Updated Fugitive Greenhouse Gas Emissions for Natural Gas Pathways in the GREET1_2015 Model

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1 BACKGROUND

Argonne National Laboratory researchers have been analyzing the environmental impacts of natural gas (NG) production and use for more than 15 years. With the rapid development of shale gas production in the past few years, significant efforts have been made to examine the methane (CH_4) emissions from various stages of natural gas pathways to estimate their life-cycle greenhouse gas (GHG) emissions. In 2011, Argonne researchers examined the uncertainty associated with key parameters for shale gas and conventional NG pathways to identify data gaps that required further attention (Burnham et al. 2011). Burnham et al. (2011) based much of their analysis on the United States Environmental Protection Agency's (EPA's) 2011 greenhouse gas inventory (GHGI), as this was the first EPA GHGI to incorporate shale gas and included significant revisions to its liquid unloading leakage estimates (EPA 2011). In 2013 and 2014, Argonne researchers updated the GREET model based on EPA's latest GHG inventories, which included several methodological changes for estimating natural gas CH_4 emissions (Burnham et al. 2013; Burnham et al. 2014). Methane emissions continue to receive significant scrutiny as many studies have analyzed whether the EPA's inventory fully captures the actual emissions from the natural gas industry. In addition to properly estimating emissions, regulatory and voluntary efforts have been proposed to reduce current emissions. The Obama Administration has set a goal to reduce oil and gas CH_4 emissions by 40-45% from 2012 levels by 2025, so further scrutiny of the sources of these emissions is needed (White House, 2015).

Two recent studies by the University of Texas examined two of the largest sources of natural gas production CH_4 emissions, (1) pneumatic controllers and (2) liquid unloadings, by directly measuring emissions from equipment at numerous sites across the U.S. (Allen et al. 2015a; Allen et al. 2015b). The pneumatic controller study found that emission rates varied by region, type, and application and that 19% of the devices accounted for 95% of the emissions (Allen et al. 2015a). On average, the emission rates of the controllers were 17% higher than those reported in the 2014 EPA GHGI. In addition, the controller activity factors in the GHGI might be too low as the study found 2.7 controllers per well, while the GHGI only estimated 1.0 controller per well. Variability in CH_4 emissions was also found in the liquid unloadings study, which analyzed wells with and without plunger lifts. Though two of the key factors that explained the variability were unloading frequency and well age; the higher the unloading frequency and the older the well, the higher were the emissions (Allen et al. 2015b). Overall, the

average CH_4 emission from this study was within a few percent of the 2014 EPA GHGI. In the most recent GHGI, the EPA did not incorporate these findings but suggested that these data, along with others, would be analyzed for possible inclusion in the 2016 inventory (EPA 2015a).

Howard (2015) published a study indicating that the high-flow sampling equipment used in the University of Texas studies (Allen et al. 2013; Allen et al. 2015a; Allen et al. 2015b) had a sensor failure that caused a systematic underestimation of CH_4 emissions. The key evidence was the lack of high emitting observations in those studies at gas compositions where the sensor is known to fail. Separate tracer measurements done by Allen et al. (2013) at some of the well sites suggest the high-flow measurements were a factor ranging from three to five too low. This could have significant impacts on the EPA GHGI as about 40% of emissions may be affected by this equipment failure.

Marchese et al. (2015) analyzed tracer measurements of natural gas gathering and processing facility-level CH_4 emissions at many sites across the U.S. Using facility counts from state and national databases, the researchers performed a Monte Carlo simulation to estimate total U.S. gathering and processing emissions. Gathering facilities are imbedded in the production segment of the EPA GHGI and the researchers attempted to apportion activity data from the GHGI to compare to their results for the gathering sector. In the 2014 EPA GHGI, the researchers estimated that the GHGI gathering sector emissions are 404 Gg (178 Gg for gathering pipelines and 226 Gg for gathering facilities), representing about 20% of the inventory's production emissions (1,992 Gg). However, their estimate using tracer measurements for gathering facilities emissions was 1,697 Gg [1,512 to 1,886 Gg based on 95% confidence interval (CI)], more than seven times higher than the inventory's value and almost equal to the GHGI production sector's total emissions. The researchers were able to directly compare their processing plant estimate of 506 Gg [454 to 561 Gg based on 95% CI] to the 851 Gg reported in the EPA inventory for normal operations.

