, I have shown (Table 3) that the assumptions of 100% methane and 100% flare efficiency underestimate actual flaring GHG footprint by another factor of 2.1. Further considering that natural gas flaring in the Bakken play increased from 216 MMscf/d in 2017 to 500 MMscf/d in 2019, I find the present rate of greenhouse gas emissions in the Bakken is expected to be a factor of 11 larger than the 2017 EPA GHGRP estimate.

The national greenhouse gas emission inventory is based on the emission factor method, comprehensively documented in studies like the fifteen volume "Methane Emissions from the Natural Gas Industry" [EPA, 1996]. Given the large scale and dispersed nature of the U.S. natural gas supply industry – a million wells, thousands of processing and distribution facilities, millions of miles of pipelines [Alvarez et al., 2018] – the emission factor method was a rational first approximation needed to understand the scale of greenhouse gas emissions at the national scale. However, as more sophisticated measurement campaigns are being undertaken, the limitations of the emission factor approach are becoming increasingly apparent [Alvarez et al., 2018].

This study points out the limitations of the emission factor approach applied to flaring. The likely GHG footprint of flaring 500 MMscf/d in the Bakken is, as noted, 56,400 t(CO_2eq)/d. This is considerably larger than naive estimate of 31,400 t(CO_2eq)/d based on methane-only flares operating at 98% efficiency.

Small surveys have not observed low-efficiency flares [Caulton et al., 2014; Lavoie et al., 2017] although this problem was evident in earlier studies [EPA 1996]. The high degree of variability in all emission sources suggests that large, repeated surveys are needed to understand the full spectrum of flare emissions [Gvakharia et al., 2017; Lavoie et al., 2017]. The temporal variability of flare efficiency implies that a survey, no matter how careful, is not a reliable predictor of the future efficiency of any particular flare stack. For example, wind speed is a significant complication that reduces both flare efficiency [Blackwood, 2000] and methane plume detectability [Ball Aerospace, 2017]. The contribution of unignited flare stacks to greenhouse gas inventories remains completely obscure.

The state of industry understanding of the problem of greenhouse gas emissions from natural gas and petroleum systems was perhaps best summarized by Ben van Beurden, Chief Executive Officer of Royal Dutch Shell, who has said that we can't measure methane, we just get an impression; we need real measurements, otherwise the discussion is artificial [van Beurden, 2018].

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Disclosure

The author declares no competing financial interest.

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