Zimmerle et al. (2015) analyzed numerous direct equipment and site-level tracer measurements, as well as about one-third of the activity data of the transmission and storage sector. In emission models developed from this data, a majority exhibited long-tail behavior with the largest 5% of measurements accounting for 40-75% of measured CH_4 emissions; super-emitting facilities accounted for 23% of emissions. While their emission rates for specific equipment tended to be higher than the GHGI, the researchers found fewer facilities and a larger portion of lower-emitting equipment compared to those in the GHGI. Overall, the researchers' estimated that transmission and storage sector emissions were 1,503 Gg [1,220 to 1,950 Gg based on 95% CI], which were lower than the 2,071 Gg [1,680 to 2,690 Gg based on 95% CI] reported in the 2014 EPA GHGI; however, the confidence intervals do overlap.

McKain et al. (2015) performed a top-down CH_4 emissions analysis of the urban region of Boston, MA using one year of tower-based measurements and atmospheric modeling. The scope of the study included NG transmission, distribution, and end-use emissions. The Boston area has a significant amount of older cast iron and unprotected steel pipelines, which have higher leak rates than newer plastic pipes. These emissions were differentiated from other sources of CH_4, such as landfills, by using ratios of propane to CH_4 observed in the atmosphere and NG pipelines serving the region. The study estimated an average leakage rate (based on

consumption) between 2.1 and 3.3 percent, and that CH_4 emissions were about two to three times higher than those in GHGI. The emissions estimated in this study were significant as they were equal to 8% of the U.S. total transmission and distribution emissions and 23% of distribution emissions in the 2014 EPA GHGI, whereas only 3% of U.S. residential and commercial gas is consumed in the Boston area.

Lamb et al. (2015) analyzed direct measurements of CH_4 emissions from underground pipeline leaks and metering and regulating facilities of 13 urban natural gas distribution systems. The researchers found that the northeastern states accounted for 34% of CH_4 emissions from pipeline leaks, while the western states only accounted for 20%. As suggested by McKain et al. (2015), cast iron and unprotected steel pipes were a significant source, accounting for 70% of eastern and 50% of total U.S. emissions. As found in the previously mentioned studies, a few large leaks accounted for the majority of emissions. However, as compared to 2013 EPA GHGI, which largely uses data from a 1992 (Harrison et al.), the researchers found the emission rates to be two times lower than those in the GHGI. Similarly, metering and regulating stations had much lower emission rates than the GHGI; specifically large emitting categories were 14 times lower. Through regulations and investment by the utilities, the distribution system has undergone significant upgrades in the past two decades. While it seems like the GHGI underestimated CH_4 emissions, the authors noted that just a few large leaks highly influenced their results, so it is important to recognize their upper bound estimate when doing comparisons. Even so, the researchers' estimated that distribution emissions were 393 Gg [854 Gg upper 95% CI], significantly lower than the 1,329 Gg reported in the 2013 EPA GHGI. The researchers suggested that more research is needed to understand the discrepancies between their bottom-up analysis and the top-down results of distribution systems, such as those from McKain et al. (2015). This should include further examination of emissions downstream of customer meters, pipeline leaks that migrate into sewers, transmission equipment in urban areas, and other sources.

The above studies show some shortcomings in the EPA's GHGI and suggest that further research is needed to improve CH_4 emissions estimates for the NG industry. As there is still uncertainty regarding the results from these studies and the need for detailed process-level emissions, we used the 2015 EPA GHGI to update GREET. We will continue to monitor and evaluate emerging research in this area and update GREET accordingly.

2 DATA

2.1 Key GREET Parameters

Table 1 and Table 2 list the key parameters and data sources for natural gas pathways used to update GREET1_2015. The data from EPA (2015a) and EIA (2014 and 2015) natural gas throughput is for calendar year 2013. In the following sections, we briefly summarize where changes have occurred since the previous release of GREET (Burnham et al. 2014).

2.2 Shale Gas Well Completion and Workover CH_4 Emissions

In the latest inventory, the EPA (2015a) incorporated the latest Greenhouse Gas Emissions Reporting Program (GHGRP) data into their estimate of net (i.e. controlled) emission factors for completions and workovers. The EPA continues to separate completions and workovers into four categories: (1) hydraulic fracturing completions and workovers that vent, (2) flared hydraulic fracturing completions and workovers, (3) hydraulic fracturing completions and workovers with reduced emission completions (RECs), and (4) hydraulic fracturing completions and workovers with RECs that flare. The data shows that 2013 CH_4 emission rates for each category has decreased by 25%, except for RECs which stayed consistent with 2011-2012 values (EPA 2015b).

EPA also uses the GHGRP dataset to estimate completion and workover activity data, which were also updated to take into account changes in REC counts and flaring. We use these activity data to estimate the percentage of wells that vent versus the ones that use RECs. From 2012 to 2013, the percentage of wells that vent decreased from 58% to 35%. Flaring emissions from completions and workovers are included in the shale gas "well equipment flaring" category in Table 1.

Table 1 Key Parameters for Natural Gas Simulations in GREET1_2015

	Units	Conventional	Shale	Source/Notes
Well Lifetime	Years	30	30	Argonne assumption
Well Methane Content	mass %	76	82	EPA 2015a
NG Production over Well Lifetime	NG billion cubic feet	N/A	1.6	INTEK 2011
NG Production over Well Lifetime	NG million Btu	N/A	1,600,000	INTEK 2011 and Argonne assumption of NG LHV
NGL Production over Well Lifetime	NGL million Btu	N/A	210,000	EPA 2015a and EIA 2014
Well Completion and Workovers (Venting)	metric ton NG per completion or workover	0.71	37	Conv: EPA 2010 and Shale: EPA 2015a
Well Completion and Workovers (w/ REC)	metric ton NG per completion or workover	N/A	3	EPA 2015a
Well Completions/ Workovers that Vent	%	N/A	35	EPA 2015a
Controlled CH_4 Reductions for Completion/Workovers	%	0	0	EPA 2015a
Average Number of Workovers per Well Lifetime	Workovers occurrences per lifetime	0.2	0.2	EPA 2012
Liquid Unloading (Venting)	g CH_4 per million Btu NG	10	10	EPA 2015a
Controlled CH_4 Reductions for Liquid Unloading	%	0	0	EPA 2015a
Potential Well Equipment (Leakage and Venting)	g CH_4 per million Btu NG	104	104	EPA 2015a
Controlled CH_4 Reductions for Well Equipment	%	50	50	EPA 2015a

Table 1 (Cont.)

	Units	Conventional	Shale	Source/Notes
Well Equipment Flaring	Btu NG per million Btu NG	9,716	9,558	EPA 2015a
Well Equipment (CO_2 from Venting)	g CO_2 per million Btu NG	12	12	EPA 2015a
Processing (Leakage and Venting)	g CH_4 per million Btu NG	27	27	EPA 2015a
Processing (CO_2 from Venting)	g CO_2 per million Btu NG	807	807	EPA 2015a
Transmission and Storage (Leakage and Venting)	g CH_4 per million Btu NG	84	84	EPA 2015a
Distribution (Leakage and Venting)	g CH_4 per million Btu NG	89	89	EPA 2015a
Distribution - Station (Leakage and Venting)	g CH_4 per million Btu NG	69	69	EPA 2015a and EIA 2013

Table 2 Natural Gas Throughput by Stage for GREET1_2015

	Units	Values	Sources
Dry NG Production	Quadrillion Btu	23.9	EIA 2015
NGL Production	Quadrillion Btu	3.0	EIA 2014
NG Production Stage (Dry NG and NGL)	Quadrillion Btu	27.0	EIA 2015 and EIA 2014
NG Processing Stage (Dry NG and NGL)	Quadrillion Btu	27.0	EIA 2015 and EIA 2014
NG Transmission	Quadrillion Btu	23.9	EIA 2015
Percent of Local Distribution NG Deliveries	%	63.0	EIA 2013
NG Distribution	Quadrillion Btu	15.0	EIA 2015 and EIA 2013

2.3 Natural Gas Throughput Leakage Rate

In GREET, natural gas CH_4 emissions are presented on a throughput basis for each stage in a pathway, e.g., transmission CH_4 emissions divided by transmission NG throughput (Burnham et al. 2013). In our previous analyses, volumetric throughput leakage rates by stage (CH_4 emissions as a percent of NG throughput) have been presented for EPA and GREET, and the total emissions rate was estimated by adding together each individual stage. However, this does not properly account for the fact that leak rates at later stages, are impacted by the upstream leakage. For example, if a pathway is two stages and each has a 50% leak rate, the total throughput leakage is 75% and not 100%. Figure 1 shows a representation for a volume of gas Q_0 moving through *n* sectors, with sector throughputs Q_0, Q_1, $Q_2 \ldots Q_n$; sector emissions E_0, E_1, $E_2 \ldots E_n$; and fractional throughput leak rates L_0, L_1, $L_2 \ldots L_n$ (Alvarez 2013). Figure 2 shows the resulting adjusted throughput leak rate equation (Alvarez 2013), while Figure 3 shows the equation in its simplified form.

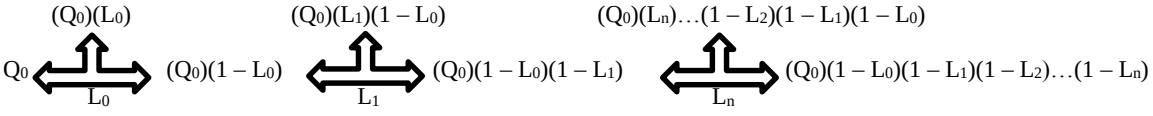

Figure 1 Throughput Flow, Emissions, and Leak Rates

$$\sum_{0}^{n} L = \frac{L_0 + L_1(1 - L_0) + L_2(1 - L_0)(1 - L_1) + \cdots + L_n(1 - L_0)(1 - L_1)(1 - L_2) \ldots}{(1 - L_0)(1 - L_1)(1 - L_2) \ldots (1 - L_n)}$$

Figure 2 Adjusted Throughput Leak Rate

$$\sum_{0}^{n} L = 1 - [(1 - L_0) \times (1 - L_1) \times (1 - L_2) \times \ldots \times (1 - L_n)]$$

Figure 3 Simplified Adjusted Throughput Leak Rate

2.4 Summary

Table 3 summarizes the CH_4 fugitive emission for both shale and conventional NG in GREET1_2015 and compares them to previous estimates in GREET1_2014. Shale gas CH_4 emissions are reduced significantly for completions and workovers due to the inclusion of the most recent EPA's GHGRP data, while flaring has increased (as seen in Table 1). Liquid unloading emissions was reduced slightly, while well equipment, transmission, and distribution were slightly higher. Table 4 compares the leakage rate based on NG throughput by stage from several EPA reports with those used in the GREET1_2015 model, while Table 5 lists reported and calculated leakage rates based on gross NG production of various studies. As mentioned previously, leakage rates are not always comparable if they use different denominators.

The EPA's estimates of NG system CH_4 emissions have decreased significantly since its 2011 inventory, while top-down analyses suggest these CH_4 emissions should be higher. The recent bottom-up studies developed through a collaboration of the Environmental Defense Fund, universities, research institutions, and companies (Allen et al. 2015a; Allen et al. 2015b, Marchese et al. 2015, Zimmerle et al. 2015, Lamb et al. 2015) show some in leakage rate by stage as compared to the most recent EPA GHGI (2015); however in total, the results are similar. We will continue to update GREET as more research is pursued to reduce the discrepancies between bottom-up and top-down analyses of CH_4 emissions in the NG system.

Table 3 Summary of Differences in CH_4 Emissions per Throughput of Each Stage between GREET1_2014 and GREET1_2015

Sector	Process	Unit	Conventional GREET1_2014	Shale GREET1_2014	Conventional GREET1_2015	Shale GREET1_2015	Conventional % Change	Shale % Change
Production	Completion	g CH_4/million Btu NG	0.5	12.4	0.5	7.2	0%	-42%
	Workover		0.0	2.5	0.0	1.4	0%	-42%
	Liquid Unloading		10.4	10.4	9.6	9.6	-7%	-7%
	Well Equipment		51.3	51.3	52.2	52.2	2%	2%
Processing	Processing	g CH_4/million Btu NG	26.7	26.7	26.7	26.7	0%	0%
Transmission	Transmission and Storage	g CH_4/million Btu NG	81.2	81.2	84.5	84.5	4%	4%
Distribution	Distribution	g CH_4/million Btu NG	83.1	83.1	88.9	88.9	7%	7%
Distribution	Distribution (station pathway)	g CH4/million Btu NG	63.6	63.6	69.1	69.1	9%	9%
Total		**g CH_4/million Btu NG**	**253.2**	**267.5**	**262.4**	**270.5**	**4%**	**1%**
Total (station pathway)		**g CH_4/million Btu NG**	**233.8**	**248.1**	**242.5**	**250.6**	**4%**	**1%**

Table 4 GREET and EPA Leakage Rates Based on NG Throughput by Stage

	CH_4 Emissions: Percent of Volumetric NG Stage Throughput					
Sector	EPA GHGI - 5yr avg (2011)	EPA GHGI - 2011 Data (2013)	EPA GHGI - 2012 Data (2014)	EPA GHGI - 2013 Data (2015)	GREET - Conv. Gas (2015)	GREET - Shale Gas (2015)
Gas Field	1.32	0.45	0.34	0.34	0.30	0.34
Completion/ Workover					0.00	0.04
Unloading					0.05	0.05
Other Sources					0.25	0.25
Processing	0.17	0.12	0.13	0.16	0.13	0.13
Transmission and Storage	0.49	0.44	0.39	0.44	0.41	0.41
Distribution	0.57	0.36	0.40	0.43	0.43	0.43
Total	2.53	1.37	1.25	1.36	1.26	1.30

Table 5 Selected Leakage Rates Based on Gross NG Production

	CH_4 Emissions: Percent of Volumetric NG Stage Throughput								
Sector	EPA GHGI - 2011 data (2013)[a]	Univ. Texas - Production (2013)[b]	EPA GHGI - 2012 data (2014)[c]	Stanford - US (2014)[d]	IUP - Bakken (2014)[e]	IUP - Eagle Ford (2014)[e]	EPA GHGI - 2013 data (2015)[f]	CSU / WSU - US Combined (2015)	Harvard - Boston (2015)[j]
Gas Field	0.44	0.38	0.33		2.8-17.4	2.9-15.3	0.31	0.58[g]	
Completion/ Workover	0.14	0.03	0.04				0.01		
Unloading	0.04	0.04	0.05				0.04		
Other Sources	0.26	0.31	0.25				0.25		
Processing	0.16		0.15				0.15	0.09[g]	
Transmission and Storage	0.34		0.35				0.36	0.25[h]	
Distribution	0.23		0.21				0.22	0.07[i]	2.1-3.3
Total	1.17		1.03	3.6-7.1			1.03	0.99	

[a] EPA - US GHGI 2011 data (2013) divided by EIA 2011 gross withdrawals

[b] Univ. Texas - Production (Allen et al 2013) - equipment measurements divided by EIA gross withdrawals, used EPA 2011 data (2013) for some Other Sources

[c] EPA - US GHGI 2012 data (2014) divided by EIA 2012 gross withdrawals

[d] Stanford - US (Brandt et al. 2014) estimate is based on allocating all excess leakage from NG, oil, and geologic seep sources to the NG industry; values are an upper level bound and not a best estimate

[e] IUP - Bakken and Eagle Ford (Schneising et al. 2014) - leakage rate is based on both NG and oil production in those areas converted to energy basis

[f] EPA - US GHGI 2013 data (2015) divided by EIA 2013 gross withdrawals

[g] CSU / WSU - US Combined – Production and Processing (2015) estimate from Marchese et al. (2015) - NG gathering and processing facility-level emissions used to model US and replaced respective estimates in EPA 2012 GHGI (2014); total production and processing divided by EIA 2012 gross withdrawals

[h] EPA - CSU / WSU - US Combined – Transmission and Storage (2015) estimate from Zimmerle et al. (2015) equipment and site-level measurements and activity data used to model US transmission and storage emissions divided by EIA 2012 gross withdrawals

[i] EPA - CSU / WSU - US Combined – Distribution (2015) estimate from Lamb et al. (2015) direct measurements used to model US distribution emissions divided by EIA 2011 gross withdrawals

[j] Harvard - Boston (2015) - tower measurements including NG transmission, distribution, and end-use emissions in Boston divided by consumption

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